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Introductory Lecture

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Introductory Lecture for the VDEh-Seminar „Electrotechnics of the Electric Arc Furnace“

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1. Introduction

In 1982 the chairman of the sub-committee 'Electric arc furnace'. Dr. Ameling and Prof. Timm decided to organise a seminar dealing with the technology of the electric arc furnace. This successful seminar has permanently been updated and will today be held in the English language for the fifth time.

As current chairman of the sub-committee 'Electric arc furnace' of the "Stahl Institut VDEh" I will hold this introductory lecture.

Subsequent to the historical development of the production of crude steel and in particular of the production of electric arc furnace steel I will put the special emphasis on the raw materials of the electric arc furnace. Apart from scrap I also deal with the sponge iron. After a cost comparison between the main processes for the production of crude steel, the BOF-steel and the electric arc furnace I will come to speak to the stage of developments of the electric arc furnace with a brief outlook on further developments.

Even now I would like to draw your attention to the completely revised edition of the book "Elektrostahl-Erzeugung" by Mr. Heinen published by Stahleisen where all aspects of the production of electric arc furnace steel are discussed in detail. Additionally I would like to present the english version of the handbook of "Thermoprocessing Technologies" published by "Vulcan".

2. Development of the production of crude steel and the processes of steel production

The Iron Age we are living in today began with the production of objects made of meteoric iron. The metallurgical treatment of iron ores developed to the very advanced civilisations of the antiquity: wrought iron in the Cheops pyramid, inscriptions on the melting of iron on the walls of the temple in Luxor, but also the famous Indian column with a weight of 6 tons prove that about 2000 - 3000 before Christ iron was known as material for utensils and arms. At the Siegerland bloomery hearth furnaces from the Latène Age approx. 500 before Christ were found in which the domestic siderite was reduced by charcoal to a forgeable loop.

In the middle of the 19th century the mass production of steel started with the process of steel production by Bessemer (1855) and Thomas (1877) based on the blowing of pig iron. Even in 1864 scrap was successfully remelted to liquid steel in an open hearth furnace. In 1900 the industrial

production of steel in an electric arc furnace started with the furnace by Hérault.

Figure 1 shows the time shape of the global production of crude steel. In general the graph showing the increase in the global production of crude steel has a S-shape as it is also known from biological growth processes. The steep increase in 2003 has its reason in the steel production of China. Two main factors can be mentioned as causes for the significant increase in the production of crude steel [1]:

- the increasing demand from the sectors mechanical engineering (rolled products) housing construction, local administration (pipes and tubes), transportation engineering (railways, cars, lomes) and packaging industry (tins and cans) as well as
- Increasing availability of low-priced raw materials such as iron ore, coking coal, mechanical and electric energies, oxygen and the secondary raw material scrap.

The period of the "Cold War", the years 1950 - 1970, coincided with the flowering period of the steel industry. The effects of the two oil crises are clearly to be seen. Between 1990 and 2004 the steel production in far east, mainly in China, got a high increase. China increases the steel production from 66 mio tons in 1990 to 272 mio tons in 2004. The influence of this production increase on the scrap and alloy market will be described later. Parallel the price for iron ore, coke and cargo exploded to the highest level we ever had. (**Fig. 1a, 1b**)

The two factors mentioned above are only two components of a control loop including variables such as the increase in the global population by improved medical care and hygienic situation, political events, increasing environmental awareness etc.

For the same period **Figure 2** shows the development of the shares of the various processes used for the production of steel related to the global production of crude steel [2]. Even in 1970 there wasn't any Thomas converter left due to the tightened regulations concerning the prevention of air pollution. The nearly complete decrease of the open hearth process from a share of 43% in 1970 to only 4.3 % in 2003 was disproportionately compensated by the use of electric arc furnaces.

The increase in the share of electric arc furnaces in the global production of crude steel is based on the philosophy of the so-called mini-steel mill gaining in significance since the beginning of the seventies (see **Fig. 3**). In

smaller plants the local scrap should be processed in the line electric arc furnace - continuous casting plant for billets - wire mill respectively rod mill to simple straight products such as concrete reinforcing steel or reinforcing wire meshes which then can be sold in turn on the local markets. Consequently the North-Italian „Bresciani" turned out to be fierce competitors of the traditional steel producers. Even at the beginning of this development Willi Korf had the vision of an integrated mini-steel works: At locations near the coast sponge iron should be produced by the newly developed direct reduction process according to the MIDREX-process and should be used alternatively or additionally to scrap in the electric arc furnace. At this time natural gas and nuclear power were very favourable. Based on this idea the integrated mini-steel works in Georgetown (GSC), USA and Hamburg (Ispat HSW) are founded.

Besides the classic mini-steel works on a 100% scrap basis which - depending on the final product - have a production capacity of 0.5 to 1.2 million tons p.y. there are today several metallurgical plants which via the line direct reduction - electric arc furnace produce some million tons p.y. such as IMEXSA, Mexico, and HADEED, Saudi Arabia with more than 3 million tons p.y. each and SIDOR, Venezuela with more than 6 million tons p.y.

The advantages of the mini-steel works are on the one hand given by the relatively low capital expenditures of 300 - 400 US\$/t annual capacity as well as on the other hand by the low staff costs. Mini-steel works can be operated with approx. 1 man hour/ton - compared with approx. 3 man hours/ton at the large integrated steel mills. Concerning these comparisons we, however, must proceed with caution as quite often only the man hours provided by the own employees are recorded but not those provided by subcontractors on the respective plant site. After a period of partly drastic outsourcing - Germany is just passing this phase - some mini-steel works in the US (e.g.: Charparral Steel) have started remembering that the quality of any process - no matter whether tailored to internal or external customers - can be improved best by highly motivated own employees.

2.2 Europe

When reflecting the distribution of the various processes for the production of crude steel in the European Union of 15 Nations (**Figure 4**) a steady increase in the total production of crude steel can be stated for the time after 1985. With 41 % the share of electric furnace steel is higher than the respective share in the global production with 33 % and considerably higher than in Germany with 31 %. After the German Reunification the

open hearth process came to a standstill. Among other reasons the disproportionate increase in the share of electric furnace steel was caused by the restructuring of the Aceralia-corporation in Luxembourg from an integrated metallurgical plant with blast furnaces and BOF steelmaking plants to steel works with electric arc furnaces.

2.3 Germany

The development of the share of the electric arc furnaces in the total production of crude steel in Germany can be seen from Fig. 5 [3]. The decrease in the steel production by means of the open hearth process could not be compensated by the electric arc furnaces. Until 1989, the year of the German reunification, even a slight decrease in the steel production by electric arc furnaces can be seen. After that there is a steep increase up to the current share of 31 %. This increase results from the intensified utilisation of the capacities for electric furnace steel in the former German Democratic Republic in Hennigsdorf, Brandenburg and Riesa as well as from the substitution of basic oxygen steelmaking plants in Unterwellenborn, Georgsmarienhütte and Peine by modern direct current arc furnaces.

Compared with 41% in the EU and 33 % for the whole world the steel production by means of electric furnaces is in Germany with a share of 31 % a factor of lower importance although - as we will see in the next chapter - Germany is a country with a export rate for scrap. Despite this advantage concerning the availability of this raw material the high power rates didn't encourage the steel production by means of electric furnaces in Germany in the past (see **chart 1**). Whilst in 1993 this disadvantage concerning the power rates against France amounted to 0.0245 €/kWh, this difference decreased to 0.017 €/kWh from 1996 due to new legal regulations [4].

Due to the liberalisation of the European power market this disadvantage has considerably decreased. New legal provisions, however, supporting regenerative energies and the disembarkation from the atomic power produce additional costs for the power used in German electric arc furnace steel works resulting in a continued distortion of competition. The actual figures are shown in Fig. 6.

The long historical development of the German steel industry can be regarded as a further reason for the lower share of electric furnace steel. The existing integrated steelworks were first able to handle the scrap volumes increasing after World War II without any problems as apart from

the increasing total production the emerging basic oxygen steelmaking process allowed to process larger volumes of scrap. Furthermore due to the structure of the processing industry 70% of the output in Germany have been flat products, considerably more than in our European neighbouring countries. So why investing in new production processes for bulk steel when the existing plants were in the position to produce the required products in a cost-effective way?

The following reasons accounted for the fact that in Germany and finally also in Luxembourg and France the BOF Vessels were substituted by electric arc furnaces in the middle of 1990:

- Due to the continuously increasing availability of scrap the prices for scrap decreased so that the production process via pig iron got more expensive for products with lower requirements concerning the content of tramp elements,
- the electric arc furnace was developed to a high-performance aggregate both for the UHP-AC- and UHP-DC technology, and
- due to a changed environmental awareness it got politically more difficult to realise the refurbishment of existing coke oven plants and sintering plants.

Concerning the demand for primary energy the relatively low requirements of $9.6 \text{ GJ/ton}_{\text{rod wire}}$ compared with $18.4 \text{ GJ/ton}_{\text{rod wire}}$ for the pig iron line speaks well for the electric-steel process [5]. We, however, should be aware of the fact that without our colleagues at the BOF steelmaking plants we would not be provided with the secondary raw material scrap. Its high energy content resulting from the reduction of iron already effected must be used in an efficient way saving the environment as far as possible.

Today crude steel is produced in 28 electric arc furnaces at 22 locations in Germany. In **Figure 7** the high number of smaller furnaces with a melting weight of 5 to 10 tons is not considered as they are used in foundries only on request. Apart from the locations on the Rhine, Ruhr and in the Siegerland with a long metallurgical tradition there are younger plants being built up closer to the consumers and the sources of scrap.

The tap weights of the electric arc furnaces used by the European steel industry range from approx. 20 tons to approx. 150 tons (see **figure 8**). One third of these furnaces have a tap weight of more than 80 tons [3]. The DC-furnaces have a presence of only 14 furnaces (7.5%) as the DC-technology has been utilised for larger furnaces only since the beginning of

1990 and the more stable European main supplies coped with the high performances of AC electric arc furnaces.

The installed transformer capacities of the furnaces are for these furnaces between 700 and 800 kVA/t, for single furnaces even at 1400 kVA/t (see **Fig. 9**). In the years past his trend resulted in fewer, but more powerful furnaces [3].

The new constructions realised in Germany and the neighbouring countries of the EU from 1993 are shown on **chart 2**.

According to a survey performed by the VDEh beginning from the year 1992 the product ranges of the German electric steel works are shown on **chart 3**. Lower quantities of special alloys with an [Fe]-content of less than 50% [3] must be added.

3. Raw materials for the production of electric furnace steel

3.1 Development of Fe-carriers world-wide and in Germany

The secondary raw material steel scrap is the most important raw material for the production of crude steel by means of an electric arc furnace. With increasing requirements concerning the purity of electric furnace steel directly reduced iron as well as pig iron in a solid state and sometimes in a liquid state gain in significance. Furthermore ferriferous recyclings such as skulls are used in single cases. Their price, however, must be that attractive that the disadvantage of a lower melting efficiency can be compensated.

The importance of the individual raw materials for the total production of crude steel can be seen best from a iron balance based on reliable figures provided by IISI, EUROSTAT and the Federal Statistical Office. For our processes of steel production currently in use a metallic surplus charge of approx. 10% is usual. The [Fe]-requirements resulting from this are met by pig iron with a [Fe]-content of approx. 95% and by sponge iron and similar products with a [Fe]-content of approx. 88% . The difference to the total demand for iron must be covered by the utilisation of scrap, that means due to this balance a statement concerning the use of scrap is possible. **Fig. 10** shows the iron balance for the global production of crude steel [6].

The following statements can be derived: With a fluctuating global production of crude steel, which however altogether remains on a constant level the input of steel scrap slightly decreases. Currently the share is

approx. 38% of the iron input. The fluctuations of the production of crude steel influence the use of scrap only in a damped way. The use of iron derived from directly reduced ore continuously increases without, however, having influenced the input of scrap or the demand for scrap so far. From the global view it can only be concluded according to **Figure 10** that the volume of the global scrap market is currently stagnating and that the question how many steel scrap is available for recycling and whether the globally installed process lines can be supplied in a sufficient way cannot be easily answered.

In its tendency the situation in Germany is quite similar (see **Fig. 11**), but with a clearly different level for the total recycling of steel scrap which only reaches about 36% [6]. With a share for flat steel products of 70% in the total production the design of our production lines is quite different to those in other European countries. It, however, can also clearly be seen that the trend for the recycling of steel scrap remains on a nearly constant level and the necessary flexibility concerning the production levels is gained via the input of pig iron. A shortage of scrap cannot be the reason for Germany as we have known for several years that we export large volumes of scrap to other European countries.

3.2 Scrap

3.2.1 Availability of scrap

When considering the different grades of scrap according to their origin the following statements concerning the future scrap volumes can be made:

The arising interplant scrap of the steel works is available for remelting directly after its occurrence. The volume of the arising interplant scrap depends on the efficiency of the conversion of crude steel into rolled steel products. Since the middle of the seventieth the volume of arising interplant scrap has been decreasing. It can be expected that due to the continuous efforts made by the steel works to improve the production, the further implementation of continuous casting plants and the increasing utilisation of "Near-Net-Shape-Casting" the volume of arising interplant scrap will continuously decrease.

The new scrap coming from the steel-processing industry is also available for remelting short after further processing of the rolled products into finished products. Dressing and sorting are necessary. Due to the mostly grade-specific collection new scrap has a high quality so that the large steel

works are very keen on an immediate return from the larger processing plants.

The capital scrap resulting from the collection and processing of consumer and industrial goods not longer usable and worn out comes up in light and heavy fractions. It is partly contaminated and compounded with other materials. It must be prepared before being directly used in steel works and foundries. The volume of capital scrap has steadily risen in the past years. The highest volumes are to be found in traditional developed countries with a high share of consumer goods in the industrial output.

The volumes of scrap available essentially depend on the produced quantity of crude steel, partly, however, after a certain time-lag [7, 8]. The volume of intercompany scrap and new scrap runs parallel to the respective production of crude steel and finished steel. The capital scrap, however, is available for reuse only after a time-lag. Cans produced from steel, for instance, have a service life of only a few weeks. For cars a working life of 10 to 15 years is assumed. Steel used in buildings or bridges is scrapped in relatively large volumes only after a period of 50 to 100 years. A certain proportion of steel is lost in the form of rust or on any other way. It is currently assumed that in the average 40 - 50% of the consumer goods made of steel return into the recycling process already after 15 years.

Based on this assumption the volumes of scrap available can be calculated (see **Figure 12**) [8]. Assuming that 40% of the consumer products made of steel really return to the recycling process after a working life of 15 years the total global scrap volume can be estimated to 489 million tons for the year 2003. From this volume approx. 224 million tons fall upon capital scrap, approx. 159 million tons on interplant scrap and approx. 106 million tons on new scrap.

A 10-year comparison shall illustrate the regional changes concerning the consumption and input of scrap. The regional structure of the scrap consumption given in **chart 4** shows clear changes in favour of developing and emerging countries. The industrialised countries in Europe, North America and Japan, however, still consume more than the half of the scrap world-wide. The regions with the largest resources of scrap are traditionally the countries with the longest history of industrial production and utilisation of steel as already mentioned above [8].

Whilst North America was in the past an important exporter of scrap (Fig. 13) the export gets lower due to new construction activities in the field of

electric arc furnaces in the US. But they are still exporting 10,8 million tons in 2003. In Germany we have a similar situation. The scrap export decreased from a volume of 8 million tons in 1993 to only 2.3 million tons in the year 2003. In 1998 the EU imported 4 million tons and currently edges towards a balanced import-export ratio. A new trend is that Japan has become a scrap exporter for the south-east Asian market, in 2003 was the Japanese exporting figure 5,7 million tons.

For Germany the total volume of scrap arising, the consumption of scrap and the export surplus are shown once again in **figure 14 [8]**. In the period under review the total volume of scrap arising and the export surplus increased considerably. The reasons for this can be seen in:

- The utilisation of considerable stocks in the new Federal States,
- the beginning collection of packaging made of tinplate and
- the intensified utilisation of scrapped cars.

The nearly constant consumption of the steel industry in an amount of approx. 19 million tons is striking. In 2003 the export surplus amounted to nearly 2,3 million tons.

What are now the estimates concerning the fixture scrap output and scrap consumption? A recent IISI-Study [9] points out that the development of the scrap output does not exclusively depend on the fact that 42 % of the consumer goods made of steel return to the recycling process after a working life of 15 years; the remaining volume of 55%, however, minus a certain proportion which cannot be recycled shall be accumulated to a potential source of scrap increasing from year to year, (**figure 15**)

3.2.2 Scrap price

On the raw material markets of the steel industry pricing occurs on a global level so that the scrap prices in Germany and the other EU-countries are bound to the international scrap prices. This can be seen from **figure 16**. The non transparent situation is demonstrated in the **figure Nr. 16a, 16b, 16c**

When having a look at the prices for steel scrap in Germany and comparing them with the production volume of crude steel it can be stated that the scrap price could be regarded as an indicator for the cyclical movement in the steel industry for a long time. The prices fluctuated according to the economic cycle, partly with a certain time-lag. In 1999 the scrap price remained on a lower level despite an increasing production of crude steel, in the year 2004 the scrap price increased again. At the end of 2003 to now

the scrap price rises up to an unknown level [22]. The high demand in China is the main reason for that situation. When comparing the development of scrap prices with the shares of electric furnace steel in Germany so a development can be stated for 1999 which is contrary to the extension of production (**Fig. 17**). In **Figure 18** scrap price and consumption of steel scrap are compared, also underlining the special situation in the year 1999. When considering the export prices ex Rotterdam the influence can be explained as the Asian Crisis resulted in a reduction of the total exports thus causing a special situation.

The high demand for raw materials and alloys increases the prices for these materials. I'll show the example for alloys, coke, ironore and cargo [21]. **Fig. Nr 18a, 18b, 18c, 18d, 18e**

3.2.3 Quality requirements

The steel industry has to meet the customer requirements in a cost-efficient way while observing all aspects of occupational safety and environmental protection. So all materials used for the production of steel have to meet high quality requirements. This is particularly true for the secondary raw material steel scrap.

Steel scrap does not exclusively consist of metallurgically clean carbon steel but there are depending on the grade of scrap several accompanying substances included in the supplied scrap. Many accompanying substances remaining partly or in full in the steel during the process of steel production cause negative changes of the material properties if analytic specifications are exceeded. A revaluation or reduction of quality may be the consequence. **Chart 5** shows for several products the typical input ratios of pig iron, sponge iron and scrap in the LD-converter respectively the electric arc furnace [6]. In this connection I would like to point out that the German producers of the ingoing material for tinplate have obliged to take tinplate scrap back from the Dual System and to passed it again to the steel production process. This consequently will cause an increase of the tin-level, a fact no steelworker is delighted with.

Substances and elements passing into the slag or the waste gas in parts or in lull are in particular subject to the requirements of environmental provisions. Due to an increased slag output and a consequently higher demand for melting energy inert materials result in increasing disposal and conversion costs. New scrap is largely free of such substances whereas capital scrap may have contents between 0.5 and 1.5%.

Hollow bodies and ammunition included in the scrap considerably influence the safety-on-the-job. Explosions may cause serious injuries and even mortal danger to our employees as well as severe damages to the production equipment.

Special attention has to be paid to the occurrence of ionising radiation within the scrap, this means radioactivity which is measurably higher than the natural background radiation. Apart from the natural radioactivity caused by the constant presence of natural radionuclides in all substances around us and in ourselves an increased intensity of radiation can occur in the scrap. This can be caused for instance by:

- radiation sources from technical or medical fields of application
- surface contamination by means of adhesions, for instance after using the components in the field of mining or oil production, and
- components which were used in nuclear power plants for a longer time and thus carrying additional radionuclides.

When exceeding the limiting values not only the field of occupational safety but also the field of environmental protection and in particular the good reputation of the material steel would be adversely affected.

But attention has to be paid not only to any radioactive contamination of the raw materials as limiting values have also to be met concerning cadmium (paints, nickel cadmium batteries) and mercury (mercury infiltration by gas gathering) in the waste gas.

The quality requirements mentioned in the paragraph above have been largely considered by the new European List of Steel Scrap Grades. The European head organisations of the steel producers (EUROFER) and of the scrap recycling industry (EFR) mutually prepared this list for unalloyed carbon steel scrap with the goal to increase the transparency in the international scrap trade and to take the increased quality requirements into consideration.

When having a look at **chart 6** it can be seen that the new list closely follows the German List of Scrap Grades [6]. Apart from the dimensions density and allowable amount of debris have been added to the European list Furthermore two new scrap grades have been introduced in order to provide the scrap trade with a market for alloyed scrap parts such as gear cases of lorries and axle housings. So steel works get the chance to add both grades to the melting process in a calculated way as far as it is allowed by the analyses of the steel grades to be produced.

The list was designed as simple as possible and is limited to the scrap grades most often traded. For the first time the European List of Scrap Grades sets standard values for the most important elements other than iron in the various grades (**see chart 7**) [6]. The values stated correspond with the current state of scrap processing on a well-managed scrap yard and can definitely be met by the trade. This European List of Scrap Grades is to be seen as a guideline, not as a standard. The steel works, of course, are free to agree additional terms of delivery with the scrap trade.

In this connection I would like to ask you to make sure that also at your steel works scrap is purchased according to this new European List of Scrap Grades as otherwise the steel works do not form an integrated whole and can be played off against each other by the scrap recycling industry.

3.3 Direct-reduced raw materials, in particular sponge iron

3.3.1 Product properties

DRI (direct reduced iron) is normally produced and sold as sponge iron and HBI (hot briquetted iron). **Chart 8** shows a standard analysis for MIDREX - sponge iron [11,12].

HBI is produced by the same process. Before cooling, however, the hot material is compressed to briquettes. Due to the compression the material is resistant against moisture and can be transported without special care. Nearly all direct reduction plants especially designed for the sale of sponge iron are equipped with a briquetting press. Melting of this material which is mostly charged to the electric arc furnace by means of the scrap basket is much more complicated than melting of continuously produced DRI and is comparable in this respect with pig iron.

In general sponge iron can be regarded as a high-quality raw material which is mainly used in electric arc furnaces as supplement to scrap. The flexible use of sponge iron in combination with respective scrap grades is particularly suitable for a cost-efficient production of high-grade steels in the electric arc furnace which otherwise are produced by the integrated ironworks by means of the conventional production line blast furnace - converter.

Important quality characteristics of sponge iron are the Fe_{total} -content, the level of metallization ($\text{Fe}_{\text{met}}/\text{Fe}_{\text{total}}$) as well as the carbon content. The processes of gas-type reduction - and here especially the MIDREX-process - are superior to the processes for the reduction of solids. By means of the

gas-type reduction a level of metallization of more than 92% and carbon contents of up to 4% can be achieved.

Sponge iron differs from pig iron especially in that way that the gangue of the ore is still existent so that it must again be molten down in the process of steel production and must be integrated into the metallurgical process.

3.3.2 Production Process

Today there are many different processes of direct reduction which shall not be discussed here in detail. The processes of gas-type reduction based on natural gas are among the most important ones. As shown in **Figure 19 [10]** they by far the most important process in relation to the total production in 2002.

In view of the processes of gas-type reduction the MIDREX-process and the HYL-III-process have to be mentioned in the first place. Both processes are established on the market with the MIDREX-process having certain advantages concerning the process technology.

3.3.3 Availability

According to statistics compiled by the MIDREX-Corporation since 1970 **[13]**, the development of the global annual production of sponge iron shows - after a relatively flat course for the first years - a much steeper increase for the past years (**Fig. 20**). It does not require a lot of fantasy to imagine that the incline of the graph will increase in the fixture years when considering how many electric arc furnaces are currently taken into operation and when particularly considering that these furnaces shall produce increasing quantities of high-grade steel for instance for near net shape casting. But if the gas price rises up, like in Mexico in the last two years, the produktion of sponge iron decreases.

Sponge iron is predominantly produced in countries with low energy costs. This are also as a rule oil-exporting countries. The country with the highest production of sponge iron is currently India with a volume of 5.7 million tons, followed by Venezuela with 5.4 million tons and Mexico with 3.7 million tons. **Figure 21** shows a breakdown of the production of sponge iron in 2003 according to regions **[10]**. According to this chart Latin Amerika is first with 16,5 million tons ahead of the Middle East with 14 million tons, Asia Oceania (12,2 million tons) and the group "former USSR/East Europe" with 2,5 million tons. The capacity utilisation of the

MIDREX-plants is in the average at roughly 90%, the one of the other types between 40 and 70%.

In Europe only the plant in Hamburg at ISPAT Hamburger Stahlwerken with an annual production of nearly 540,000 tons in 2003 and is currently in operation. The facilities in Emden built by the Korf-Group were sold to India in 1983 and produce there approx. 1.0 million tons a year.

The availability of sponge iron is limited due to reasons of capacity, freight and storing. Sponge iron is mainly produced in the individual plants for internal requirements. So only limited quantities are for sale, normally in form of HBI (hot briquetted iron). Quantities of sponge iron offered for sale are mostly from Venezuela, India and Malaysia, sometimes also from the Arabian region. Often this are spot quantities.

The graph for the quantities of sponge iron not further processed at the place of production shown in **figure 22** has risen parallel to the total production [10]. Approx. 6.3 million tons - this means a quarter of the total production - were dispatched in 2000, slightly more than the half by ship.

3.3.4 Production and processing costs

By means of two publications [2, 14] we tried to estimate the costs of MIDREX-sponge iron (from new plants) produced at a location near to the coast in Europe as well as at locations in Venezuela. (**Chart 9**).

The debt service with 15% of the capital expenditure (220 US\$/t a) and the maintenance costs with 4% of the capital expenditure must be estimated independent of the location. When assuming that the production indexes are also identical at all locations the differences in the production costs result from the costs for iron ore caused by the different transport distances as well as in particular from the prices for the energy transfer media natural gas and electric energy.

In Venezuela sponge iron can be currently produced for approx. 100 US\$/t. For the marine transport to Europe approx. 20 US\$/t must be estimated, for the cargo handling approx. 3 US\$/t and for the further transport approx. 7 US\$/t.

At the current energy costs a production at a location in West-Europe is only efficient if the costs for new scrap of the grades E 2 and E 8 are high. Otherwise the import of sponge iron can be more favourable.

When taking the even higher production costs for MIDREX-sponge iron at a Japanese location into consideration plans by BHP can be understood to produce HBI in north-west Australia from local high-quality ore and existing natural gas and to sell it in the Pacific area.

3.4 Pig iron

About a total 13 million tons of pig iron are traded every year, mainly in form of pigs. Most of it is used in foundries. At steel works pig iron is - like sponge iron, too - used as a raw material with lower contents of tramp elements as well as with an additional energy content due to the [C]- and [Si]-contents. In general it is charged by the scrap basket.

In the meantime there are electric steel works using hot metal. Pioneers for this process are the steel works of ISCOR in South Africa at the locations Pretoria and Vanderbijlpark. A large variety of raw materials - pig iron, sponge iron and scrap - is used at the steel works ISP AT SALDANHA-STEEL Ltd in South Africa. According to the CONARC-process the added raw materials are either oxidised similar to the LD-process or smelted by means of an electric arc furnace. Depending on the availability of the raw materials or the quality to be produced in relation to tramp elements all mixing ratios are possible. The plant was taken into operation in 1998. In Europe hot metal is used at UNIMETAL in Grandange and at COCERILL. In Southeast Asia power rates and scrap prices are higher than in Europe. Both can be optimized by using hot metal which is done in several plants in Japan (Mitsushima) and in China (Bao Steel, Shagan Steel Works)

The increasing availability of HBI could lead to an additional variant concerning the use of hot metal in the electric arc furnace. In Central Europe HBI, sponge iron and/or even cheap scrap coming from refuse incineration plants can be remelted in a cupola furnace to a synthetic, low-silicon pig iron with a Carbon-content of 3 - 4% at conversion costs of about 20 €/t. The capital expenditure for a cupola furnace must be calculated with 45 US\$/t_{liquid}p-a.. This variant in combination with the use of scrapped cars and residuary substances from shredding plants as energy transfer media together with a respective purification of the waste gas was planned for several times but has not been realised in Europe so far.

4. Processing costs

Figure 23 shows a comparison of the processing costs of a 125 ton-electric arc furnace with the ones of BOF converters with a tap weight of 150 tons

and 245 tons respectively [15]. In case of an electric arc furnace melting energy (44%) and graphite electrodes (17%) contribute to more than 50% of the processing costs. Expenditures for the additional burner, cooling water, operating power, heating and warming of the ladles as well as the oxygen are included in the costs for fuel and energy. These costs account for 5%. 10% must be calculated for refractory costs and the cooling element for wall and cover. Further costs such as wages and salaries, maintenance and transports amount to 25% of the total cost.

In contrast to this the processing costs of BOF converters amount to only 29.3% for a tap weight of 150 tons respectively 23.1% for a tap weight of 250 tons. So an economic operation of the electric arc furnace is only granted if the difference in operating costs for both processes is clearly in favour of the electric arc furnace. **Figure 24** shows a comparison of both steel production processes in relation to the utilisation [1]. It is clearly demonstrated that the steel production by means of an electric steel work is significantly less dependent on the plant utilisation rate than the steel production in an integrated steelwork.

5. Current stage of development of the electric arc furnace with outlook on further developments

The workhorse of the mini-steel - the electric arc furnace - has seen a rapid development in the last three decades. **Figure 25** gives some stages of development in connection with the changes of some significant indices of the furnace [17]. This technological development has resulted in a significantly improved efficiency of the mini-steel works.

Among others the following important steps of development are to be mentioned:

- Water-cooled side walls

The water-cooled side walls allow an operation with longer electric arcs. The increased energy losses due to higher radiation losses are more than compensated by an improved melting performance as well as reduced costs for the operation of the cooling elements in contrast to the refractory lining. Today cooling boxes made of steel have a life-time of 4000 - 8000 melting processes. At the Georgsmarienhütte the highly stressed cooling elements in the "hotspot" are made of copper.

- Cooling Block (Figure 26)
- Eccentric bottom tapping

This construction allows a reduction of the tilting angle of the furnace from 45° to 15° when tapping. So on the hand the water-cooled area of

the side wall can be enlarged. On the other hand the high-current cables can be shortened so that the operating reactance is reduced and the input of power is increased. Further advantages are the low-slag tapping as well as the reduced capture of nitrogen and hydrogen.

- Foamed-slag procedure

In nearly all electric steel works - apart from those producing RSH-grades - it has been standard since the end of the seventieth to allow the electric arc to burn in foaming slag. So the refractory lining as well as the water-cooling tanks of the upper furnace are protected against the high radiation. With a well-foaming slag the electric energy is transferred to the steel melt in a better way so that savings of 10 to 30 kwh/t can be achieved. The consumption of injection coal for AC arc furnaces is approx. 5 kg/t and for DC arc furnaces 10 to 12 kg/t, in single cases up to 20 kg/t as due to the longer electric arc at the DC-furnace more foamed slag has to be produced.

- Cooling of electrodes

In order to reduce the surface oxidation of the electrodes they are sprayed with water. So savings of up to 30% of the costs for electrodes can be achieved. The water which is not vaporised sprinkles on crossing of the cover. By this cooling effect the life-time of the crossing is significantly improved.

- Lance manipulator

Apart from oxygen and injection coal other solids such as filter dust or lime can be injected by the remote-controlled lance manipulators through the slag door into the furnace. Only with the lance manipulator it is today possible to inject the volumes of oxygen into the furnace which are today usual and to blow the injection coal to the optimal place of reaction.

- Direct-current technology

Besides the reliable highly advanced AC-technology the direct-current technology has been established as a process with comparable benefits. These furnaces are usually equipped with different types of bottom anodes:

- the conducting hearth
- the steel anode inserted into the refractory material (Multipin, fin type)
- the water-cooled steel anode

Due to reasons of consumption the graphite electrode is normally switched as cathode. As the design of large electrodes is limited due to technical reasons to a size of 32" and a secondary current of 170 KA the input of power via an electrode is limited as well (Fig 27). Increases in input of power for the DC-technology can be achieved by dual-cathode

furnaces. Here the dual-cathode furnace at HYLSA in Mexico must be mentioned. With 4 x 52 MVA transformers (208 MVA) sponge iron is melted which is pneumatically conveyed between the electrodes. 2 cathode furnaces used in Japan and the USA for melting scrap have only partly solved the problem of the electric arc burning between the cathodes.

- Intelligent electrode control systems
The newly developed intelligent electrode control systems which are partly based on neuronal networks or high-speed computers operate the electric arc furnaces online at their maximum thermal loadability while considering the thermal stress of the upper furnace. At any moment of melting the optimal operating point is achieved.
- Technology of dual-furnace vessel
By arranging two furnace vessels next to each other which are operated with a single swivelling set of electrodes it shall be achieved that the non-productive times such as charging of scrap, maintenance of the furnace etc. are largely avoided. During this periods the set of electrodes are turned over the other vessel so that the melting process can be continued. The experiences with this type of furnace made so far reveal that a significant advantage can only be achieved by this technology if in one vessel the processes of melting, refining and overheating can be continued without any interruption.
- Increased secondary voltage of 1500 V for AC electric arc furnaces
The AC electric furnaces will experience a new push of development if the current upper limit of the secondary voltage is increased from 1000 V to 1500 V. In Germany the use is only allowed with special requisitions and specific approval so far. Then transformers with a performance of significantly more 160 MVA are available.

When having a look at the Sankey-diagram of an electric arc furnace (Figure 28) the losses by flue gas directly raised the question for a possible utilisation. A pre-warming of the scrap in the basket were a first approach which, however, were waived due to the amounts of contaminants in the flue gas. More consequent solutions were found by means of the smoke flue and the Consteel-process (**Figure 29**).

Depending on local legal provisions a special treatment of the flue gas is necessary to minimize the amount of contaminants, because of the de novo syntheses of the dioxins.

Another approach currently followed is to keep the volume of waste gas as low as possible. This requires a closed furnace vessel (Air-tight

furnace) where the reaction gases are injected by a "Coherent Jet" (**Figure 30, 31**). For this purpose a high level of automatisisation for the furnace operation, sampling, measurement of temperature, handling of foamed slag etc. must be developed.

6. Final remarks

The traditionally flat, more medium-sized organisational structure of the original mini-steel works ensure due to their short formal and informal ways of communication a significantly higher flexibility than the classical integrated ironworks could achieve. Electric steel works established from integrated ironworks partly succeeded in adopting this organisational structure. Due to this structure it should take much less time to realise the philosophy of TQM-Total Quality Management. TQM means quality of all internal and external activities of a company. The idea of quality is not limited to the product alone but encompasses all activities related to its production. Quality is achieved by the employees in various processes and not only checked at the end. This requires a company philosophy which promotes the employees and entrusts them with responsibility.

Technology alone does not result in a positive overall company result. The economic success of a company is always achieved by the total number of employees. It is up to us to breathe life into the idea of TQM in order to ensure the success of the company. Certificates alone are not sufficient.

7. Acknowledgements

I am grateful to Mr. Rolf Willeke, BDSV, and Rolf Ewers, VDEh for their contribution on several, partly joint publications being the source for many figures and charts.

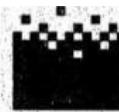
Dr. Schliephake kindly provided me with his manuscript of his introductory lecture for the VDEh-Seminar,, Electrotechnics of the Electric Arc Furnace"

I am particularly grateful to Mr. Holger Haverkamp and Mrs. Trautmann for the quick preparation of figures, charts and texts.

8. Literature:

- [1]: Fanre, H.A.: Entwicklung, Stand der Technik und Zukunftsperspektiven der Stahlerzeugung, Stahl und Eisen 113 (1993), Nr. 6, S 39/46 - updated IISI Figures up to 2004
- [2]: Szekely, J.; Trapara, G.: Zukunftsperspektiven für neue Technologien in der Stahlindustrie, Stahl und Eisen 114 (1994), Nr. 9, S.43/55 - updated IISI Figures up to 2004
- [3]: Zörcher, H.: Stand der Elektrostahlerzeugung in Deutschland, Stahl und Eisen 114 (1994), Nr. 4, S. 75/79 - updated, IISI Figures up to 2004
- [4]: Höring, A.; Joks, M.; Kron, H.; Maier, K.H.; Moritz, A.; Schüppstuhl, E.L.; Strohschein, H.: Strompreissenkung für Sonderabnehmer, Stahl und Eisen 115
- [5]: Aichinger, H.M.: Persönliche Mitteilung an A. Borowski
- [6]: Schliephake, H.; Ewers, R.: Schrottversorgung in der Stahlindustrie, Vortrag anlässlich des Eisenhüttentages 1995, 16. und 17. November, Düsseldorf
- [7]: Wienert, H.: Zur gegenwärtigen und zukünftigen Schrottverfügbarkeit in der Welt, Vortrag anlässlich der gemeinsamen Sitzung des Rohstoffausschusses und des Stahlwerksausschusses des VDEh am 29.11.95, Düsseldorf
- [8]: Willeke, R.: Development of the world market for steel scrap, IISI meeting of the board of directors, April 1996, Singapore
- [9]: Willeke, R.: Keine Schrottverknappung, Stahl- und NE-Metall - RECYCLING, 1/97, S. 14/16
- [10]: Renz, G.; Schliephake, H.; Stercken, K.: Eisenschwamm für die Stahlerzeugung, Vortrag anlässlich der gemeinsamen Sitzung des Rohstoffausschusses und des Stahlwerksausschusses des VDEh am 29.11.1995, Düsseldorf
- [11]: Safe Shipping of DRI, Steel Times International, Nov. 1994, S. 33
- [12]: Hunter, R.L.: Handling and Shipping of DRI/HBI Steel Times International
- [13]: World Direct Reduction Statistics, MIDREX Corporation, Charlotte, USA
- [14]: Steffen, R.; Lungen, H.B.: Stand der Direktreduktion, Stahl und Eisen 114 (1994), Nr. 6, S. 85/92
- [15]: Borowski, A.: Einführungsreferat zum VDEh-Seminar Elektrotechnik des Lichtbogenofens, 19. bis 21. März 1997 Dusseldorf
- [16]: 1997 World Cost Curve, World Steel Dynamics, Paine Webber, 1997, New York

- [17]: Heinrich, P.: Schubert, M.: Ministahlwerke und neuere Entwicklungen bei Gleichstromlichtbogenöfen, Stahl und Eisen 115 (1995), Nr. 5; S. 47/53
- [18]: Prospekt der Fa. Consteel, USA
- [19]: Prospekt der Fa. Mannesmann Demag, Duisburg
- [20]: Prospekt der Fa. Mannesmann Demag, Duisburg
- [21]: Rohstoff- und Beschaffungsmärkte, Stahl Zentrum
Monitoringbericht Feb. 05
- [22]: BDSV Entwicklungen auf dem Stahlschrottmarkt. Rolf Willeke,
Jan. 2005



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Introductory Lecture for the VDEh-Seminar „Electrotechnics of the Electric Arc Furnace“

1. Introduction
2. Development of the production of crude steel and the processes of steel production
 - 2.1 Global
 - 2.2 Europe
 - 2.3 Germany
3. Raw materials for the production of electric furnace steel
 - 3.1 Development of Fe-carriers world-wide and in Germany
 - 3.2 Scrap
 - 3.2.1 Availability of scrap
 - 3.2.2 Scrap price
 - 3.2.3 Quality requirements
 - 3.3 Direct-reduced raw materials, in particular sponge iron
 - 3.3.1 Product properties
 - 3.3.2 Production processes
 - 3.3.3 Availability
 - 3.3.4 Production and processing costs
 - 3.4 Pig iron
4. Processing costs
5. Current stage of development of the electric arc furnace with outlook on further developments
6. Final remarks
7. Acknowledgements

by Frank Treppschuh

Stahlwerk



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Development of the Global Production of Crude Steel

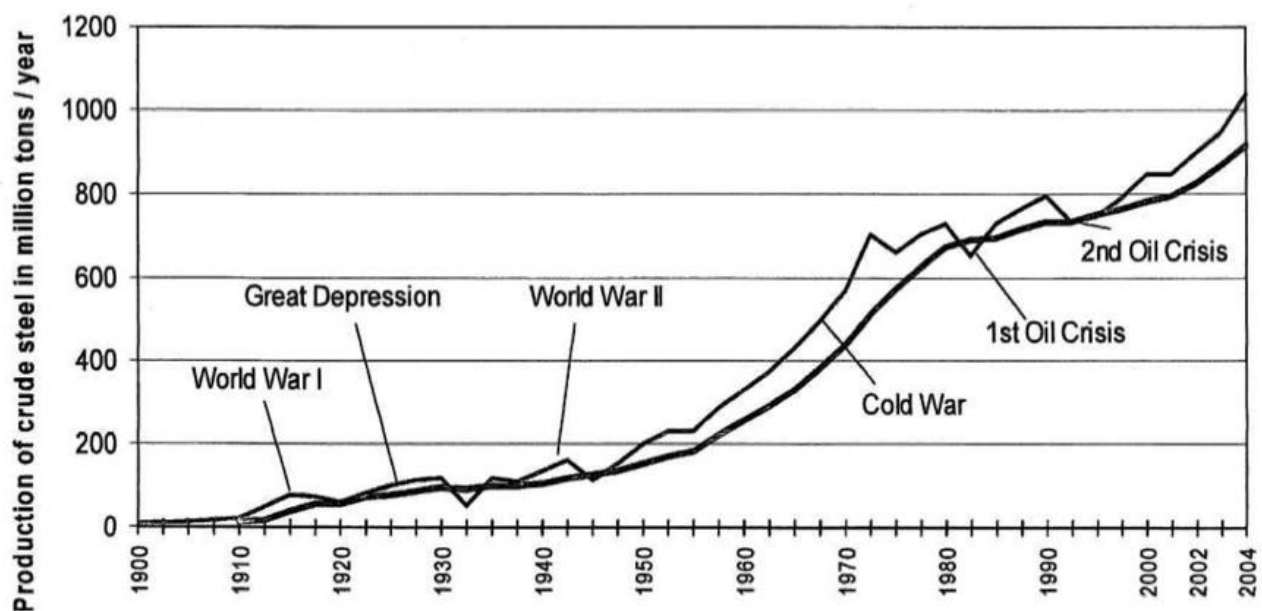
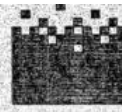


Fig 1

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Development of the Production of Crude Steel in China

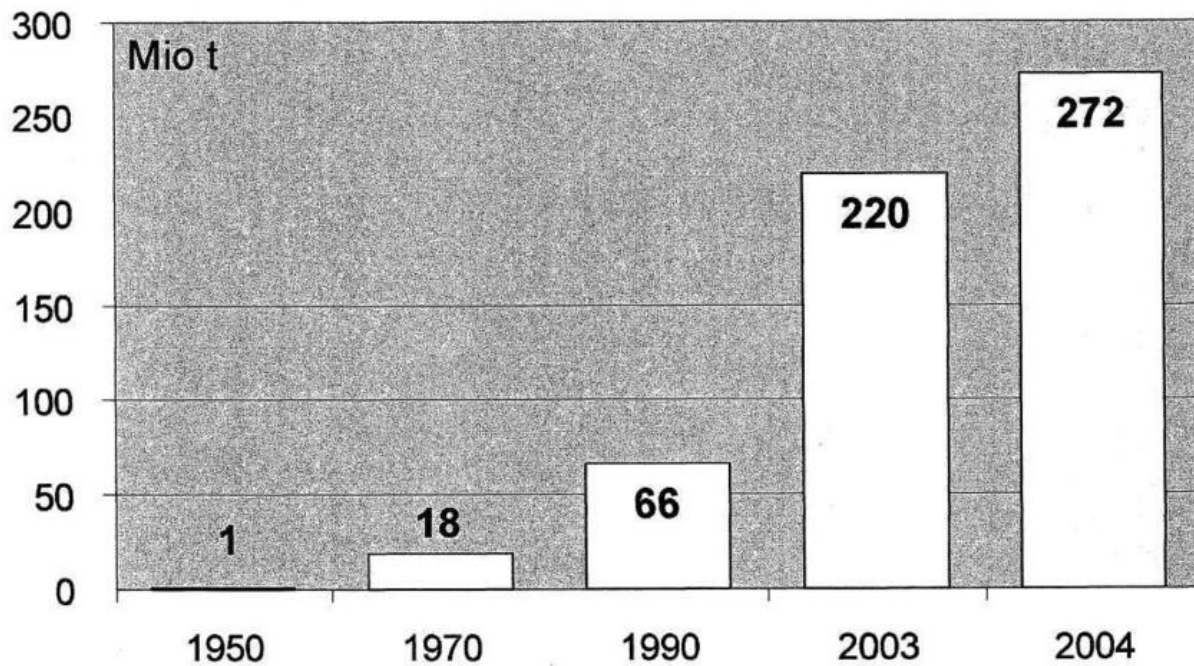
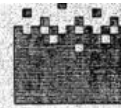


Fig 1a

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Development of the EU (15) Production of Crude Steel

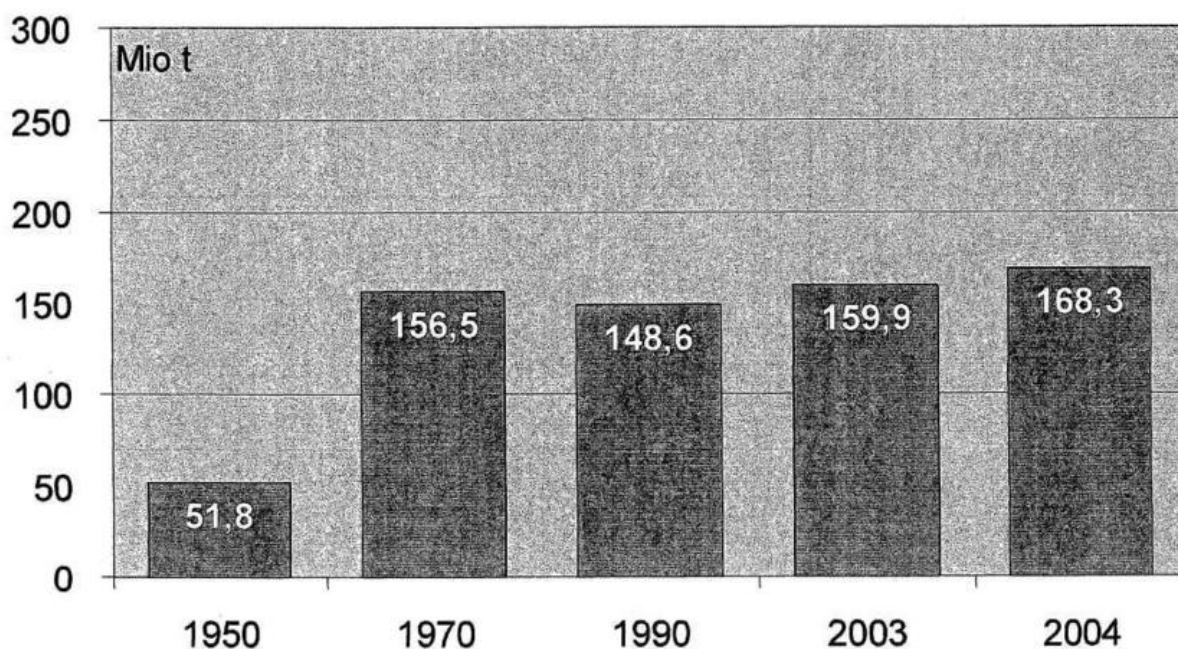
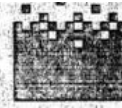


Fig 1b

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Shares of the various processes of steel production in the global production of crude steel

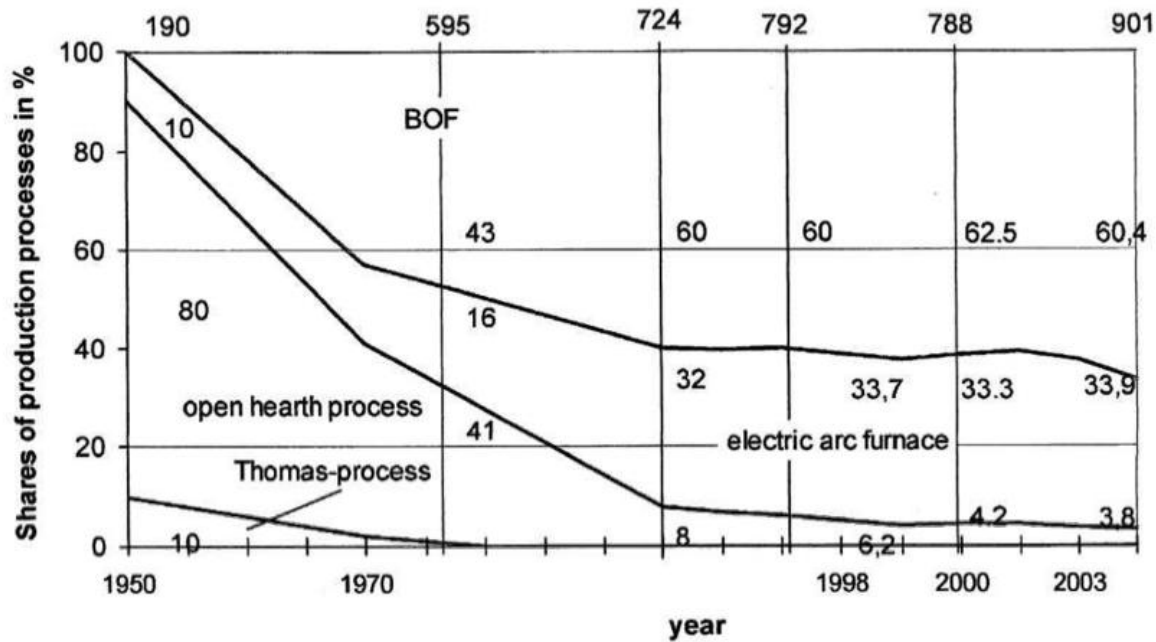
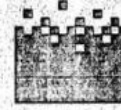
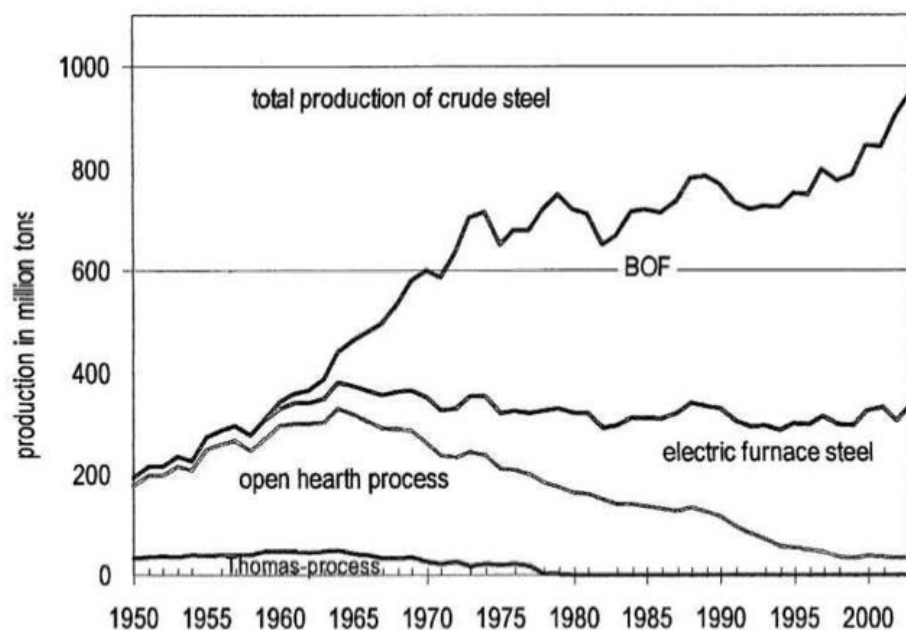


Fig 2

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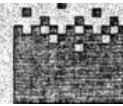
Global Production of Crude Steel according to Process



Quelle: ISI

Fig 3

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Production of crude steel in the EU (6 - 15) according to processes

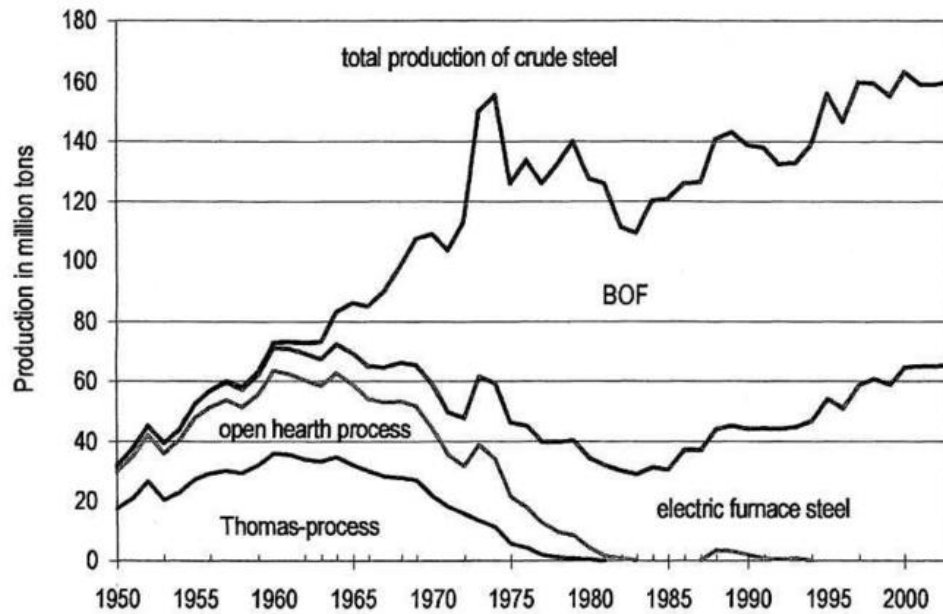
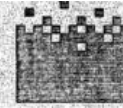


Fig 4

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Production of crude steel in Germany according to processes

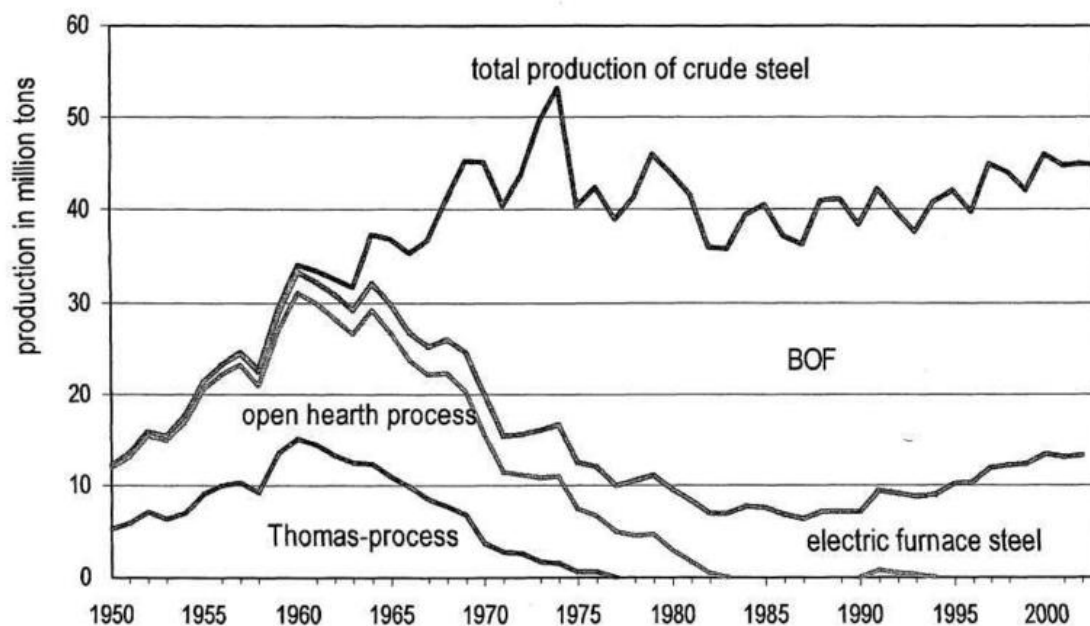
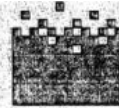


Fig 5

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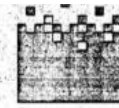
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Development of specific extra costs of German (c/kWh) power companies against France from 1986 to 1996

year	1986	1993	1996
Electricity generation by German pit coal	0,2	0,55	0,0
desulphurisation and removal of nitrogen	1,0	0,8	0,35
Nuclear energy	0,5	0,3	0,3
licence fee	0,25	0,55	0,55
political extra costs	1,95	2,2	1,2
water power	0,25	0,25	0,25
other extra costs	0,25	0,25	0,25
disadvantage against France	2,45	2,7	1,7

Chart 1

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Development of the industrial Power-Price in the EU

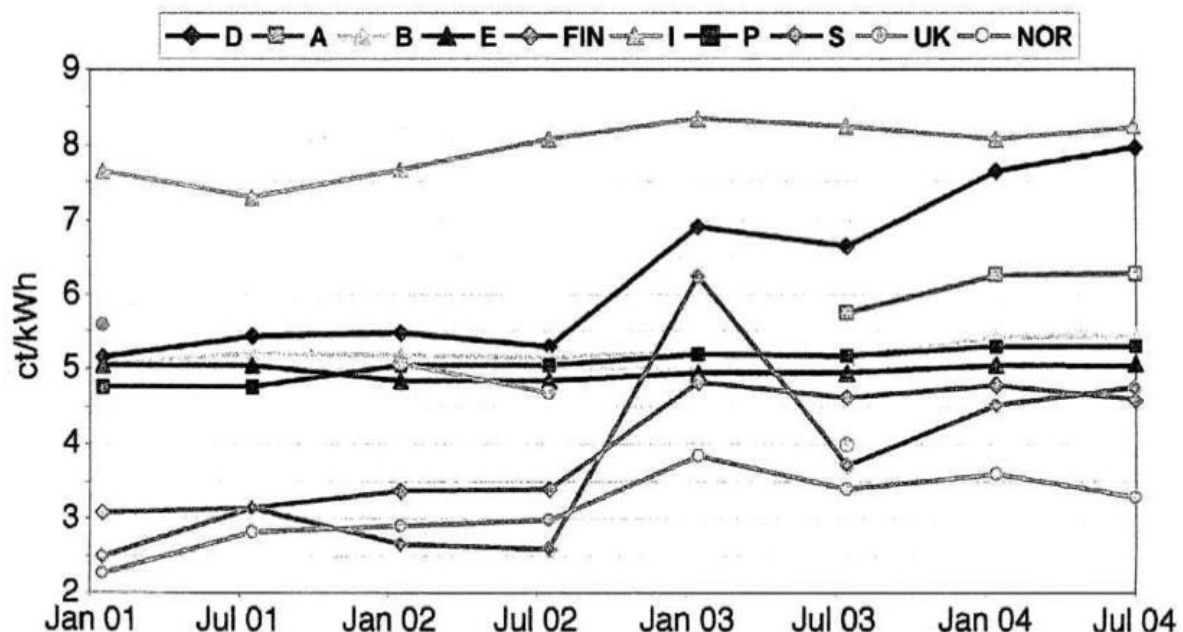
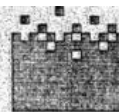


Fig 6

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Locations of electric steel production in Germany

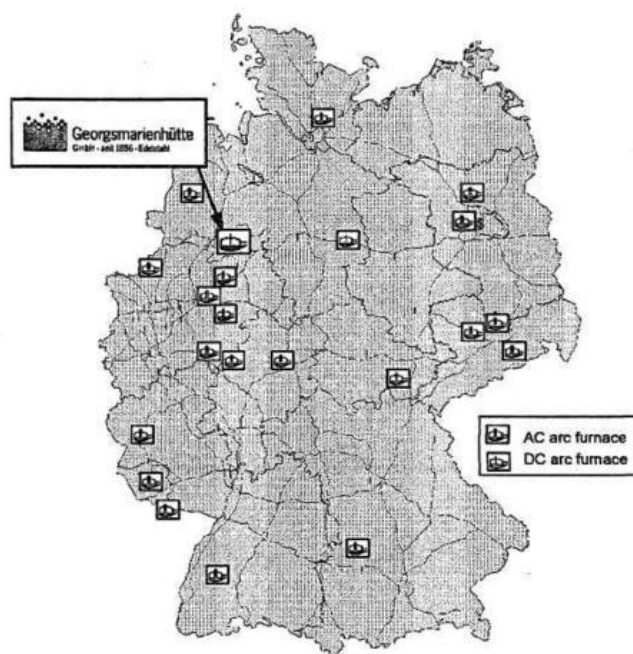
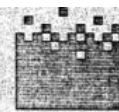


Fig 7

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Size distribution of electric arc furnaces in the EU

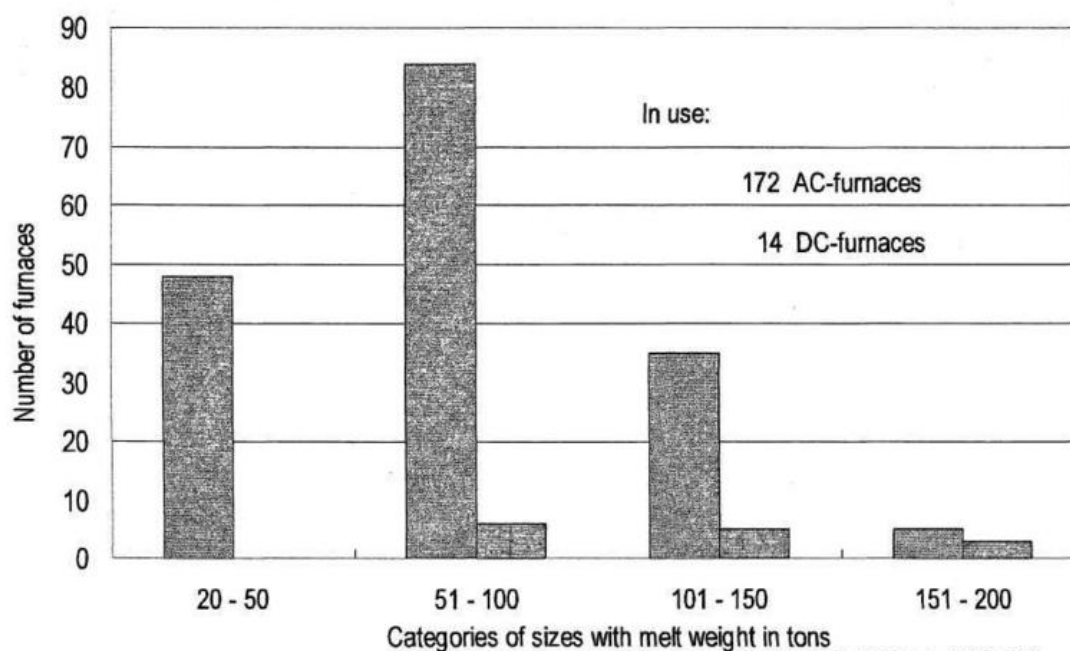
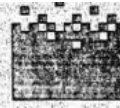


Fig 8

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tapping weight and specific transformer capacity

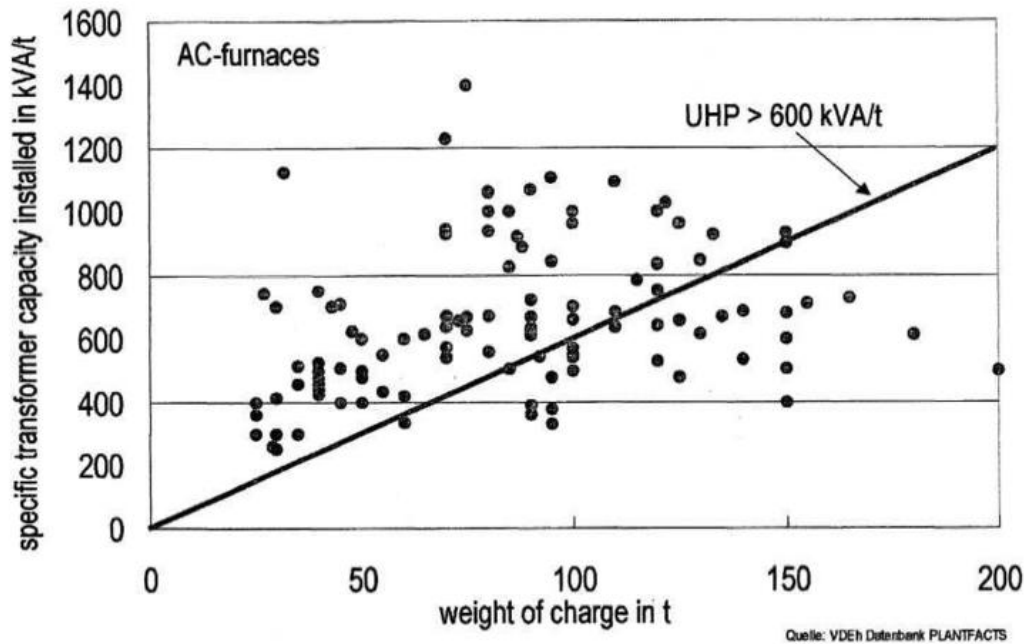
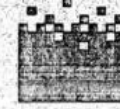


Fig 9

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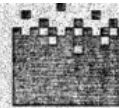
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construction projects through the last years in europe

	start of operatione	electric arc furnace	capacity t/a	remarks
Germany :				
ESF Feralpi, Riesa	1994	1 * 70 t	350,000	new construction
Henningsdorfer E-Stahlwerk	1994	2 * 70 t	900,000	repl. for EAF
Preussag Stahl, Peine	1995	1 * 100 t, DC	900,000	repl. for LDAC
Georgsmarienhütte	1994	1 * 125 t, DC	600,000	repl. for KMS
Thüringer Stahlw., Unterwellenborn	1995	1 * 120 t, DC	750,000	repl. for LD-AC
Members of the EU :				
Usines G. Boel, La Louvière, B	1993	1 * 85 t, DC	500,000	repl. for LD
Arbed, Schifflange, L	1994	1 * 95 t, dual furnace with shaft	900,000	repl. for LD
Unimetal, Gandrange, F	1994	1 * 150 t, DC / dual furnace	1,300,000	repl. for LD
Arbed, Differdange, L	1995	1 * 155 t, DC / dual furnace	1,000,000	repl. for LD
Arbed, Esch-Belval, L	1997	1 * 155 t		repl. for LD
Cokerill Sambre, B	1996	1 * 165 t, shaft	1,000,000	
Aceria Compacta de Biskaja	1996	2 * 150 t	1,000,000	new construction

Chart 2

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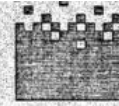
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Product range of the steel works with electric furnaces

	1992 old and new Federal States	1995		1997		2000	
		t	%	t	%	t	%
carbon steel	57 %	6612	65.2	8253	69.5	8611	70.2
low alloy steel	28 %	3531	34.8	3620	30.5	3656	29.8
high alloy steel	15 %						
total	100%	10143	100%	11873	100%	12267	100%

Chart 3

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Global Fe- balance

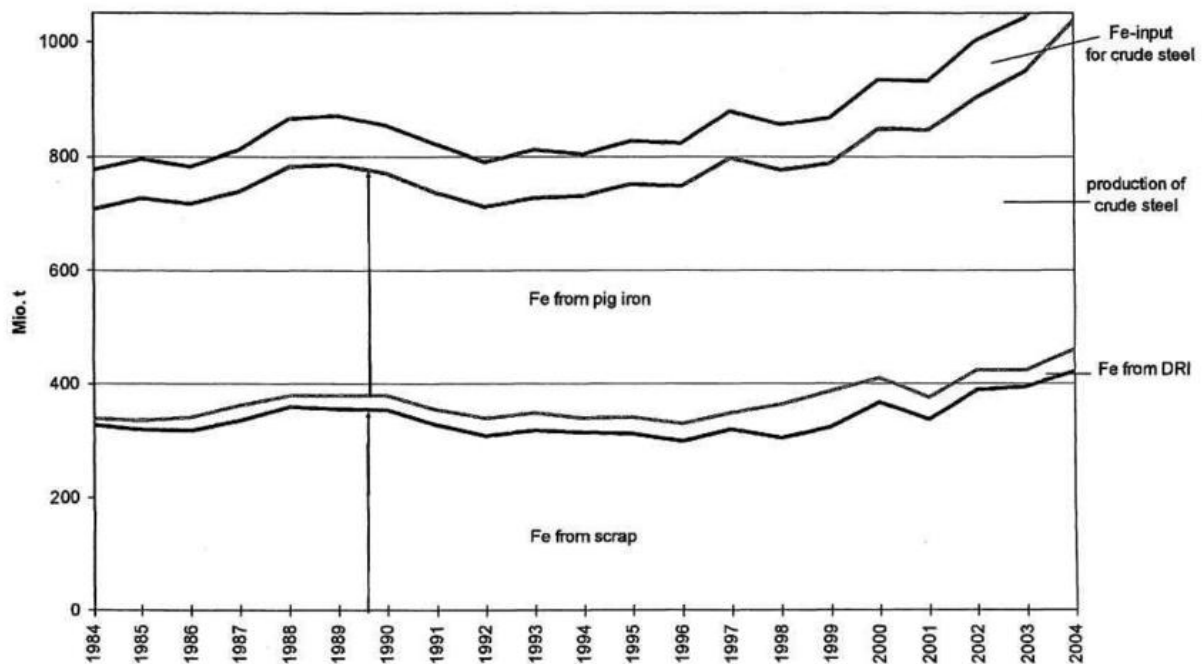
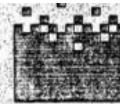


Fig 10

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Fe- balance in Germany

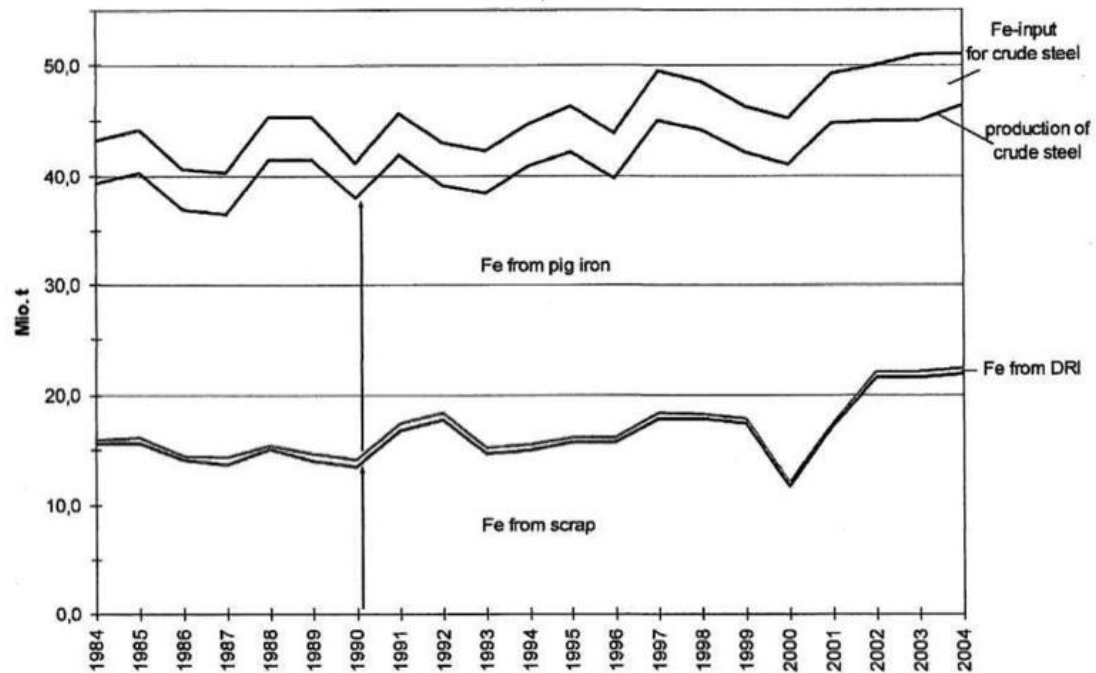
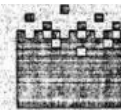


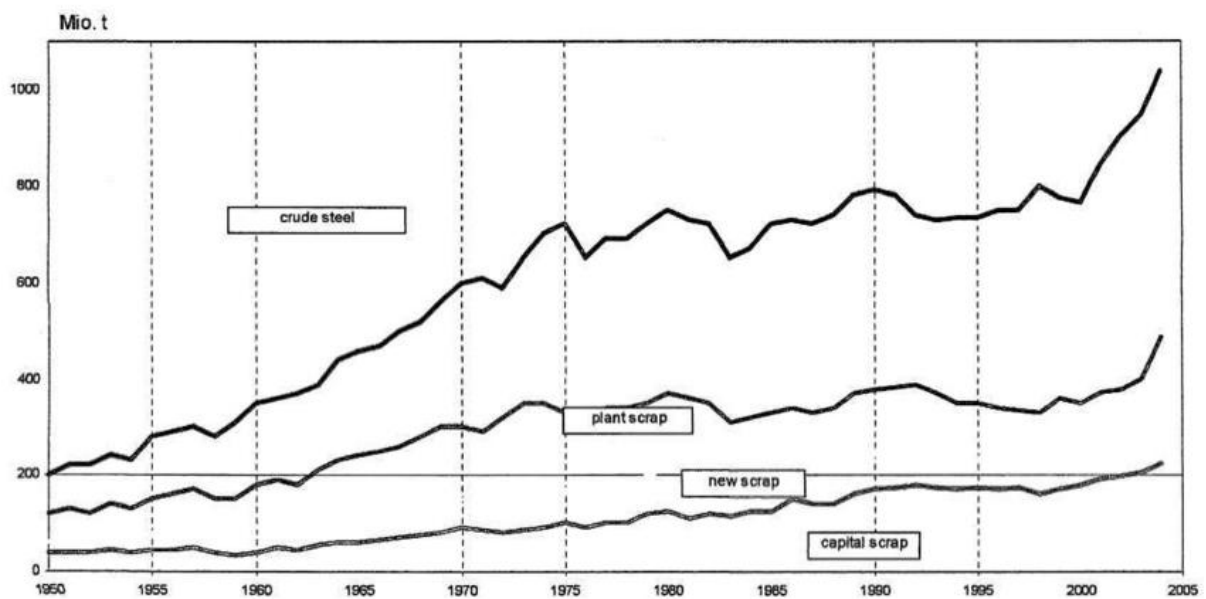
Fig 11

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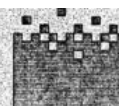
Global crude steel production and scrap consumptions



Quelle: VDEh

Fig 12

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Regional structure of scrap exports

Region	1995		1998		1999		2000	
	consumpt.	output	consumpt.	output	consumpt.	output	consumpt.	output
West Europe	21.3	21.8	23.2	23.6	23.3	22.9	23.3	22.7
East/central Europe	8.2	7.9	8.2	7.6	7.8	6.4	7.7	6.5
Former USSR	10.2	15.3	8.7	9.5	10.7	14.7	11.6	15.6
North America	23.8	22.8	23.2	23.3	21.1	21.4	20.3	20.9
Japan	12.2	11.9	11.4	11.7	11.9	13.1	11.9	12.8
Other Asian countries	17.6	15.7	18.9	15.8	20.8	16.6	20.6	16.0
Other countries	6.7	4.6	6.4	8.5	4.4	4.9	4.6	5.5
World in %	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
World in mio. tons	352.0	365.0	353.0	367.0	336.0	337.2	366.9	362.9

Chart 4

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Balance of scrap exports - imports for USA, EU (15), Germany and Japan

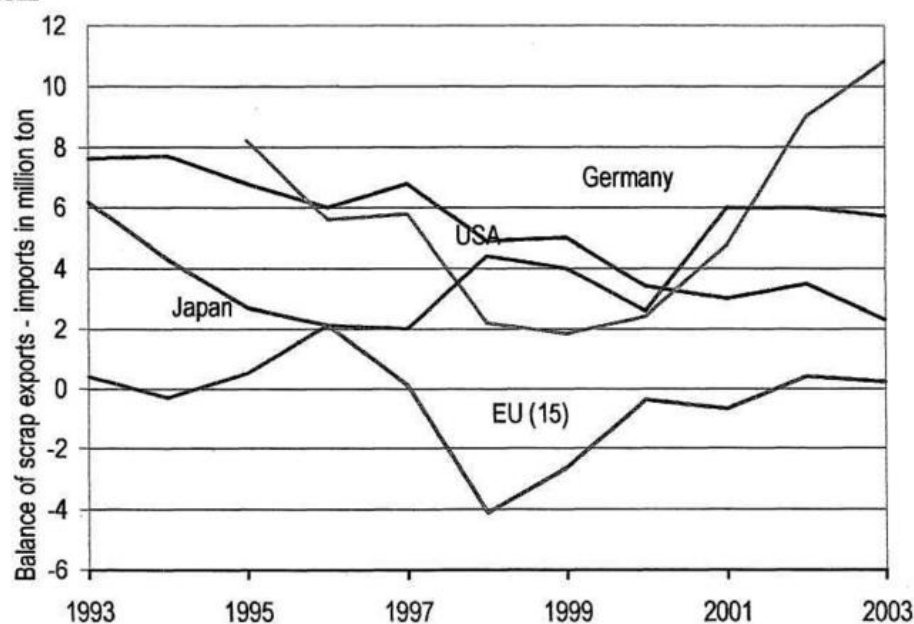
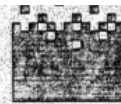


Fig 13

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Scrap movements in Germany in million tons

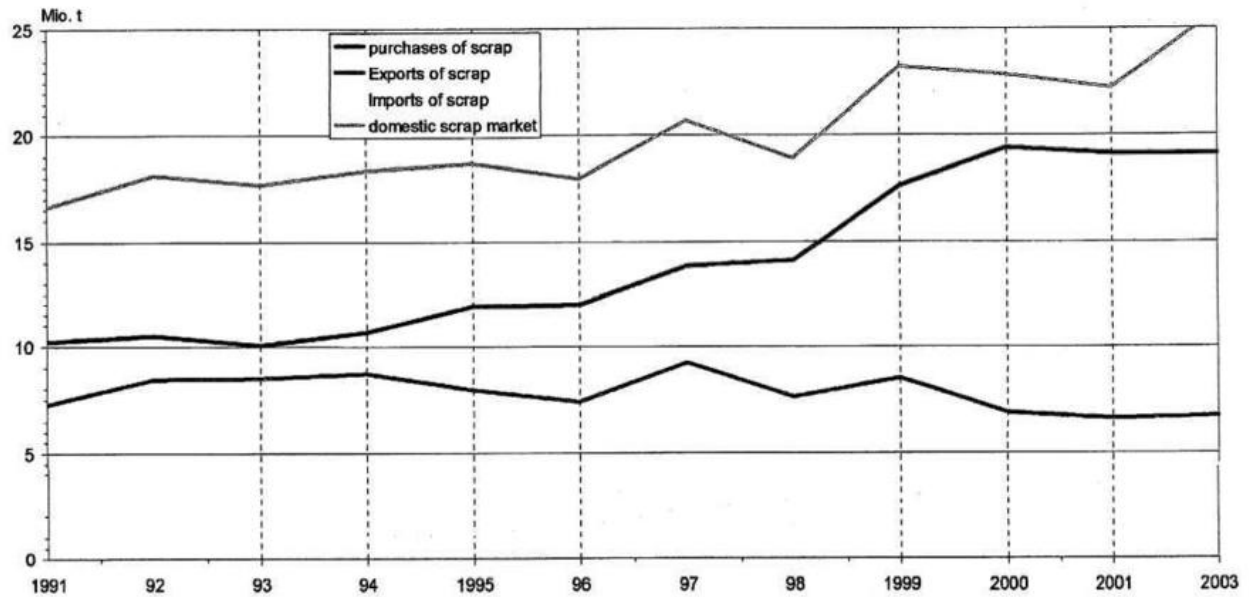
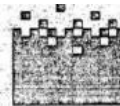


Fig 14

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Development of the Steelscrapvolume, crude steel production

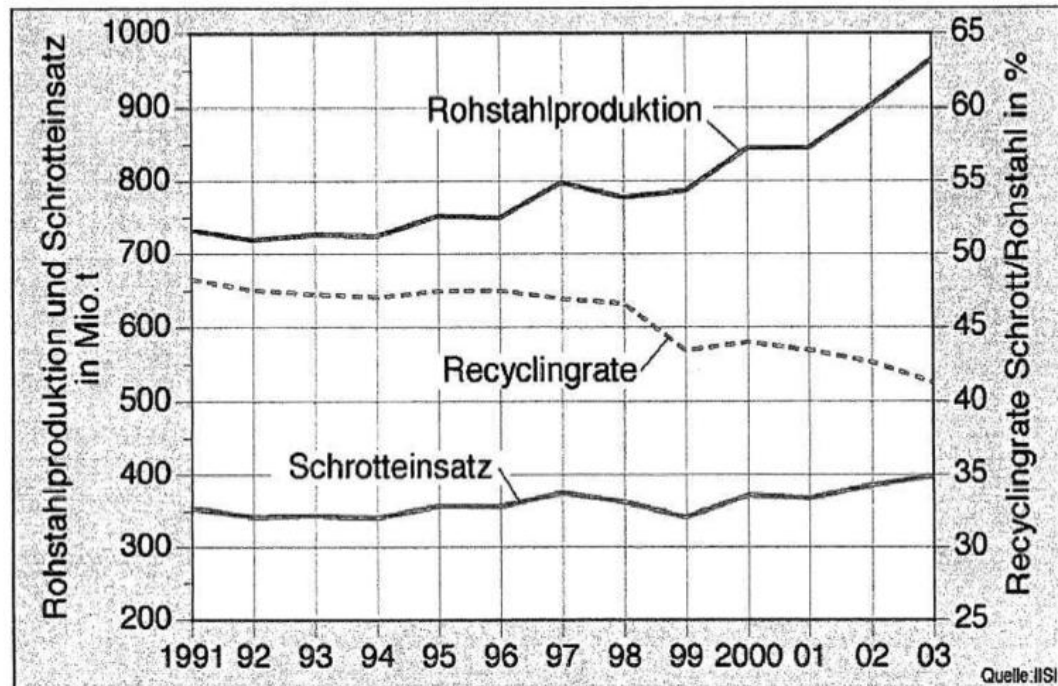


Fig 15

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Scrap movements in Germany in million tons

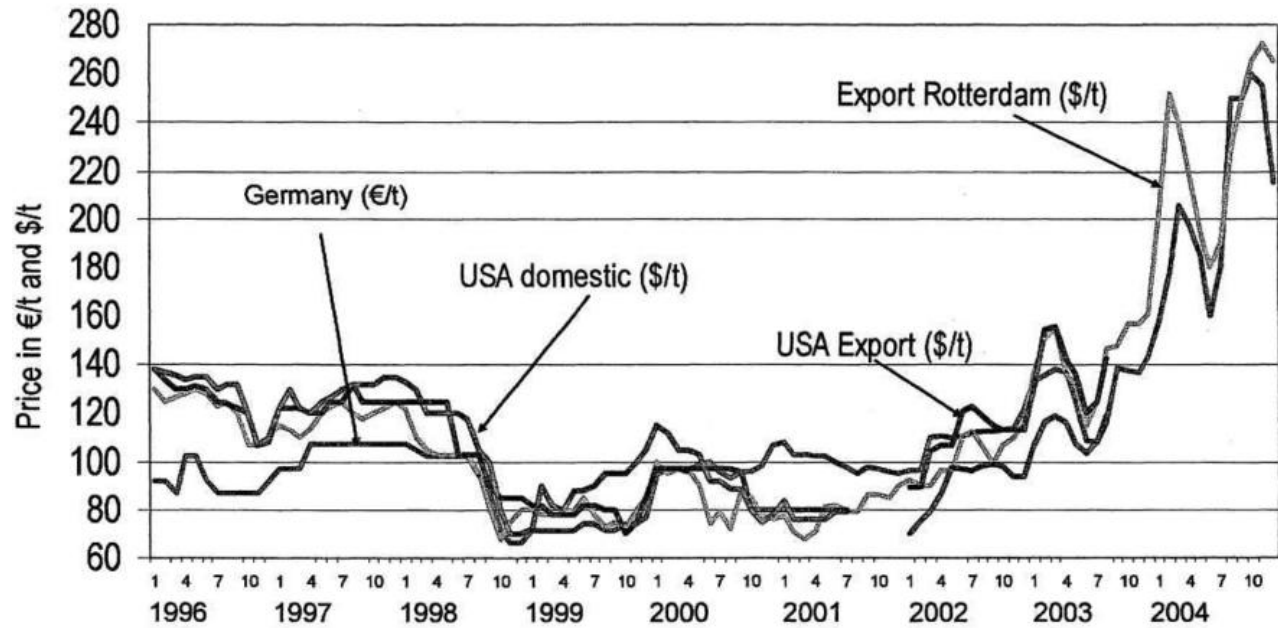
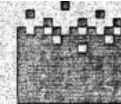


Fig 16

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Scrap price Germany

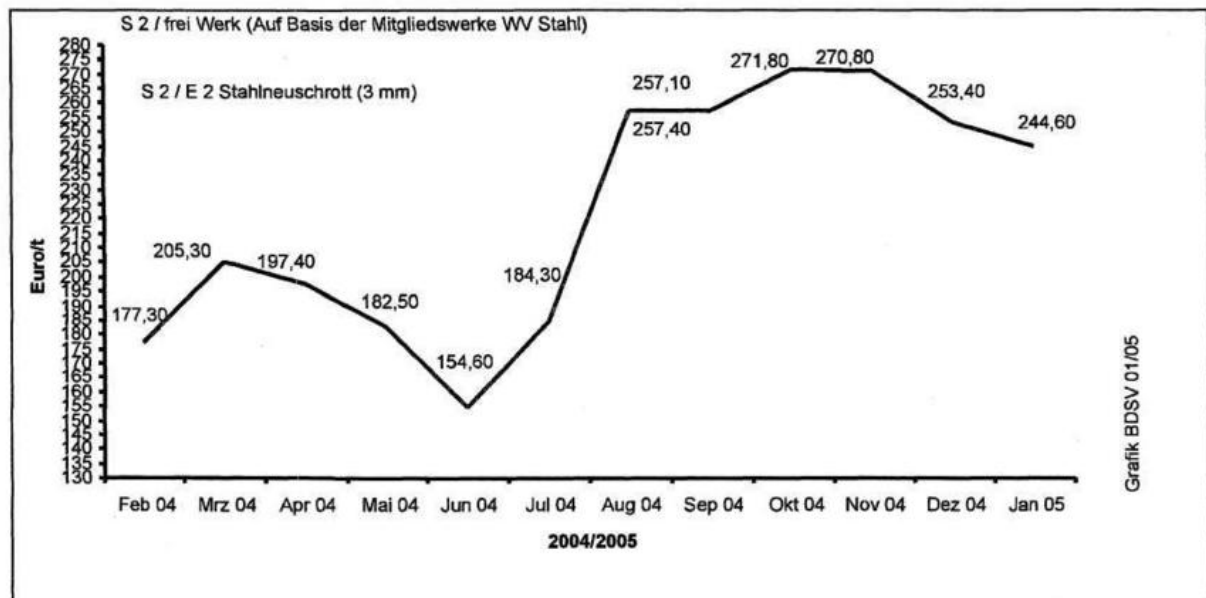


Fig 16a

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Scrap price Export Rotterdam

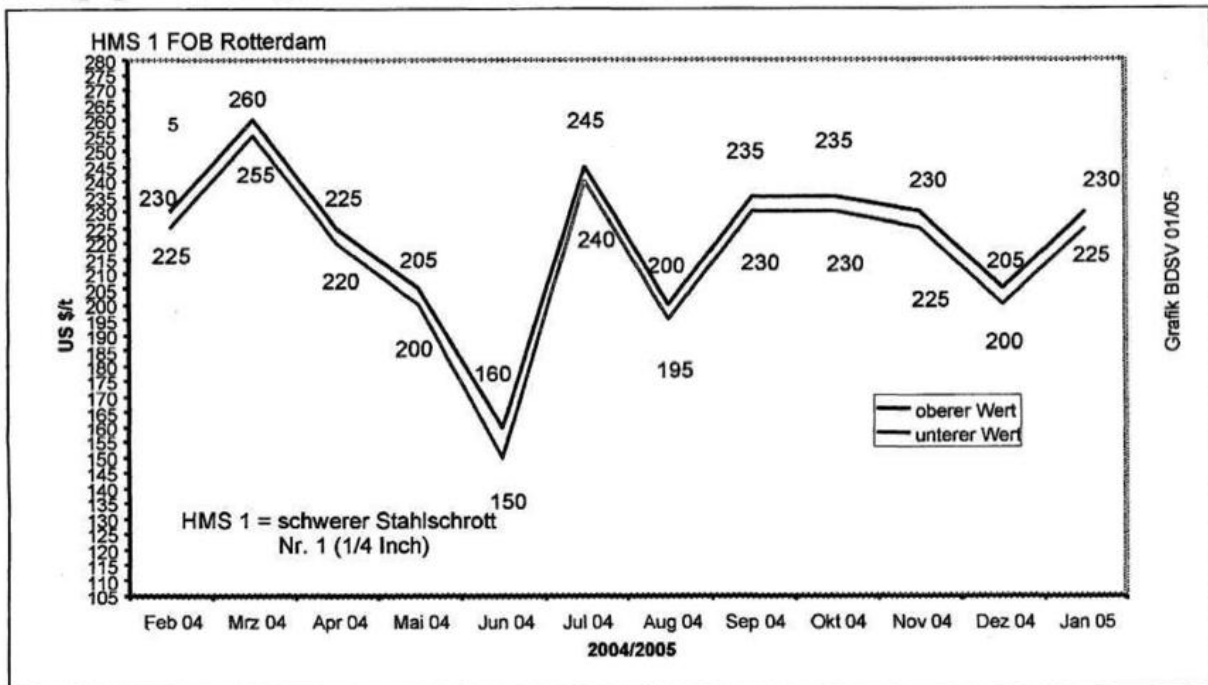
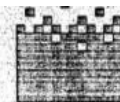


Fig 16b

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Scrap price Export USA

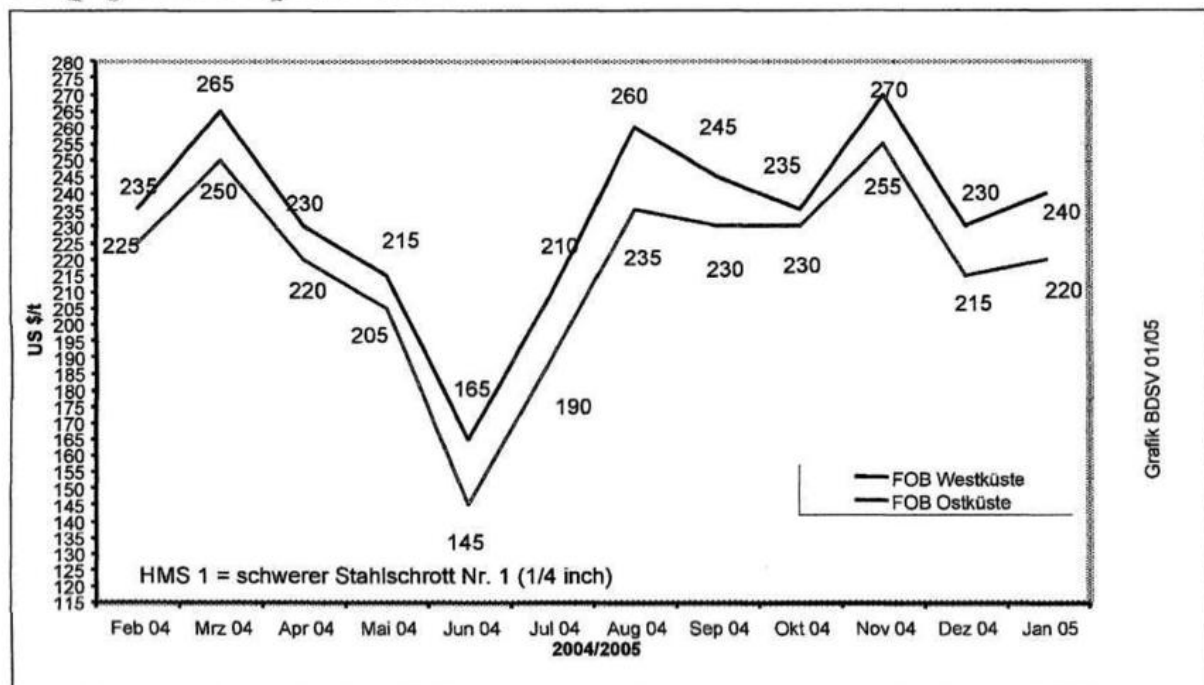
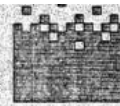


Fig 16c

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Share of electric furnace steel in the total production and development of the prices for steel scrap

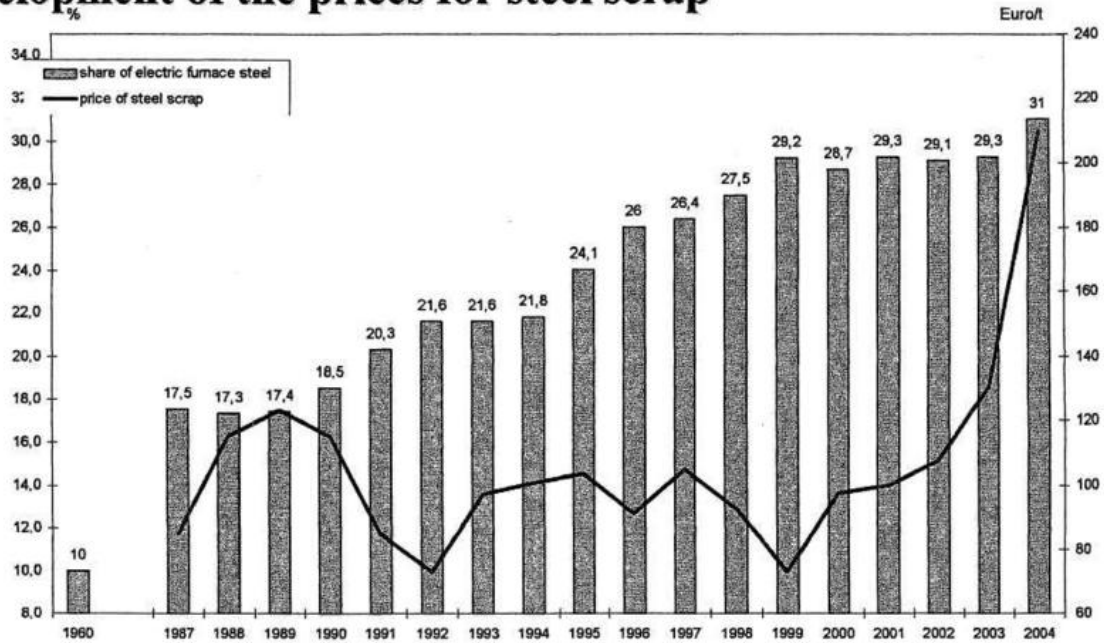
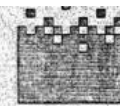


Fig 17

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Development of scrap prices and consumption of steel scrap

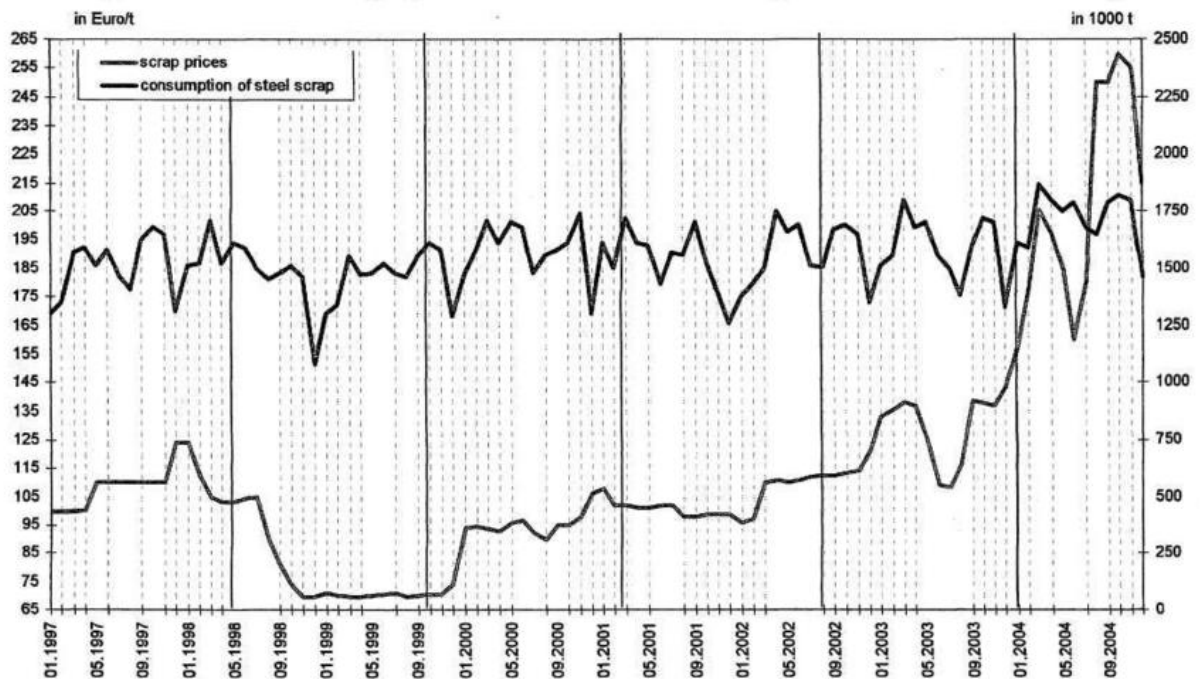


Fig 18

Stahlwerk



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Development of the price for Ferro-Molybdän

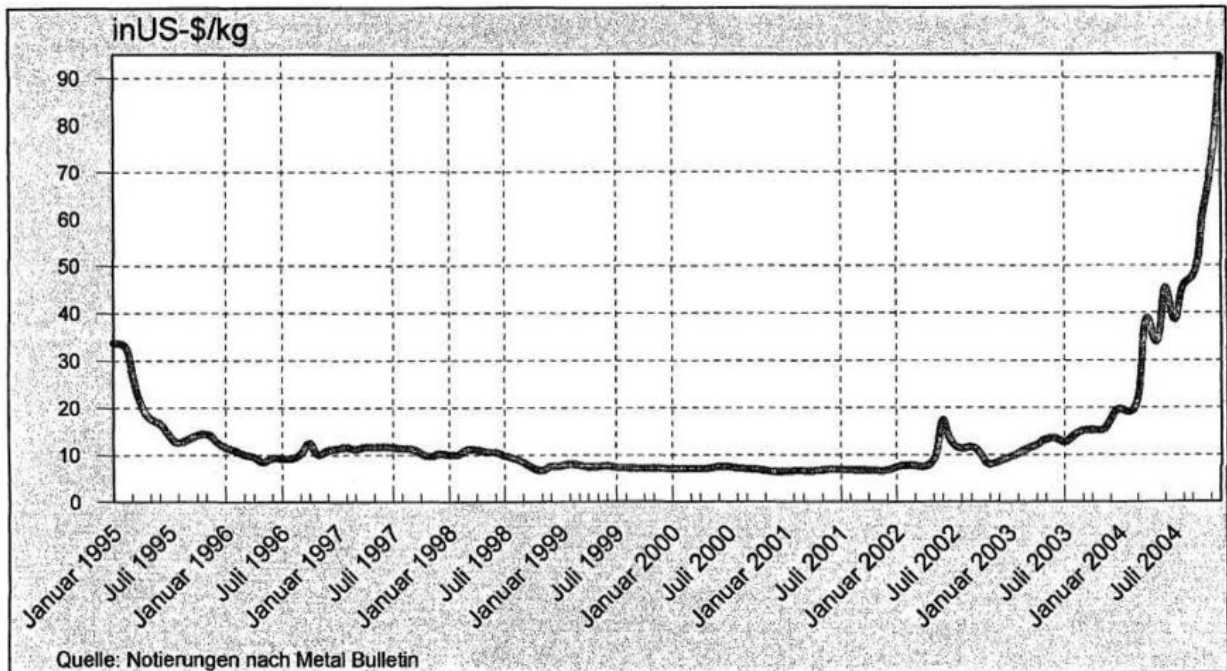
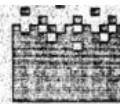


Fig 18a

Stahlwerk



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Development of the price for Nickel

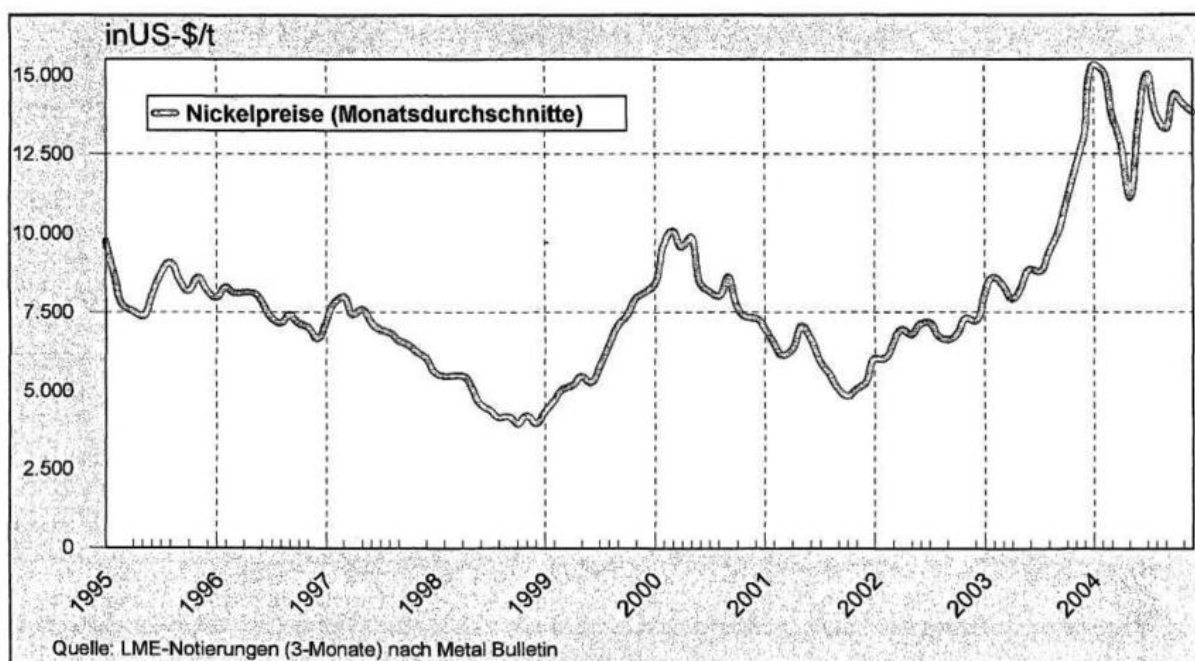
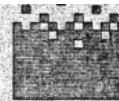


Fig 18b

Stahlwerk



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Development of the price for china coke

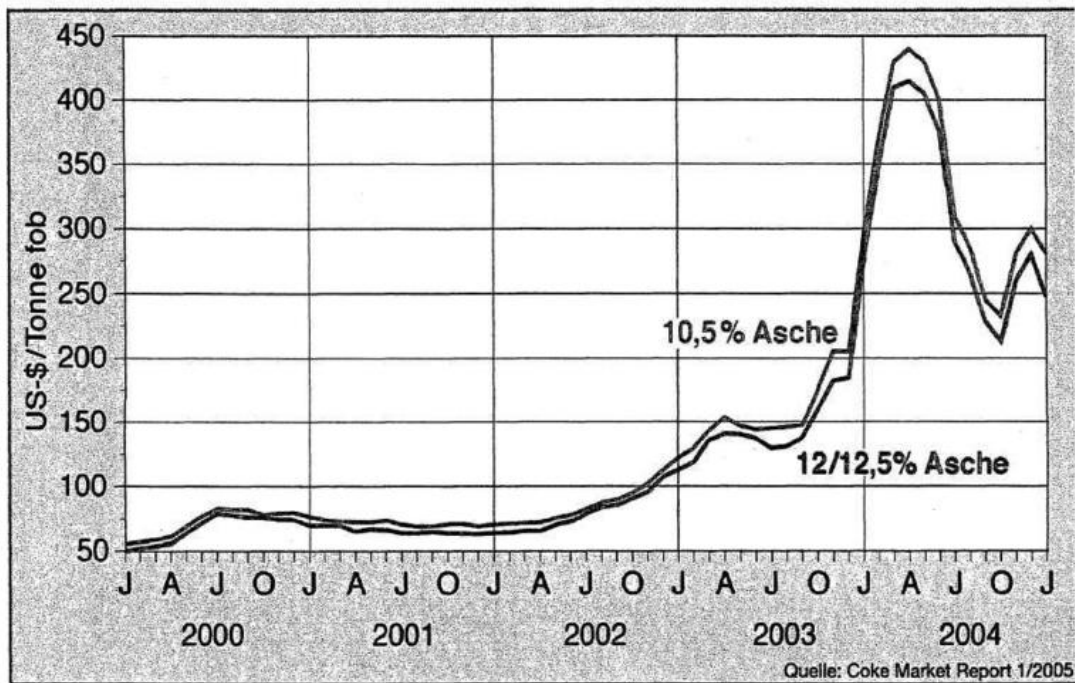


Fig 18c

Stahlwerk



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Development of the price for Carajas ironore

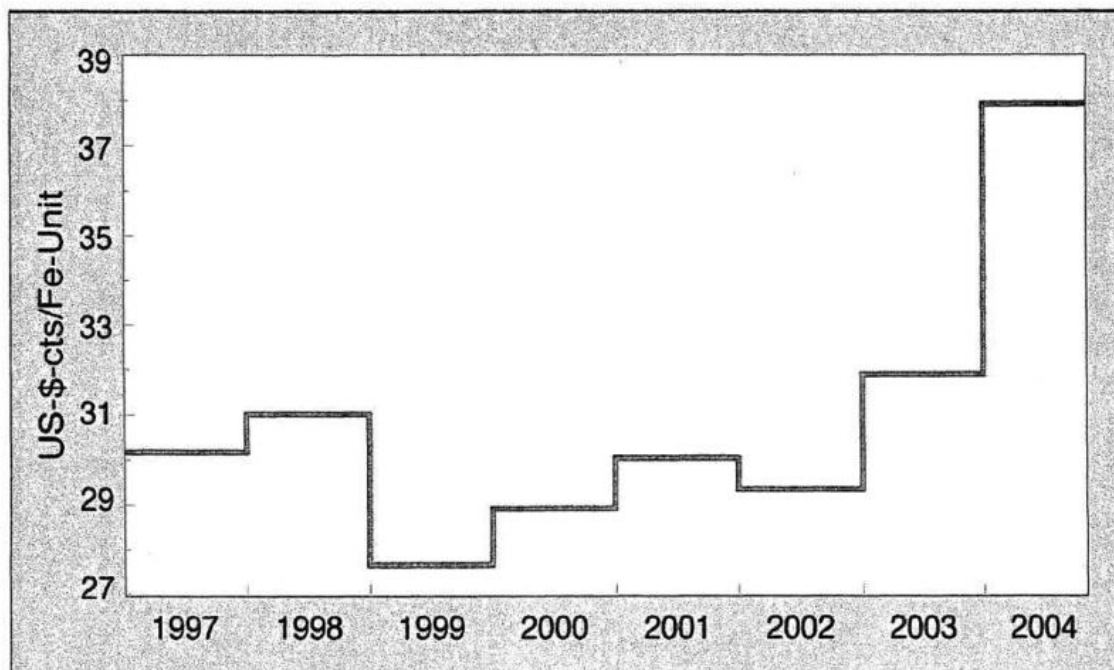
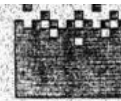


Fig 18d

Stahlwerk



Development of the cargocosts

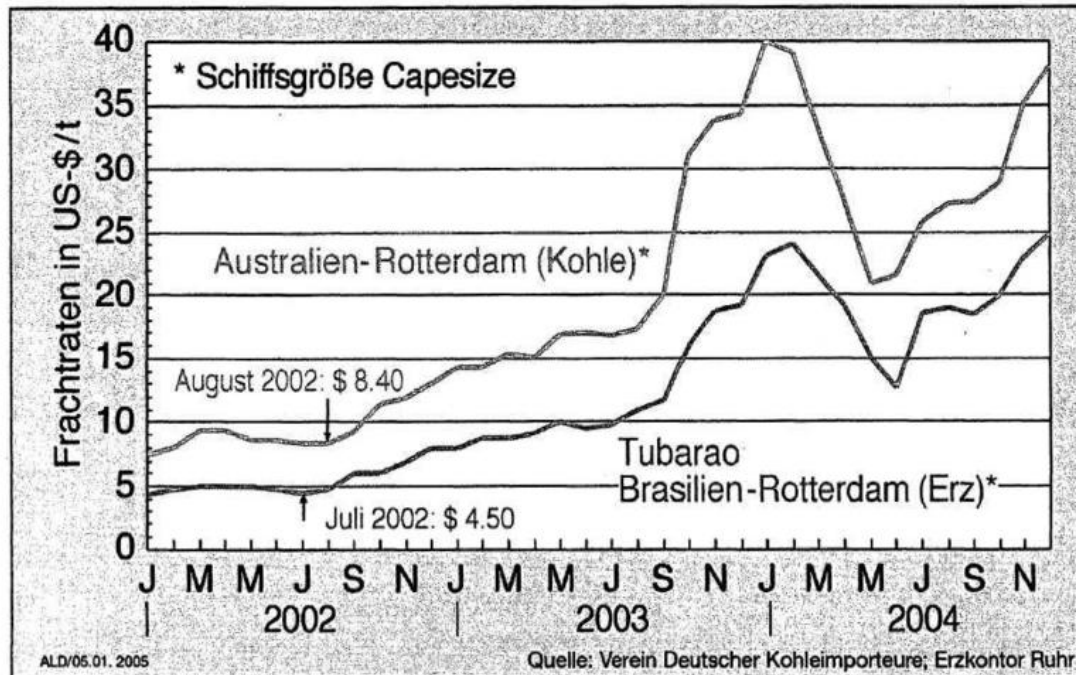
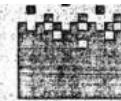


Fig 18e

Stahlwerk

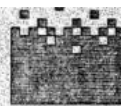


Specifications for analysis and use of material for CC-slabs and CC-billets

Element	metal sheet	slabs heavy plates tubes	hot strip grades	concrete reinforc. Steel bars	billets (long) Steelcord	grades for cold upsetting	high-grade and h.-g. structural steel
	mass contents in %			mass contents in %			
	analyses standards:						
C	0,02-0,035	0,08-0,10	0.85	0.19	0.64	0.04	0.1-1.0
Si	0.02	0,20-0,30	≠ 0,30	0.23	0.17	0.04	0.08-0.50
Mn	0,15-0,22	1,40-1,55	≠ 0,50	0.80	0.52	0.35	0.5-2.0
P	⊙ 0,012	⊙ 0,020	⊙ 0,015	⊙ 0,035	⊙ 0,010	⊙ 0,015	< 0.020
S	⊙ 0,012	⊙ 0,002	⊙ 0,010	⊙ 0,025	⊙ 0,010	⊙ 0,015	
Al	≠ 0,035	≠ 0,030	⊙ 0,010	-	-	≠ 0,035	0.04
Cu	⊙ 0,04	⊙ 0,10	⊙ 0,10	⊙ 0,40	⊙ 0,05	⊙ 0,10	0.20
Cu+Cr+Ni+Mo	⊙ 0,13	⊙ 0,35	⊙ 0,60	⊙ 0,80	⊙ 0,10	⊙ 0,20	-
	composition of pig iron			composition of sponge iron			
Cu	⊙ 0,01			⊙ 0,01			
Cr	⊙ 0,03			⊙ 0,01			
Ni	0.0			0.0			
Mo	0.0			0.0			
	use in %						
pic iron	80	80	80	0	0	0	0
sponge iron	0	0	0	0	65	65	0
scrap	20	20	20	100	35	35	100

Chart 5

Stahlwerk

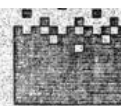


European list of scrap grades

European List of Scrap Grades, short version				
	Short description	max. dim. m	min.weight t/m ³	max.debris %
E 1	Light capital scrap, mostly < 6 mm	< 1,5x0,5x0,5	> 0,5	< 1,0
E 3	Heavy capital scrap, mostly > 6 mm	< 1,5x0,5x0,5	> 0,6	< 1,5
E 2	Heavy new scrap, mostly > 3 mm	< 1,5x0,5x0,5	> 0,6	< 0,3
E 8	Light new scrap, mostly < 3 mm	< 1,5x0,5x0,5	> 0,4	< 0,3
E 6	Light new scrap < 3 mm Stärke, compressed or in bales		> 1,0	< 0,3
E 40	Shredded scrap, crushed capital scrap		> 0,9	< 0,4
E 46	Shredded scrap from refuse incineration plants		> 0,8	Fe > 92 %
E 5 H	Carbon steel chips, homogeneous			
E 5 M	Carbon steel chips, mixed			

Chart 6

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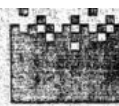


Intended values of analysis in the grades of steel scrap stated by the European list of scrap grades

European List of Scrap Grades: Intended values of analysis						
Grade	Description	Intended values of analysis (recyclings) in %				
		Cu	Sn	Cr, Ni, Mo	S	P
E 1	Capital scrap	< 0,400	< 0,020	Σ < 0,300		
E 3	Capital scrap	< 0,250	< 0,010	Σ < 0,250		
E 2	New scrap with low content		Σ < 0,300			
E 6	of accompanying elements		Σ < 0,300			
E 8	(free of coatings)		Σ < 0,300			
E 40	Shredderschrott	< 0,250	< 0,020			
E 5 H	Steel chips	A prior chemical analysis can be requested				
E 5 M	Steel chips	< 0,400	< 0,030	Σ < 1,0	< 0,100	
EHRB	Scrap with a high content of	< 0,450	< 0,030	Σ < 0,350		
EHRM	accompanying elements	< 0,400	< 0,030	Σ < 1,0		

Chart 7

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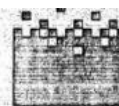


Analysis for Midrex – sponge iron

	guaranteed	typical
Fe total	min 89 %	90 - 92 %
Level of metallization	min 90 %	91 - 93 %
C	1 - 3 %	1.5 - 2.5 %
SiO ₂	max 3.5 %	2.2 %
Al ₂ O ₃	max 1.5 %	1.0 %
S	max 0.015 %	0.005 %
P (oxidised)	max 0.040 %	0.025 %
CaO		1.10 %
MgO		0.80 %
MnO		0.25 %
TiO ₂		0.20 %
Ni, Sn, Zn, Cr, Cu, V, Pb		traces
grain-size distribution	< 4 mm	approx. 8 %

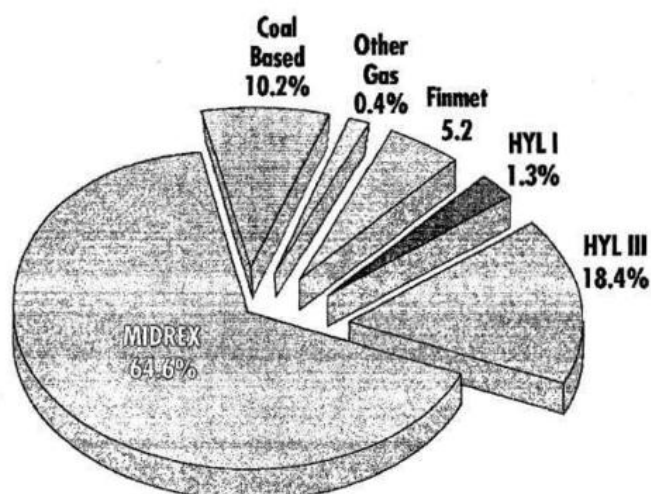
Chart 8

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Total global production of direct reduced sponge iron in 2003 according to production process

2003 World DRI Production by Process



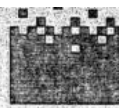
Total World
Production
49.5 Mt

	2002	2003
Midrex	66.6%	64.6%
HYL III	18.4	18.4
HYL I	1.3	1.3
Finmet	3.6	5.2
Coal Based	9.8	10.2
Other Gas	0.3	0.4

Source: Midrex Technologies, Inc.

Fig 19

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Global production of sponge iron

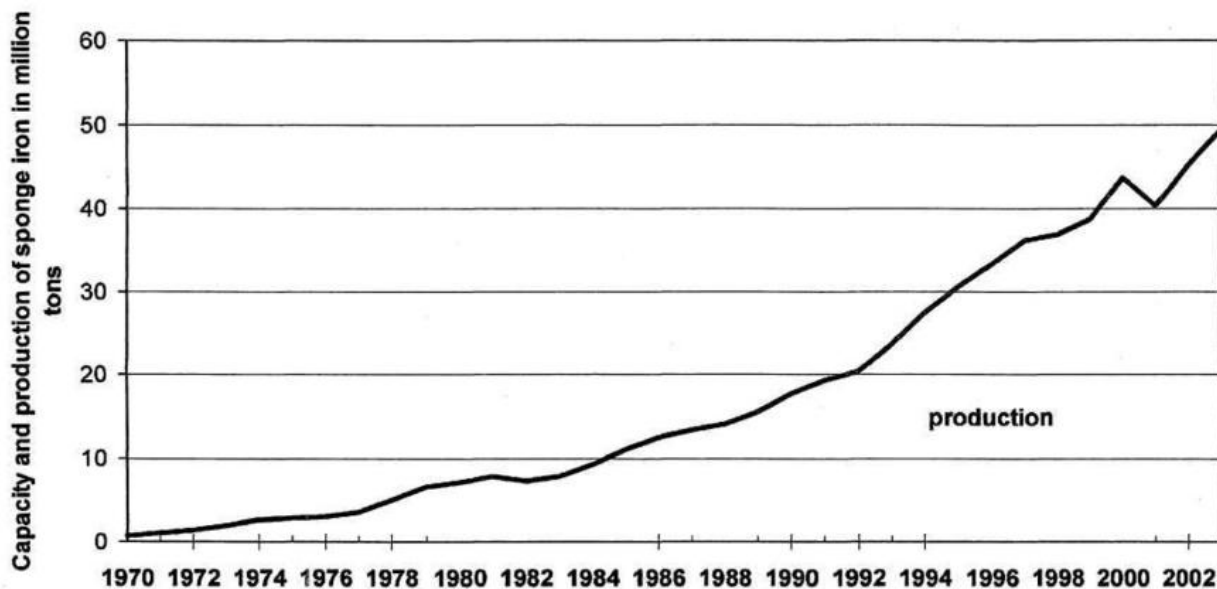
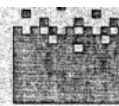


Fig 20

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Production of sponge iron in 2003 according to regions

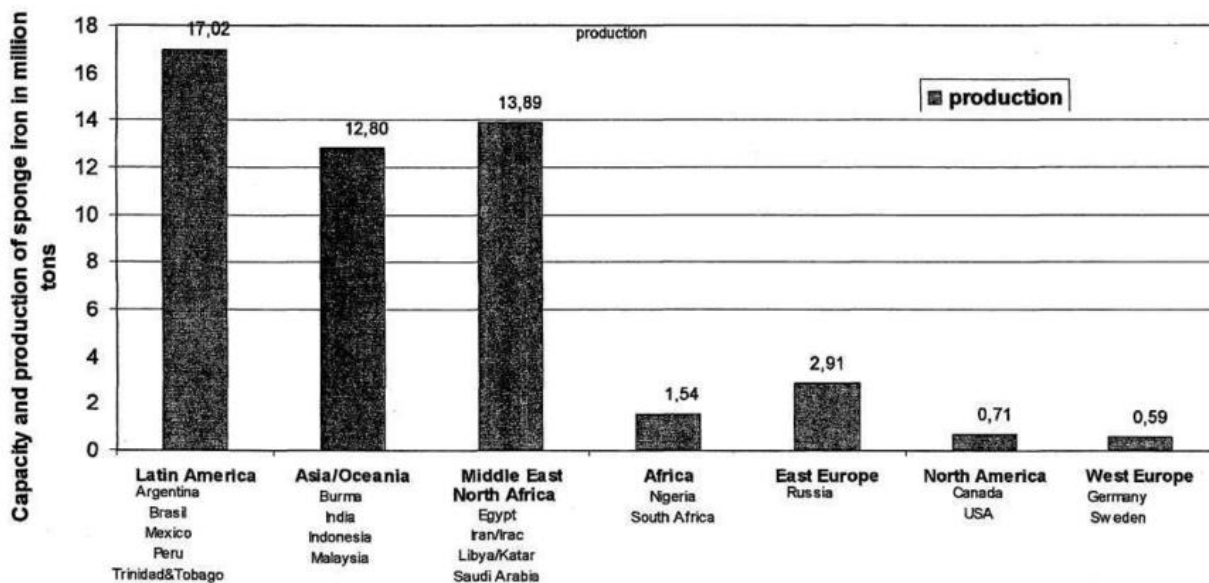


Fig 21

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Global overland and ocean transport of sponge iron

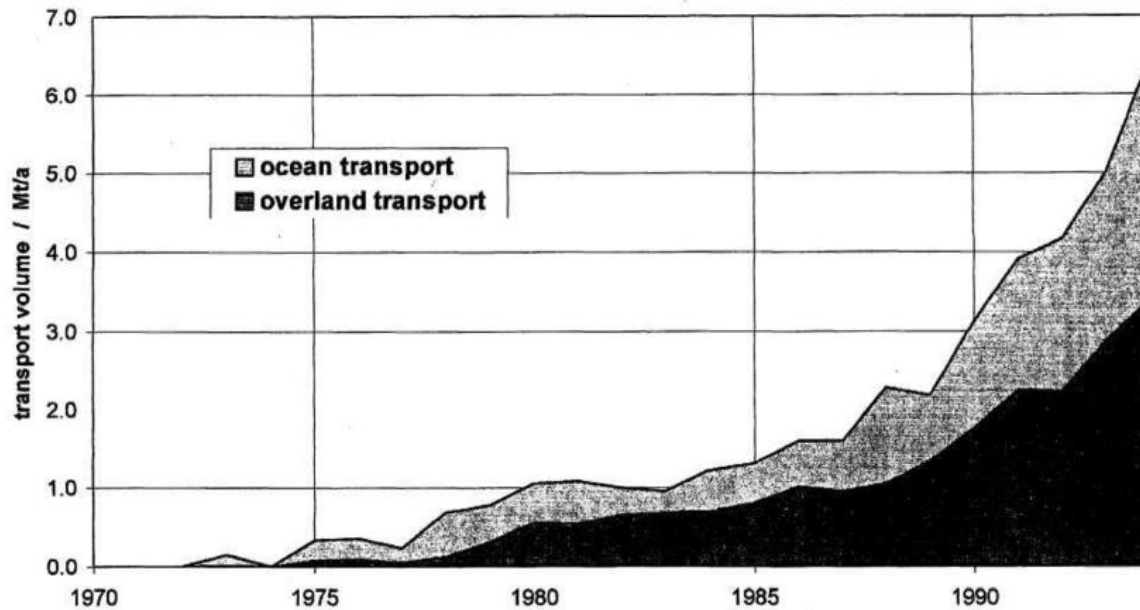
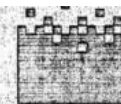


Fig 22

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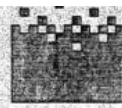


Valuation of production costs for sponge iron

	material input	Price in US\$ per unit		Costs in US\$ / t	
		Venezuela	Europe	Venezuela	Europe
Pellets	1,05 t / t	26	42	27,30	44,10
lump ore	0,45 t / t	18	32	8,28	14,40
natural gas	10,6 GJ / t	0,45	4,0	4,77	42,40
power	130 kWh / t	0,014	0,05	1,82	6,50
other processing costs 1)				9,0	12,0
maintenance	4% v.Invest.	220 US\$ / t.a		8,8	8,8
Operating cost				59,97	128,20
Debt service	15% v.Invest.	220 US\$ / t.a		33,00	33,00
Production cost				92,97	161,20
Transport		30,0	-	30,00	-
Costs for steel works in Europe				122,97	161,20
1) Wages, expendable material, internal transport etc.					

Chart 9

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Comparison of processing cost of 125 t electric arc furnace with 150 t - and 245 t BOF converter

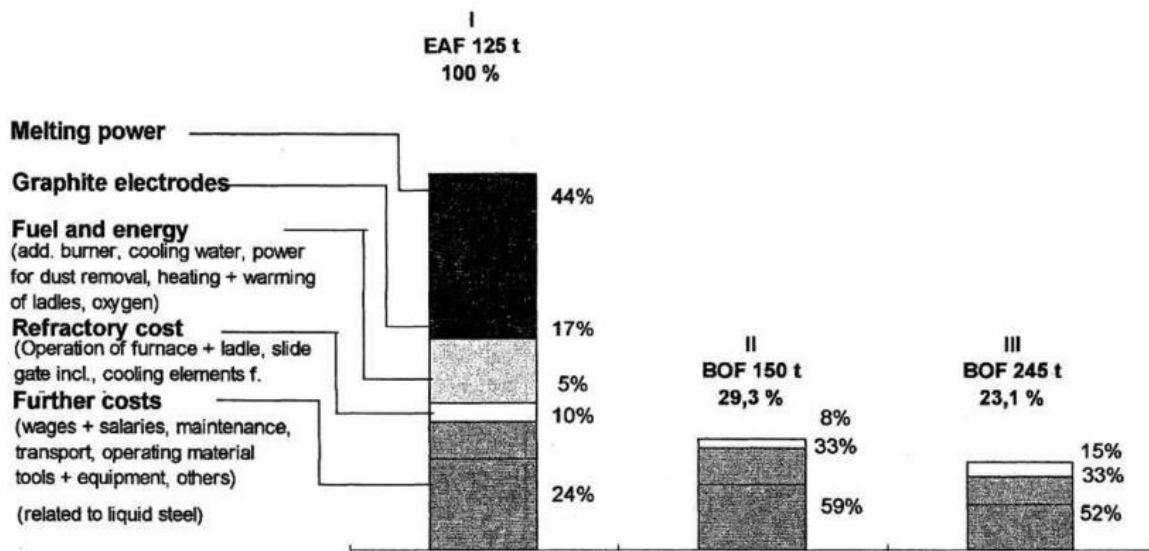
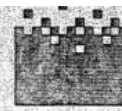
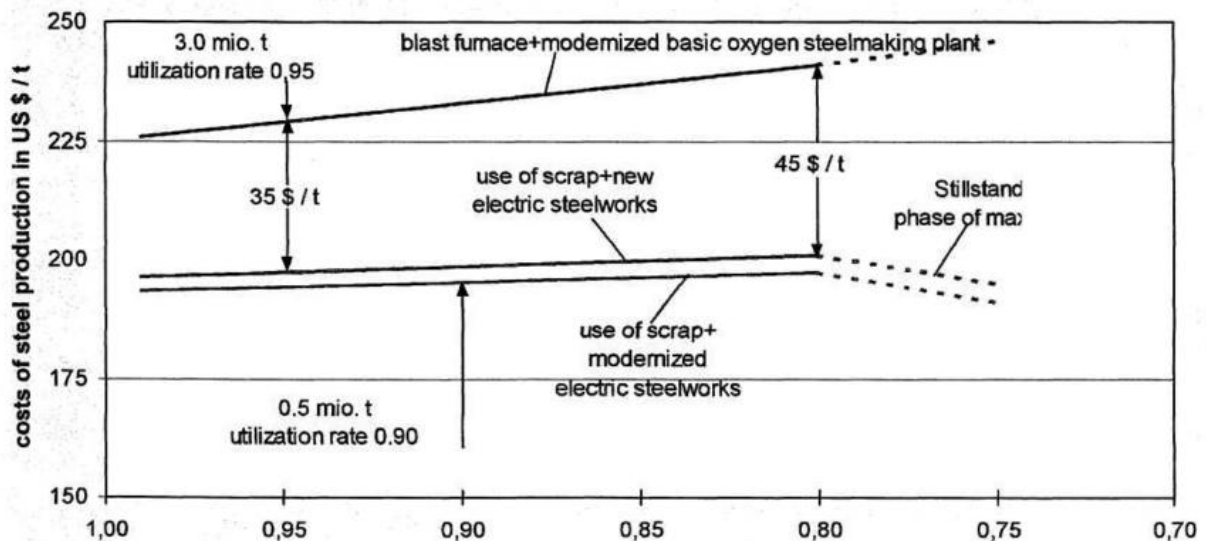


Fig 23

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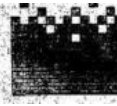
Costs of steel production in relation to production process and the utilization



(Preise unter europ. Bedingungen)

Fig 24

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Technical development of the steel production by means of an electric arc furnace

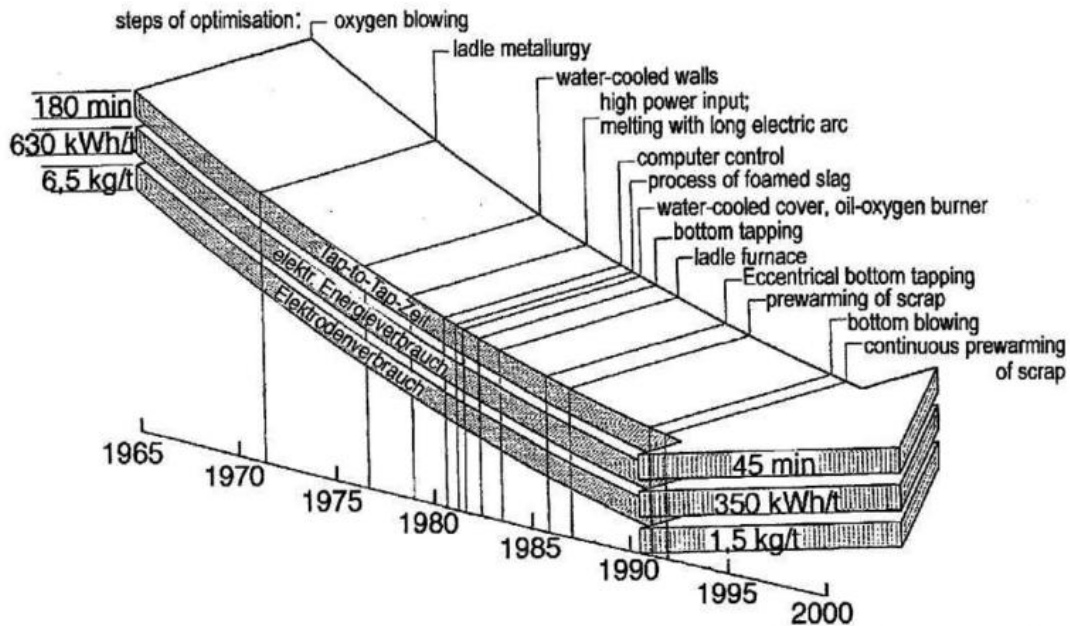
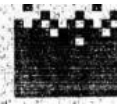
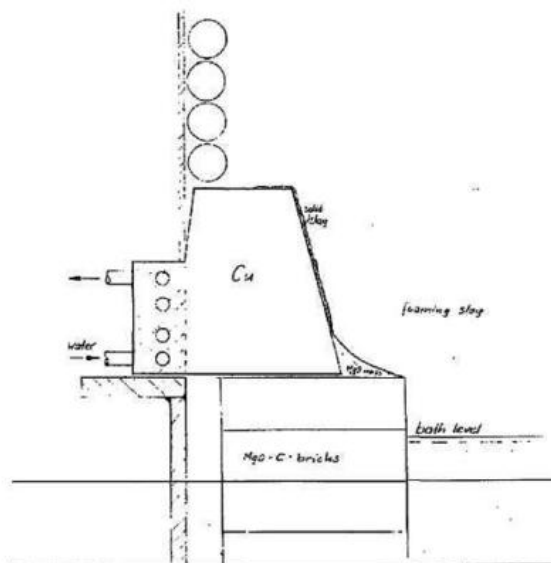


Fig 25

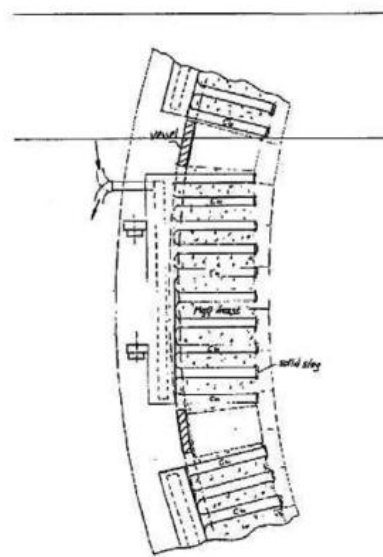
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Cooling Block



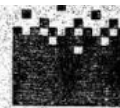
SHAPE AND POSITION OF COOLING BLOCKS IN EAF
GESTALTUNG UND LAGE VON KÜHLBLÖCKEN IM LAF



LOCATION OF COOLING BLOCKS IN THE EAF-WALL
ANORDNUNG VON KÜHLBLÖCKEN IN DER OFEN-WAND

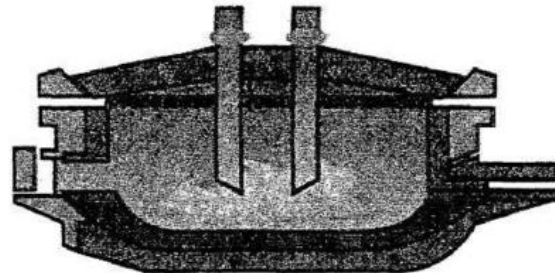
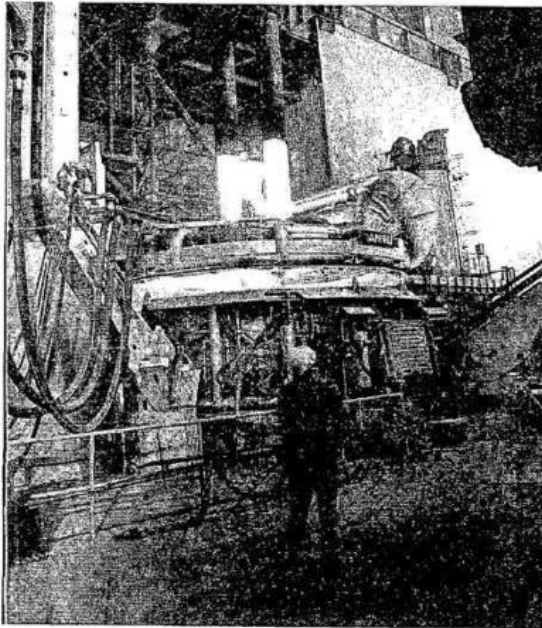
Fig 26

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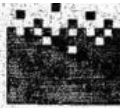
DC- TWIN electric arc furnace



Twin DC Electrodes

Fig 27

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EAF Sankey Diagram

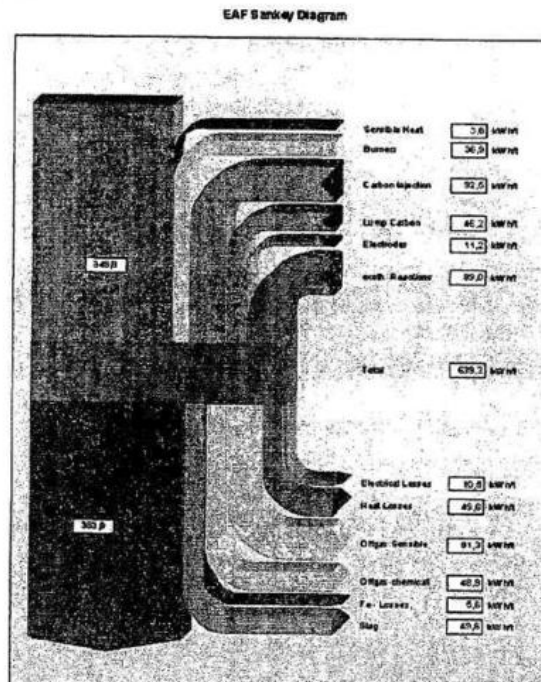
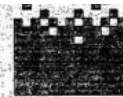


Fig 28

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Various processes with use of off-gas

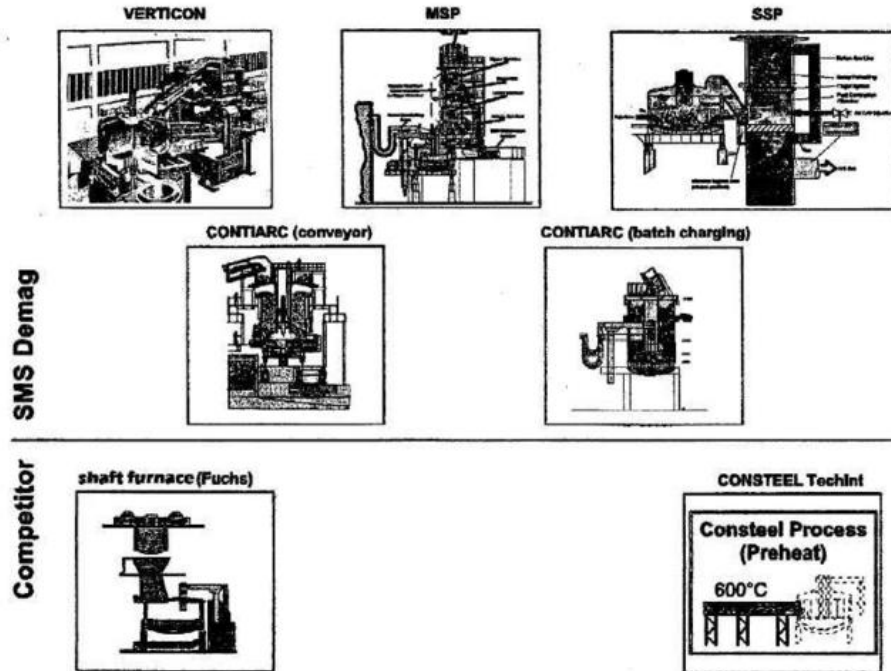


Fig 29

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COHERENT-JET

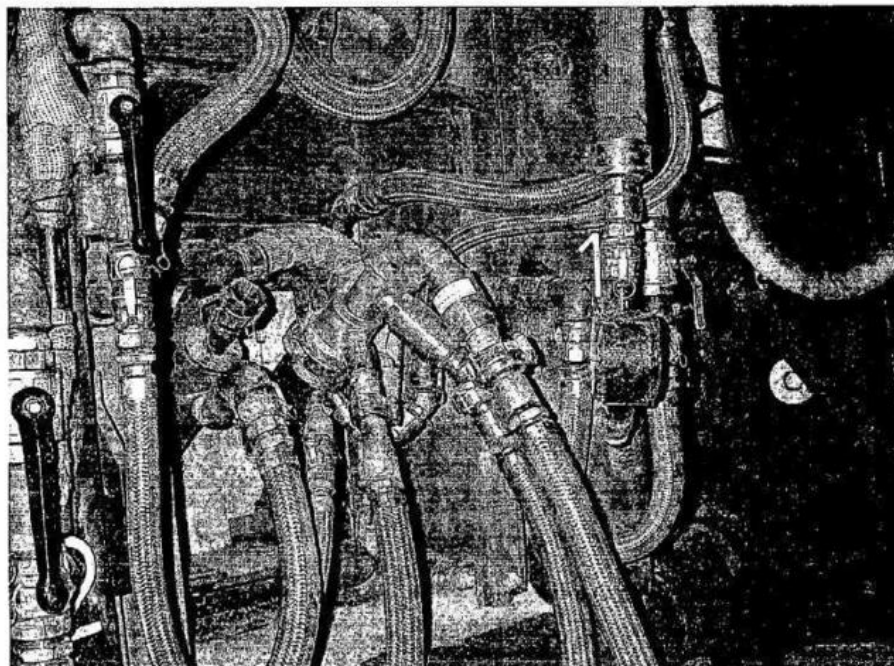
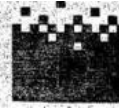


Fig 30

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RCB-BURNER

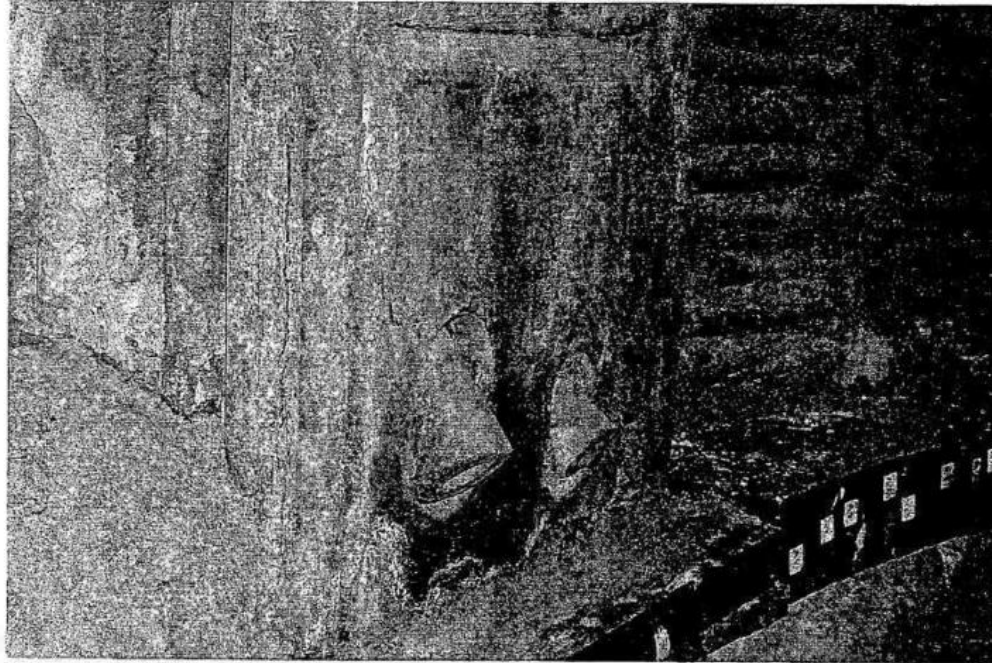


Fig 31
Stahlwerk

Steel Academy

International Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Principles of AC-Arcs

Prof. Dr.-Ing. Klaus Timm,
formerly Universität der Bundeswehr, Hamburg

1 Physics of AC arcs

Prof. Dr.-Ing. Klaus Timm

- 1 High-current circuit
- 2 Temperature and electric conductivity of plasmas
- 3 Electric arc geometry
- 4 Current density
- 5 Arc length
- 6 Arc thrust
- 7 Magnetic arc deflection
- 8 Characteristics of electric arc variables
- 9 Acoustic emissions
- 10 References

1 High-current circuit

Since 1909 the high-current circuit in alternating current (AC) electric arc furnaces (EAF) has been designed according to the principle of the *Héroult* system. It comprises three phases 1, 2 and 3 connected to the secondary terminals of the transformer in the form of a star connection. The high-current line, see **figure 1**, consists of the outgoing supply A from the transformer, the flexible high-current cables B, tubular conductors on the electrode arms or current-conducting electrode arms C and the graphite electrodes D. In AC EAFs, the arcs are burning from the tips of the electrodes towards the melt F, u_B is the arc voltage. The melt forms the free star point 0 of the alternating current system. The AC EAF does not require a bottom electrode. This, however, is necessary for a direct current (DC) EAF. Only a current-free measuring lead is connected to the furnace vessel for measuring the phase voltages u_{1M} , u_{2M} , u_{3M} of the furnace.

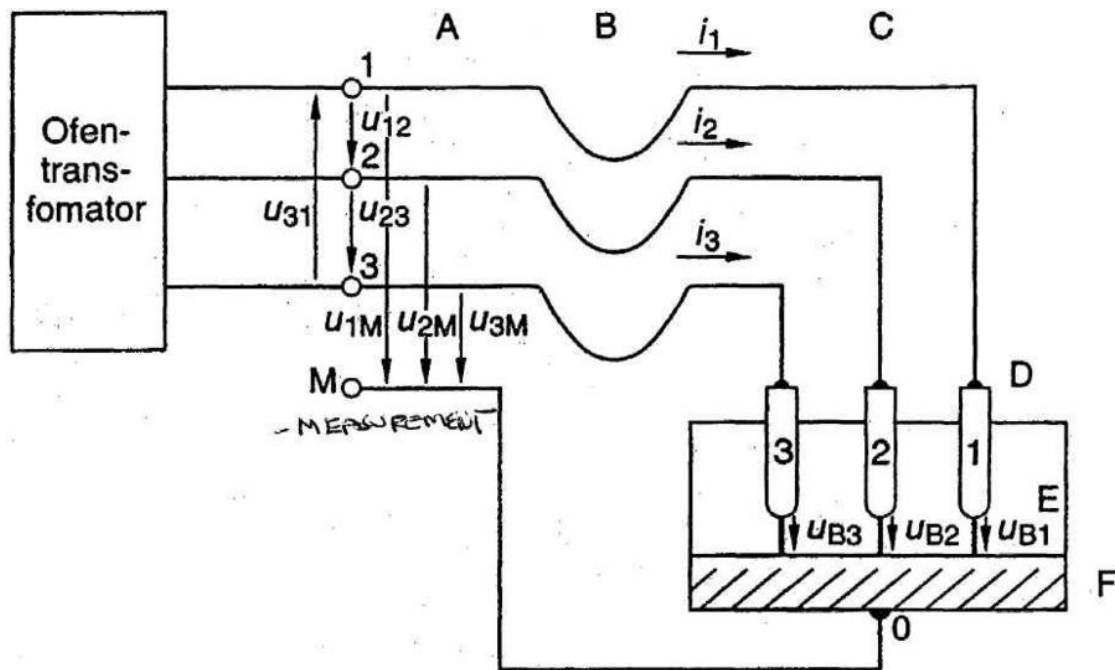


Figure 1: High-current circuit of the AC EAF

The first article on electrical engineering principles will deal with the *physical properties of the AC electric arc* relevant for the engineering and operation of EAFs.

The electric arc is a gas discharge between two electrodes (anode and cathode) connected to a voltage source. In the EAF one of the two electrodes is made of graphite. This electrode is not to be consumed. The other electrode is formed by the scrap charge to be molten. **Figure 2** shows the typical arrangement of an AC EAF with 3 electric arcs between the graphite electrodes and the molten metal. The discharge of the electric arc is also called *plasma*. The plasma consists of negative charges (the electrons) and positive charges (the gas ions).

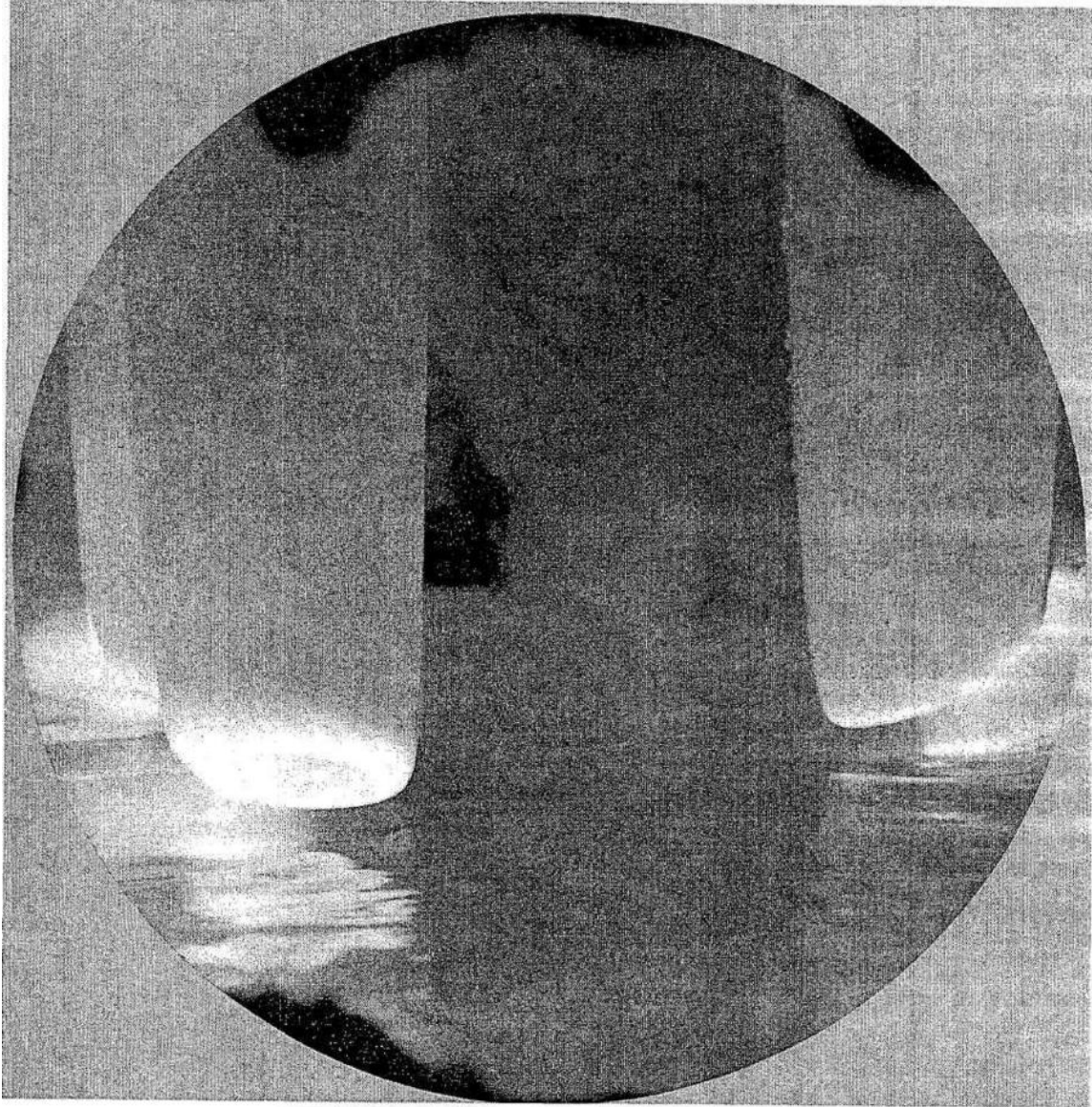


Figure 2: Arcs in the AC heat at flat bath conditions

2 Temperature and electric conductivity of plasmas

The literature provides different information regarding the temperatures and gas composition of AC electric arcs. *Jordan et al.* [1] estimate the temperature of the cathode half-wave at 12000 - 18000 K. Such values are only possible with air plasmas whose H_2 , N_2 and O_2 contents have been dissociated and ionized into atoms.

More recent investigations on direct current electric arcs from *Block* have revealed that the plasma temperature is about 8600 K [2]. The electric conductivity is, above all, determined by electrons resulting from the ionization of iron atoms whose content in the plasma is estimated at 2.5 %. It is assumed that these conditions also apply to AC electric arcs.

The electric conductivity of plasmas with different gas compositions is given in **figure 3**.

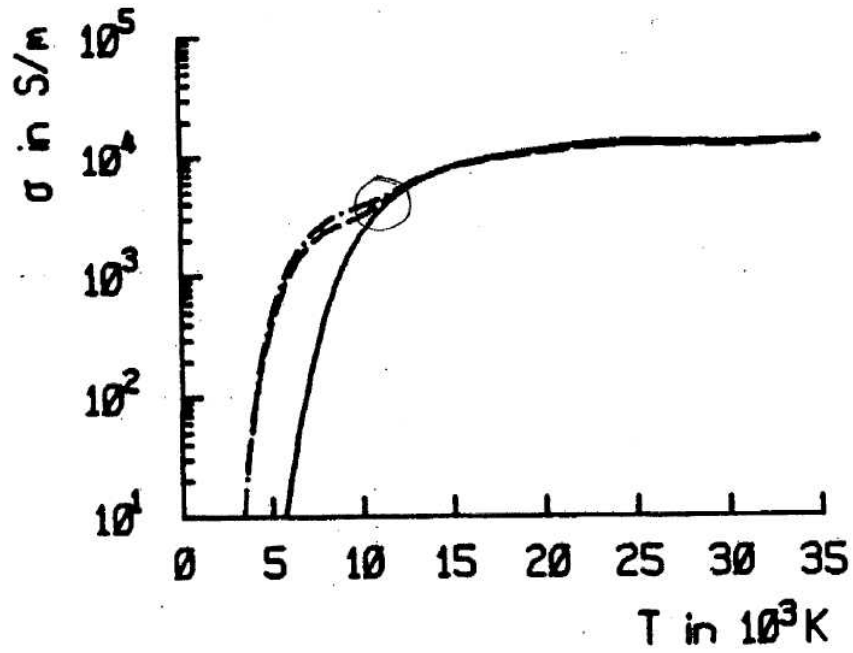


Figure 3: Electric conductivity of gas discharge in relation to the temperature.

air, - - - air + 5 % Fe, -.- air with 10 % Fe

3 Electric arc geometry

In the AC electric arc furnace the AC electric currents must be re-ignited in each half-wave. In the case of negative polarity of the graphite electrode (cathode half-wave) the gas discharge takes a cylindrical form (**figure 4a**) which is stabilized by a gas jet produced by a higher current density at the electrode tip [3]. As such a contracted column also occurs with DC electric arcs in DC EAFs, this phenomenon will be explained in more detail:

Under such polarity conditions, current densities at the cathode have been observed to be 4-5 times higher (approx. 5 kA/cm²) than at the rest of the arc column. The contraction of streamlines leads to gas currents in a fluid due to the *Lorentz* forces. In this case the *Lorentz* force $S \times B$ contains a component acting in the direction of the axis of the electric arc, causing a plasma current, the cathode jet, which enters the cathode and stabilizes the electric arc column to form a *cylindrical discharge channel*, **figure 5**.

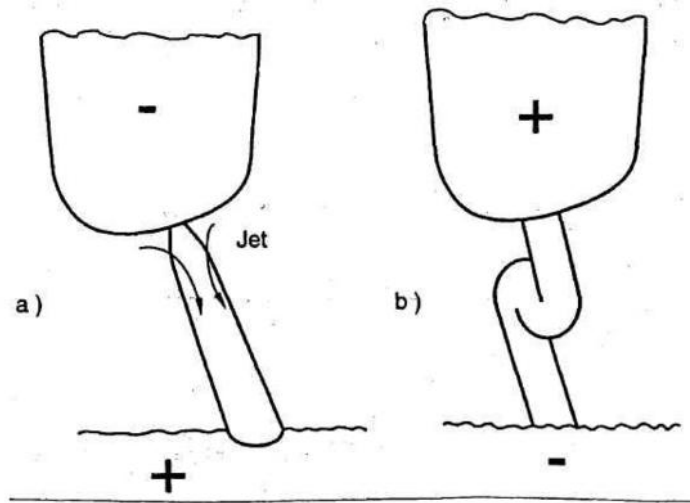


Figure 4: Discharge geometry of the cathode half-wave (a) and anode half-wave (b) of AC arcs

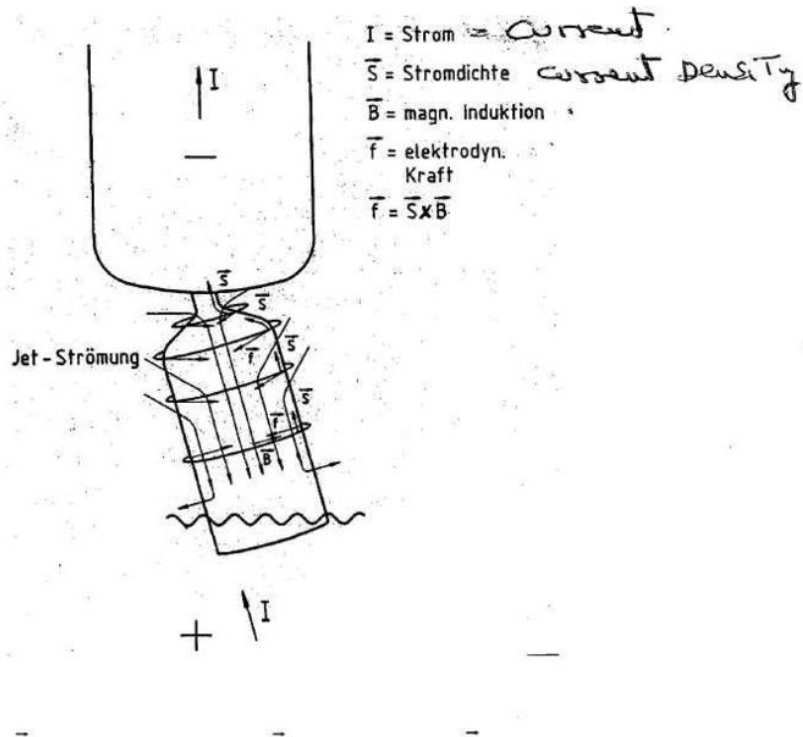


Figure 5: Stabilizing the cathode half-wave by Jet flow

(I = current, S = current density, B = induction, f = Lorentz force)

In contrast to the cathode half-wave, at the anode half-wave there is no stabilizing jet. This produces kink instabilities in the plasma column, **figure 4b**. At the cathode half-wave the plasma column is "stable", at the anode half-wave it is "turbulent".

4 Current density

The current density of the hot, current-conducting core of a high-current arc is about 1 kA/cm^2 [1]. With alternating currents the core diameter of the electric arc changes according

to the sinusoid. For example, the maximum core diameter of a 60 kA electric arc at the current peak is only about 10 cm, i.e. the channel diameter is much smaller than it visually appears.

5 Arc length

According to the principle of minimum energy, the electric arc is constantly trying to minimize its length. Therefore, arcing between the graphite tip and the metal bath is largely vertical. However, due to the rotating magnetic field the plasma column is deflected towards the furnace wall, **figure 2**.

The relationship between the arc voltage U_B and the arc length l is largely linear. Accordingly, the arc voltage is made up by the anode and cathode fall of approx. $U_{AK} = 40$ V and the voltage drop at the plasma column:

$$U_B = U_{AK} + E \cdot l.$$

The electric field intensity E in the plasma column depends on the furnace condition. It can be determined by upward and downward motion experiments in EAFs [4, 5, 6]. **Figure 6** shows the measured relationship between the arc voltage and the electrode lift in a 90 MVA EAF at varying furnace voltages. The figure also shows that the currents increase with a decreasing voltage. When the arc is covered by foaming slag (figure 6b, lower part of the characteristic curve), the field intensity is about 1 V/mm, Free arcs without foaming slag have a smaller field intensity which can be as low as 0.6 V/mm (**figure 6a**). Comparable field intensity values have been observed with direct current arcs.

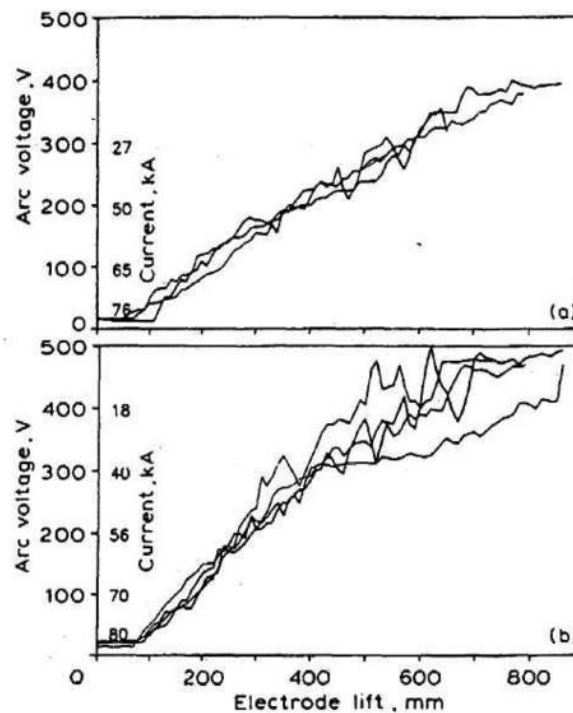


Figure 6: Arc voltage in relation to the electrode lift in a 90 MVA AC EAF [4, 5]. Phase to phase voltage 450 V (a) and 550 V (b)

6 Arc thrust

The plasma jet occurring at the cathode half-wave (**figures 4 and 5**) produces a thrust acting in the direction of the arc axis, causing the base point of the arc penetrating the melt. According to *Bowman* [5], there is a quadratic relationship between the growth of the thrust T and the furnace current:

$$T = A \cdot 10^{-7} I^2 \text{ in N} .$$

In an AC arc the factor is $A = 0.6$ and in the DC arc $A = 1$. Accordingly, in a 60 kA AC arc the arc thrust amounts to 216 N, in a DC arc with the same effective value it amounts to 360 N.

The plasma jet transmits a considerable part of the electric arc power into the bath. At the same time the penetration of the plasma column into the steel bath (penetration depths up to 60 mm have been reported) makes for a good heat transfer to the melt.

7 Magnetic arc deflection

Current-carrying conductors located in an external magnetic field are subject to an electrodynamic force, the so-called *Lorentz* force. This force also acts on the electric arcs in the AC EAF as they are affected by the external field of the adjacent phases.

In a *two-phase system*, as shown in **figure 7**, the arc in phase 1 is affected by the external field B_2 of the adjacent phase 2, producing an effective force density f_1 perpendicular to the current density vector S_1 and B_2 and deflecting the arc towards the furnace wall.

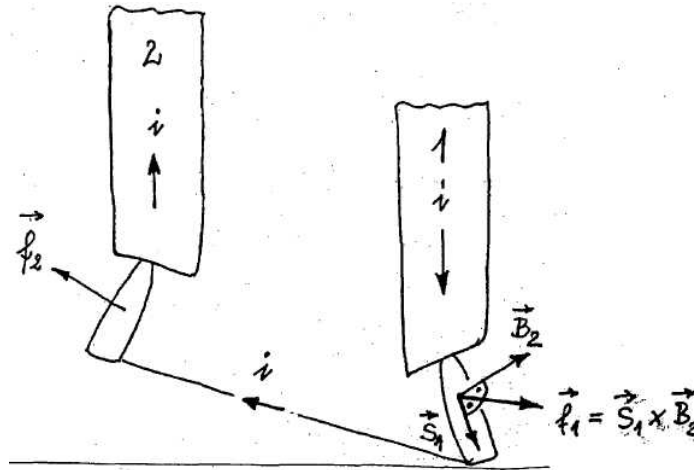


Figure 7: *Lorentz* forces on arcs in a two-phase system

(S_1 = current density in phase 1, B_2 = induction from phase 2, f_1 = *Lorentz-force* in arc 1)

The force effects on electric arcs in *three-phase system* as shown in **figure 8**, can be described by section loads q_i in the horizontal plane X/Y:

$$\vec{q}_i = \frac{\mu_0}{4\pi a} i_i \begin{bmatrix} -\sqrt{3} i_2 \\ i_3 - i_1 \end{bmatrix}, i = 1, 2, 3$$

$\mu_0 = 4\pi \cdot 10^{-7}$ Vs/(Am) permeability constant

Assuming symmetric sinusoidal currents with a clockwise phase sequence,

$$i_1 = I \cos (\omega t + 120^\circ),$$

$$i_2 = i \cos \omega t,$$

$$i_3 = i \cos (\omega t - 120^\circ),$$

for example, the following normalized line load results for the arc in phase 2:

$$\frac{\vec{q}_2}{q_m} = \begin{bmatrix} q_{x2}/q_m \\ q_{y2}/q_m \end{bmatrix} = \frac{1}{2} \begin{bmatrix} -1 - \cos 2\omega t \\ \sin 2\omega t \end{bmatrix},$$

$$q_m = \frac{\sqrt{3} \mu_0 \hat{i}^2}{4\pi a}.$$

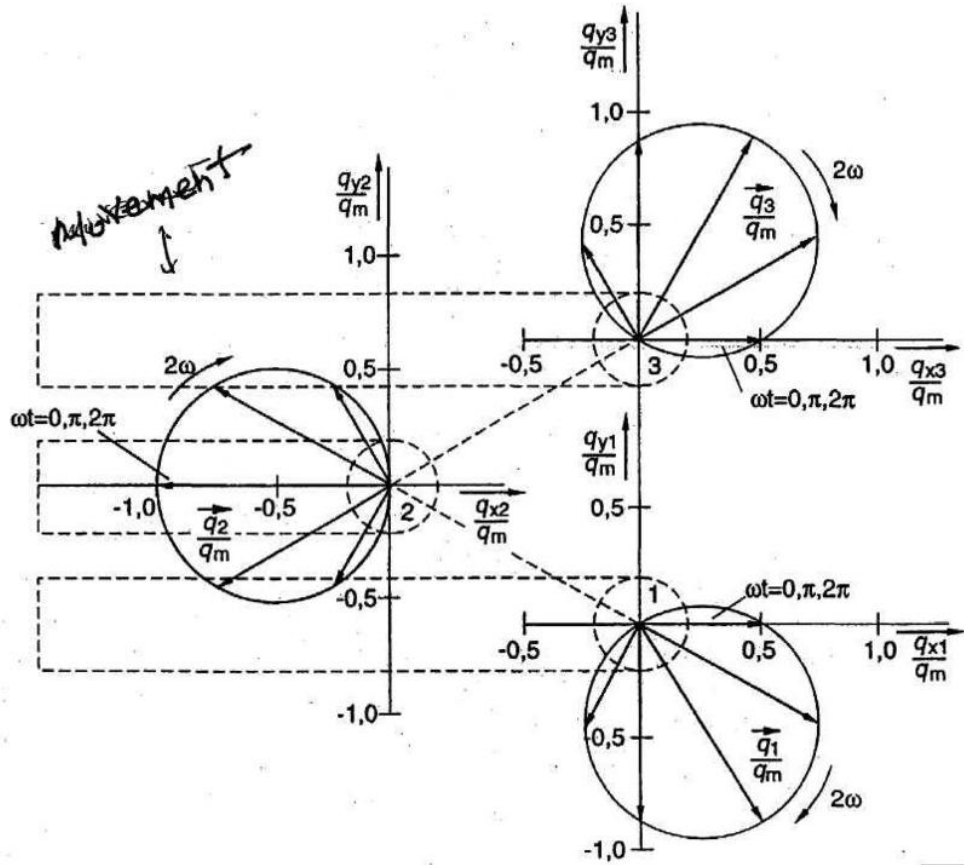


Figure 8: Electrodynamic forces on the arcs and electrodes for sinusoidal currents and phase sequence 1,2,3

As shown in **figure 8**, the locus curves of the section loads acting on the electric arcs and the graphite electrodes are circles. The circles are running through clockwise according to the phase sequence at double line frequency (100 Hz). In the case of free arcing, the arcs follow this rotation field without delay. They rotate through a deflected axis pointing towards the furnace wall. This causes the graphite electrode to form a slanted tip when being consumed, **figure 2**.

The current furnace practice is to use foaming slags. Slags covering the complete arc can insulate the arc against magnetic forces or mechanically limit the arcing volume [5]. If only a part of the electric arc is covered, the hydrodynamic stirring effect of the electric arc plasmas caused by the rotation field can promote slag foaming and the energy transfer from the electric arc to the melt.

8 Characteristics of electric arc variables

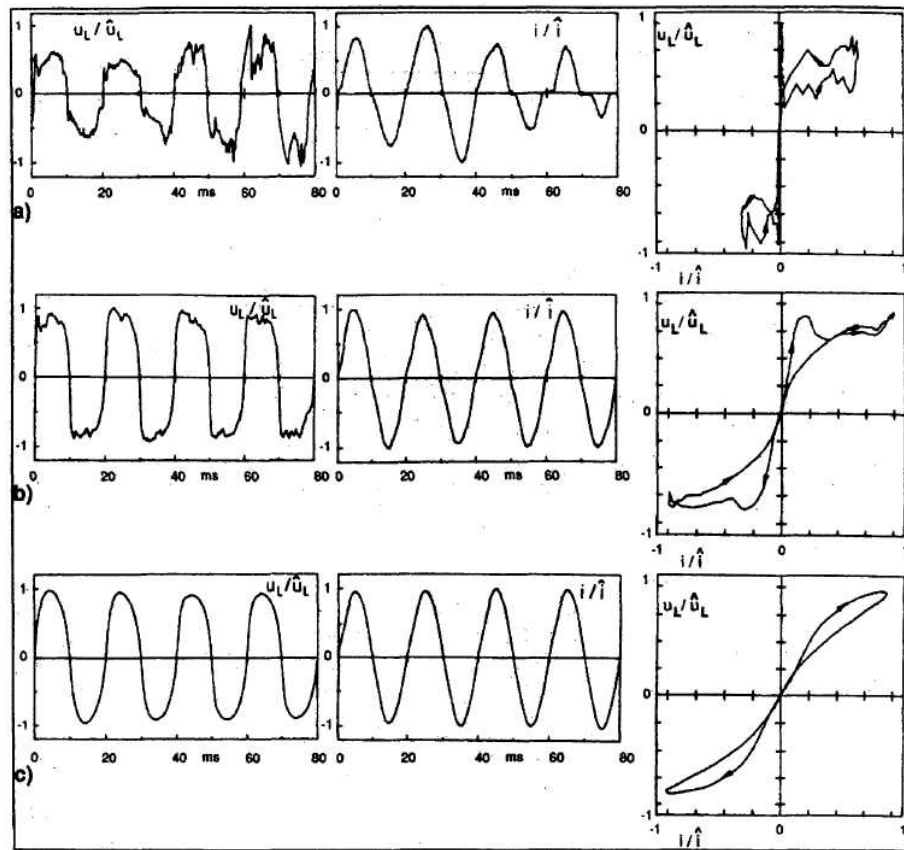


Figure 9: Time records of arc voltage and current and arc characteristics [10]

- a) instantly after start melting ($u_L = 610 \text{ V}$, $i = 81 \text{ kA}$)
- b) 7 minutes after start melting ($u_L = 429 \text{ 429 V}$, $i = 93 \text{ kA}$)
- c) 27 minutes after start melting ($u_L = 356 \text{ V}$, $i = 100 \text{ kA}$)

The waveforms of electric arc variables, which can only be measured with special measuring systems [7, 8, 9], are strongly influenced by the melt-down progress [10]. Non-stationary, rectangular arc voltages with stochastic contents occur during the start of melting. The sto-

chastic contents are caused by rapid arc movements on the cold scrap, **figure 9a**. The reignition of the arcs, which is necessary in each half-wave, can also be delayed.

The second record of signals in **figure 9b** was made during the liquid state of the bath. The stationary arc voltages are very much rectangular and the current is approaching the sine-wave form. An electric arc covered with foaming slag features virtually constant conductivity and practically acts as a linear ohmic resistance. Both the arc voltage and the current take an almost sinusoidal shape, **figure 9c**.

The arc curves for the considered measuring points are characterized by non-linear functions with hysteresis. Not only the arc length, but also the arc temperature and the arc environment, e.g. foaming slag, influence the arc characteristics and change them as the melting process progresses.

9 Acoustic emissions

Steelmaking in AC electric arc furnaces causes extreme noise emissions. Noise levels of 130 dB(A) and above are possible. The main noise sources are uncovered AC arcs. Among others, *McQueen* and *Beckmann* studied the noise generation in electric arcs, using thermal noise models [11, 12, 13]. According to measurements during AC furnace operation (**figure 10**), the noise emission during the boring period is largely a wide-band sound accompanied by a 100 Hz tone. The character of the sound signal changes with progressing melt-down, assuming deterministic components of 100 Hz and their harmonics. Covering the arcs with foaming slag considerably reduces the acoustic effect.

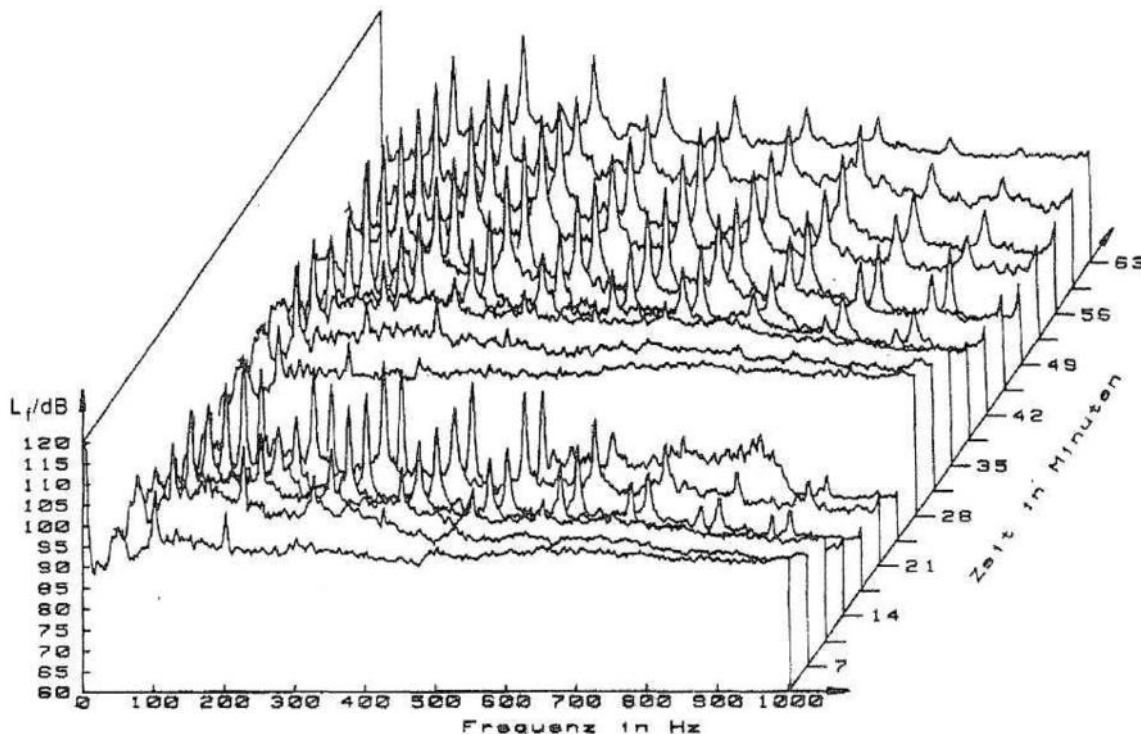


Figure 10: Spectrum of sound pressure versus time on an AC-EAF with 2 baskets [12, 13]

10 References

- [1] Jordan, G.R.; Bowman, B.; Wakelam, P.: Electrical and photographic measurements of high-power-arcs.
J. Phys. D.: Appl.Phys. 3 (1970) 1089-99
- [2] Block, O.; Timm, K.: Spektroskopische Untersuchungen von frei brennenden Gleichstromlichtbogen mit hoher Leistung an einem Elektrostahlofen. elektrowärme international 54 (1996) B1, B23-B31
- [3] Maecker, H.: Plasmaströmungen infolge eigenmagnetischer Kompression.
Zeitschrift für Physik 141 (1955) 198-216
- [4] Schwarz, B.: Regelung elektrischer Größen an Drehstrom-Lichtbogenofen.
Dr.-Ing. Dissertation, Fachbereich Maschinenbau, Universität der Bundeswehr Hamburg 1988
- [5] Bowman, B.: Effects on furnace arcs of submerging by slag.
Ironmaking and Steelmaking 17 (1990) No. 2, 123-129
- [6] Bowman, B.: Solution of arc-furnace electrical circuit in terms of arc voltage.
Ironmaking and Steelmaking 9 (1982) No. 4, 178-187
- [7] Eichacker, E.; Konrad, K.: Exakte Lichtbogenregelung an einem 100 t-Lichtbogenofen.
elektrowärme international 32 (1974) B6, B335-B339
- [8] Bretthauer, K.; Farschtschi, A.A.; Timm, K.: Die Messung elektrischer Größen von Lichtbögen in Elektrostahlöfen. elektrowärme international 33 (1975) B5, B221-B225
- [9] Lebeda, S.; Mächler, A.: Rogowski-Spulen zur exakten Strommessung bei der Elektrodenregelung von Lichtbogenschmelzöfen. Brown Boveri Mitt. 68 (1981) 10/11, 387-389
- [10] Grigat, R.R.: Messung und Modellbildung elektrischer Lichtbogengrößen in Drehstrom-Lichtbogenofen.
Dr.-Ing. Dissertation, Fachbereich Maschinenbau, Universität der Bundeswehr Hamburg 1986
- [11] McQueen, D.H.: Noise from Electric Arc Furnaces.
I. General Considerations.
II. Noise Generation Mechanisms.
III. Detailed Solutions for two Models.
Scandinavian Journal of Metallurgy 7 (1978) 5-10, 223-229 und 8 (1979) 55-63
- [12] Beckmann, H.-J.: Die akustische Emission der Lichtbögen im Elektrostahlofen.
Dr.-Ing. Dissertation, Fachbereich Maschinenbau, Universität der Bundeswehr Hamburg 1983
- [13] Beckmann, H.-J.; Timm, K.: Die akustische Emission der Lichtbögen im Elektrostahlofen.
elektrowärme international 42 (1984), B5, B220-B227

Steel Academy

International Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Energy Balance of the Electric Arc

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1. Introduction

A characteristic for the evaluation of the electric steel process is the specific electric energy and the energy costs combined with that.

About the energy transfer of the electric arc onto the melt little is known. Since there are not any physical models for electric arcs yet, there are not also any complete energy models yet.

There are only energy flow diagrams for electric arc furnaces. On that is reported at other place in this seminar. Therefore one must satisfy with simplified representations and partial results from experimental or theoretical investigations.

Already Kriz [1] and Wotschke [2] dealt with energy losses and energy balances of electric arc furnaces. Schwabe [3] stated that the wear of the refractory of the wall due to the radiation of the electric arc depends on the electrical sizes of the arc. The defined Refractory Index

$$RE = \frac{P_B U_B}{d^2} = \frac{I^3 R_B^2}{d^2}$$

as a measure of the wear of the refractory is proportionally to the product of the arc power P_B and the arc voltage U_B and vice versa proportionally to the square of the distance d of the arc to the wall.

Ottmar, Oerter and Ameling [4] modified this Refractory Index and showed considerations for a functional mode of operation and design of high power electric arc furnaces. Schmeiduch practised a modification of the Refractory Index for the case of the shielding of the arc through slag [5]. He defined for this purpose a protective factor to the correction of the radiation of the arc onto the wall.

$$f_s = \frac{\text{slag thickness}}{\text{arc length}}$$

$$RE = (1 - f_s) \frac{P_B U_B}{d^2}$$

2, Electrical efficiency

It must be considered for the transfer of electric energy from the power supply network to the arc that in the connecting devices (copper, graphite) losses occur. The entire power P

$$P = 3I^2(R_V + R_B)$$

supplied by the power supply network divides in the power of the electric arcs P_B

$$P_B = 3I^2 R_B$$

and the power dissipation P_v .

$$P_B = 3I^2 R_v$$

Thus a degree of electrical efficiency η_{el}

$$\eta_{el} = \frac{R_B}{R_v + R_B}$$

can be defined. In order to receive a maximally high degree of electrical efficiency must $R_B \gg R_v$, that can be realised by a current-weak arc or minimised loss resistance R_v .

To that an example withdrawn from the literature [6] is considered (figure 1). For a current of $I = 50,7$ kA and a resistance of $R_v = 0,68$ m Ω the losses are 1,748 MW/phase. From the active phase power $P_{str} = 17,645$ MW only $P_L = 15,9$ MW are available to the electric arc. From that an electrical efficiency of $\eta_{el} = 90\%$ results.

Example: Electric Arc Furnace (Nanjo 1973)

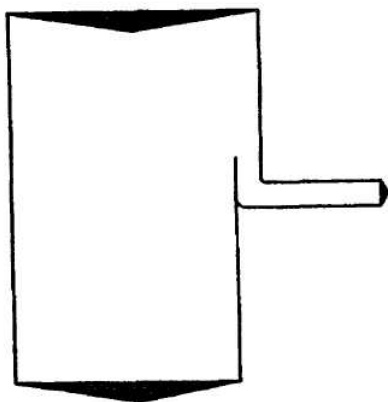
60 t, 60,153 MVA, 685 V, 50,7 kA

$\cos p = 0,88$ "long arc"

$P = 52,935$ MW (total effective power)

active phase power

$$P_{Str} = 17,645 \text{ MW}$$



losses in the
lead resistance
 $I^2 R_v = 1,748$ MW/phase

$$\eta_{el} = \frac{P_L}{P_{Str}} = 90,1\%$$

arc power

$$P_L = 15,9 \text{ MW}$$

Figure 1: Electrical efficiency

3. Energy transfer from the arc to the melt

It is estimated which part of the power of the arc contributes to the heating of the melt. This part is defined as the thermal degree of efficiency.

To that at first a theoretical example is considered. This is complemented later by an experimental study.

For the example represented in figure 2 the case is accepted, that long electric arcs burn onto the melt [6]. One recognises that the arc power of 15,9 MW assembles from the powers of the voltage drop at electrode E and melt S ($P_S/2 = 0,75$ MW) as well as the plasma column P ($P_P = 14,4$ MW).

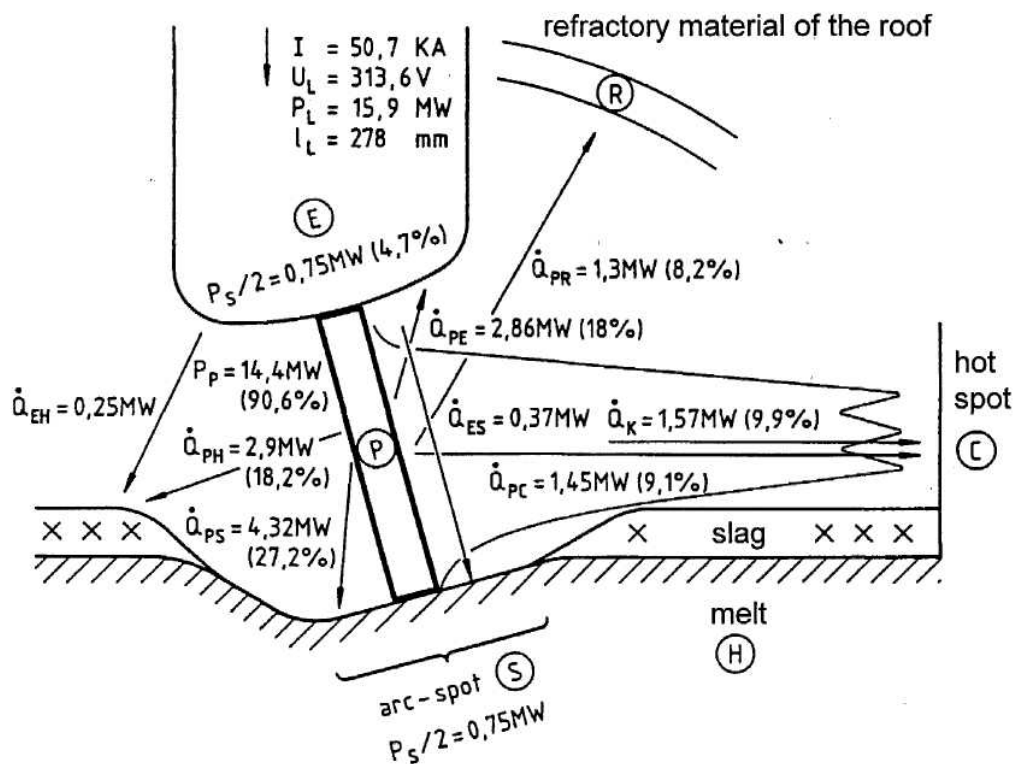


Figure 2: Power balance of the electric arc for the flat bath period [6]

The plasma column P transmits the power basically through radiation [6]

- onto the arc spot on the melt S ($Q_{PS} = 4,32$ MW),
- onto the residual steel melt H ($Q_{PH} = 2,9$ MW),
- onto the electrode E ($Q_{Pr} = 2,86$ MW),
- onto the water cooled panels C ($Q_{pc} = 1,45$ MW) and
- onto the refractory of the roof R ($Q_{PR} = 1,3$ MW).

A further part of the plasma column power of $Q_K = 1,57$ MW is transferred finally through convection of the arc flame onto the wall.

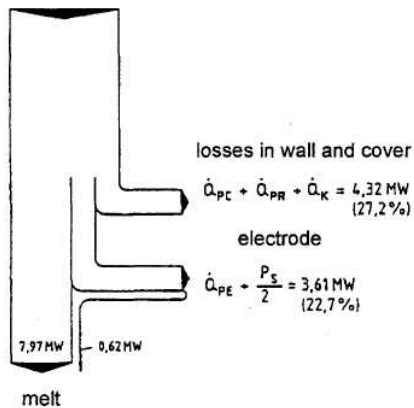
For the energy transfer of the arc onto the bath it is to be considered that $Q_{ES} + Q_{EH} = 0,62$ MW are radiated from the hot electrode onto the melt.

To the wall and the cover a power of 4,32 MW (27,2 %) and onto the electrode a power of 3,61 MW (22,7 %) will be transferred, figure 3. Considering the radiation of 0,62 MW from the electrode onto the melt the power of 8,59 MW (54 %) is transmitted to the melt.

The efficiency is 54 % for this "long arc" - operating mode. Under the consideration of the electrical efficiency a total efficiency of 48,6 % results.

In addition to this computational example an experimental example is given in the literature. In this case a 1 MW arc was investigated [7], figure 4. Here it is shown that the convective heat transfer of the arc contributes the predominant part to the heating of the melt. This result agrees better with the theory of the gas flow (Jet) directed towards the melt. In total 72,5 % of the power to the arc is transferred in this case to the melt.

$$P_i = 15,9 \text{ MW (100\%)}$$



$$H_{el} = \dot{Q}_{PS} + \dot{Q}_{PH} + \frac{P_S}{2} + \dot{Q}_{EH} + \dot{Q}_{ES} = 8,59 \text{ MW (54\%)}$$

$$\eta_{th} = \frac{H_{el}}{P_L} = 54\%$$

$$\eta_{ges} = \eta_{el} \cdot \eta_{th} = \frac{H_{el}}{P_{str}} = \frac{8,59 \text{ MW}}{17,645 \text{ MW}} = 48,6\%$$

Figure 3: Total efficiency

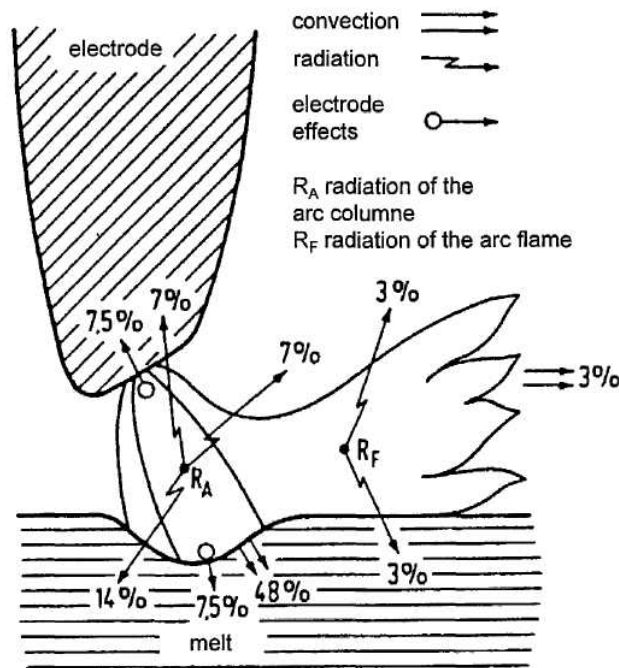


Figure 4: Experimental power balance of an AC electric arc with $I = 7 \text{ kA}$ and $U = 143 \text{ V}$ after [7]

4. Improvement of the energy transfer

4.1 Influence of the arc length

The radiation of an free burning arc directed towards the furnace wall can be reduced through the reduction of the arc length. This means that a short arc with high current is necessary. This was examined for example by Ameling [4, 8]. Figure 5 shows test results for the radiation factor RE . The heating of a melt without slag was examined in dependence of different arc lengths. The voltage of the transformer remained in this case unchanged. The variation of the arc current and the power factor is represented.

The electric losses increase with I^2 . Accordingly the electrical efficiency η_{el} decreases with increasing current.

The heat losses decrease with increasing current. With constant voltage and increasing current the $\cos \phi$ becomes smaller. The thermal efficiency η_w increases with increasing current.

Without foamy slag one could achieve the increase in performance of electric arc furnaces and simultaneous protection of the refractories only with short, high current electric arcs. The effects on the electrode consumption are known.

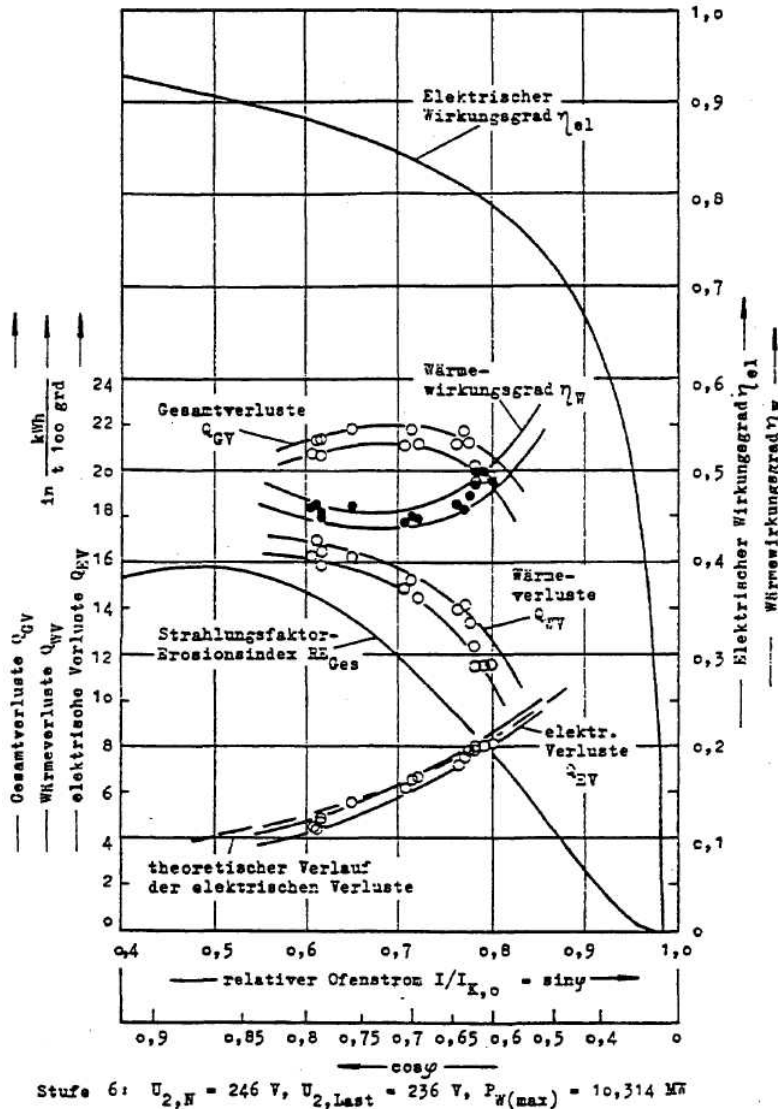


Figure 5: Test results [8]

Particularly Schwabe propagated the UHP practise with short, high current arcs. He showed at the example of a 60 MW electric arc furnace, that the heat transfer by the arc to the melt is increased from 50 % to 60 % by shortening the arc length from 21 cm to 16 cm [9], (Figure 6).

4.2 Influence of the foaming slag

The above represented conditions have changed now since the end of the seventies through the introduction of the operating parameter with a foaming slag.

First of all, was found, that through the foamy slag the burning-behaviour of the electric arc stabilises and the arc characteristic curve is linearised by that. On the one hand this leads to a reduction of the network disturbances and on the other hand for the increase of the arc power and the productivity.

With an arc shielded through slag one can have a long, low current arc. The electrode consumption is reduced by that.

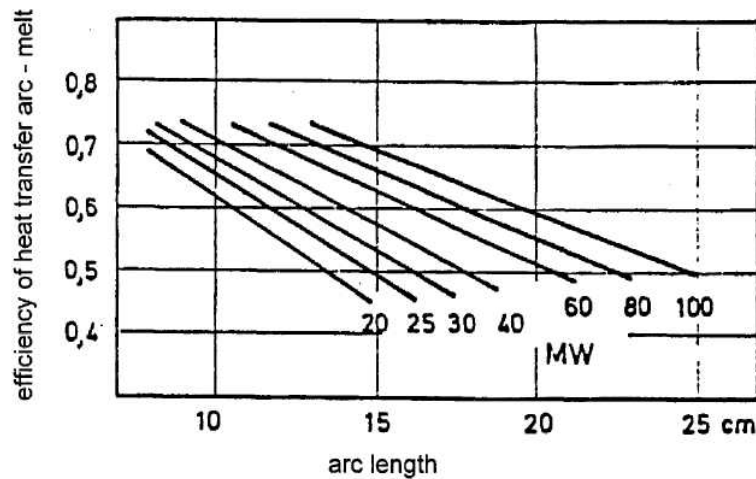


Figure 6: Thermal efficiency of the heat transfer from the electric arc to the melt depending on arc length and active power, after Schwabe [8]

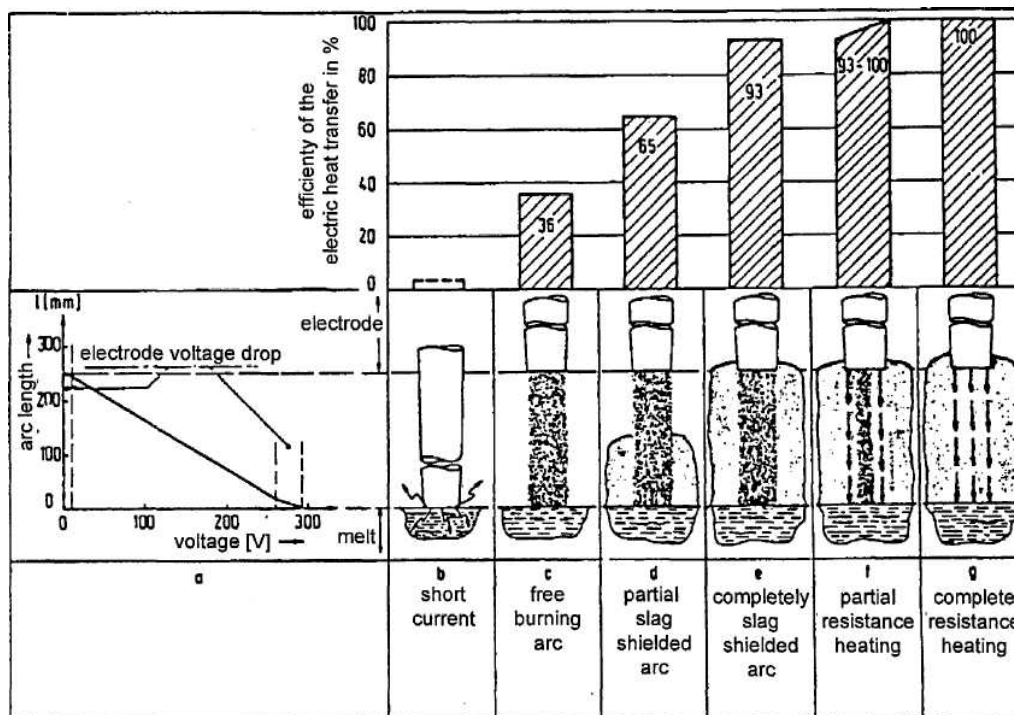


Figure 7: Influence of the foamy slag on the degree of efficiency of the energy transfer from the electrode onto the melt, after [10]

Calculations about the effects of the foamy slag on the degree of efficiency of the electrical energy transfer occurred from Ameling and Petry [10], figure 7. For an arc half enveloped with slag the degree of efficiency increases itself from 36 % to 65 % in comparison with an free burning arc. In the case of

complete covering of the arc with slag the degree of efficiency can increase up to 100 %. Through that an energy saving of 10 to 30 kWh/t results.

A borderline case is the transition onto the pure resistance heating. This case occurs, when through a high electric conductivity of the slag the field strength drops below the arc field strength. Then the arc will gone out (pure resistance heating, for example as in the ESR furnace).

4.3 Flows in melt and slag

Subsequently the influence of the electrical quantities on the mixture of melt and slag are supposed to be considered.

Ameling and Petry showed that with the application of raw dolomite an intensive mixture of melt and slag occurs. The homogenisation of temperature is improved by that. This is causal for the energy saving of 30 kWh/t.

Concerning the mixture and the stirring of the melt two effects which are dependent on electrical quantities are to be observed.

- The momentum of the arc jet onto the melt and the rotating arcs cause a mixture of the melt with simultaneously good heat transfer. For a slag-free melt a rotation of the entire melt is observed, figure 8.
- Through the inhomogeneous electrical flow fields coming from the arc spot on the melt one receives a flow at the melt surface.

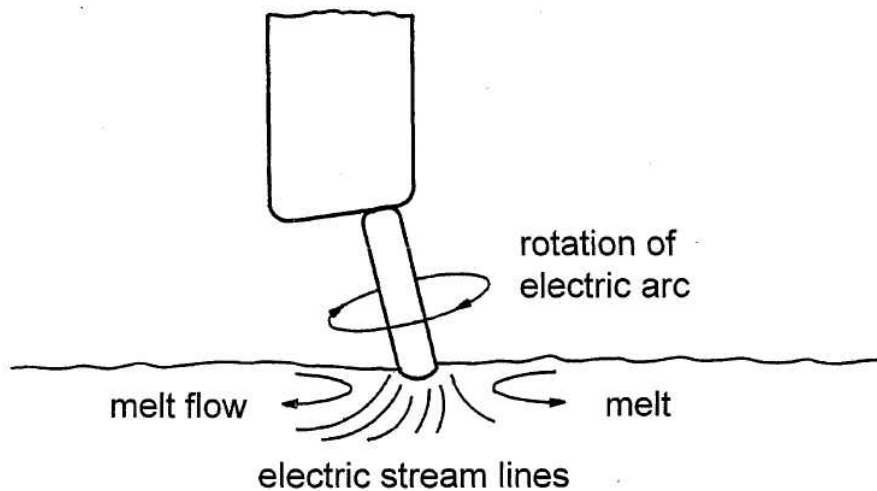


Figure 8: Mixing effect of the AC arc and flow of the melt

Both effects are dependent on the arc current. Through the transition onto the operating parameter with long, current-weak arcs these desired effects decrease. This is a procedural disadvantage of the foamy

slag practise. One must use therefore other possibilities where appropriate to the mixture of the melt, for example the bubbling with argon or the application of an electro - magnetic stirrer.

From the viewpoint of the optimal energy use the direct current arc offers special advantages [11] in the DC electric arc furnace, figure 9. The direct current arc burns between the graphite electrode seeming as a cathode and the anodic melt.

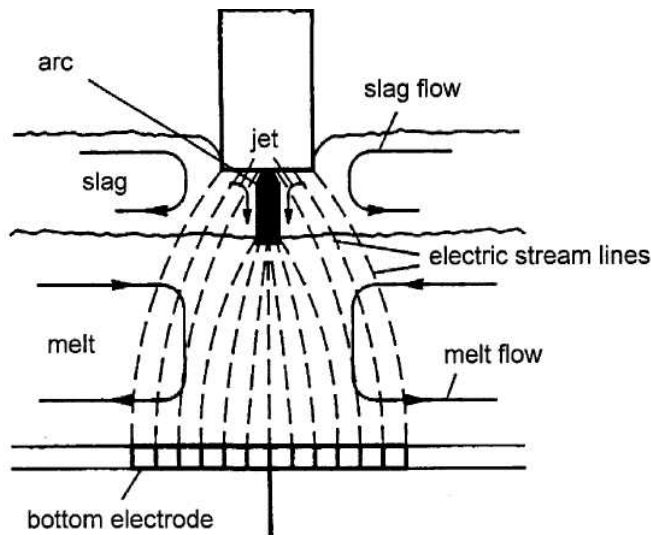


Figure 9: Flows in the DC furnace

- The voltages in the voltage drop fields of cathode and anode $U_K = 10$ and $U_A = 30$ V are oriented so that the losses are minimised at the graphite cathode and with that also the tip consumption of the electrode is reduced considerably.
- A jet directed from the cathode to the anodic melt is available. This transmits a predominant part of the arc power directly on the melt. With arcs covered from slag a radial slag flow directed towards the arc arises.
- In the melt the electric flow lines starting from the arc expand up to the bottom electrode. A mixture of the melt arises from this inhomogeneous flow field in the entire bath.

The comparison of a DC furnace with an AC arc furnace at NUCOR-Steel (USA) from the energetic viewpoint showed, that the electric energy consumption of a DC furnace is 8 % less as a comparable AC arc furnace.

5. Outlook

The energy transfer from the AC arc onto the melt is difficult to describe because no physical models for electric arcs are available. Therefore these comments have partially qualitative character.

For a free burning arc on a melt only half of the electrical power fed to the arc will transfer to the melt. The shortening of the arc length improves the energy transfer of the arc to the melt. For the same amount of power the current will be higher. This means, that the electrode consumption will increase in this case.

An improvement of the efficiency resulted through the operating of EAFs with foaming slag. The knowledge about these phenomena still is however imperfect. Therefore further studies are necessary about the arc behaviour in foamy slag from the viewpoint of an optimisation of the electro-thermal energy conversion. This is valid also for the arc in the ladle furnace.

One receives comparably favourable conditions during the energy conversion in the DC arc. Also the flow fields through inhomogeneous electrical flow fields are advantageous in this case in melt and slag.

Literature

- [1] Kriz, S.: Die Energieverluste an Lichtbogen-Elektrostahlöfen. Archiv für das Eisenhüttenwesen 1 (1927), S. 413-419
- [2] Wotschke, J.: Grundlagen des elektrischen Schmelzofens. Verlag W. Knapp, Halle (1933)
- [3] Schwabe, W. E.: Arc heat transfer and refractory erosion in electric steel furnaces. Proc. Electr. Furn. Steel Comm., Iron Steel Div., Amer. Inst. metallurg. petrol. Eng. 20 (1962), S. 195-206.
- [4] Ottmar, H.; Oerter, A.; Ameling, D.: Der Zusammenhang zwischen den elektrotechnischen und wärmetechnischen Grundlagen bei Hochleistungs-Elektrolichtbogenöfen. Radex-Rundschau (1973), S. 519 - 527.
- [5] Schmeiduch, G. F.: Einfluss einiger Betriebsparameter auf den Feuerfest-Verschleiß im Elektrolichtbogenofen. Dr.-Ing. Dissertation, Fachbereich Werkstoffwissenschaften, TU Berlin, 1978.
- [6] Nanjo, T.; Yasukawa, S.: The improvement of productivity in steelmaking electric arc furnace. Kogyo Kavetsu (Industrial Heating) 10 (1973), No. 2, S. 39-51, No. 3, S. 27-41, No. 4, S. 51-63.
- [7] Jordan, G. et.al.: Basic properties of high-intensity electric arcs used in steelmaking. British Steel Corporation. ECSC Convention No. 6210.93/8/801.

- [8] Ameling, D.: Über den Zusammenhang zwischen den elektrischen Bedingungen und den Strahlungsverhältnissen des Lichtbogens am Elektrolichtbogenofen bei Einstellung verschiedener Arbeitspunkte im elektrischen Leistungsschaubild. Diplomarbeit Bergakademie Clausthal (1966)
- [9] Schwabe, W.E.: Electrical and thermal factors in UHP arc furnace design operation. BerichtNr. IICa4, 9. UIE-Kongress Cannes (1980)
- [10] Ameling, D.; Petry, J.; Sittard, M.; Ulbrich, W.; Wolf, J.: Untersuchungen zur Schaumslaggenbildung im Elektrolichtbogenofen. Stahl und Eisen 106 (1986), S. 625-630.
- [11] Timm, K.; Ahlers, H.: Untersuchungen von Gleichstromlichtbögen an Elektrostahlöfen. BerichtNr. C4.1, 11. UIE-Kongress, Malaga(1988)

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THERMODYNAMIC ANALYSIS OF EAF ENERGY EFFICIENCY AND COMPARISON WITH A STATISTICAL MODEL OF ELECTRIC ENERGY DEMAND

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ABSTRACT

Specific data like specific electric energy consumption or specific electrode consumption are important reference numbers for EAF steelmakers. In this paper mass and energy balances are formulated to calculate the factors in the statistical approach of Köhle [2,4]. The difficulty is formulation of the relations between effects detected from the coupled mass and energy balances and the electric energy consumption of the EAF. The calculations show, that the statistical developed coefficients after Köhle and the based on mass and energy balances calculated coefficients for the variation of the input masses of DRI, hot metal and slag formers and of gases (natural gas via burners, oxygen by lancing and post combustion oxygen) similar.

INTRODUCTION

In the field of electric steelmaking it is usual to discuss specific data as electric energy per ton of liquid steel, electrode consumption per ton of steel, productivity in tons per hour or the tapping rate in heats per day.

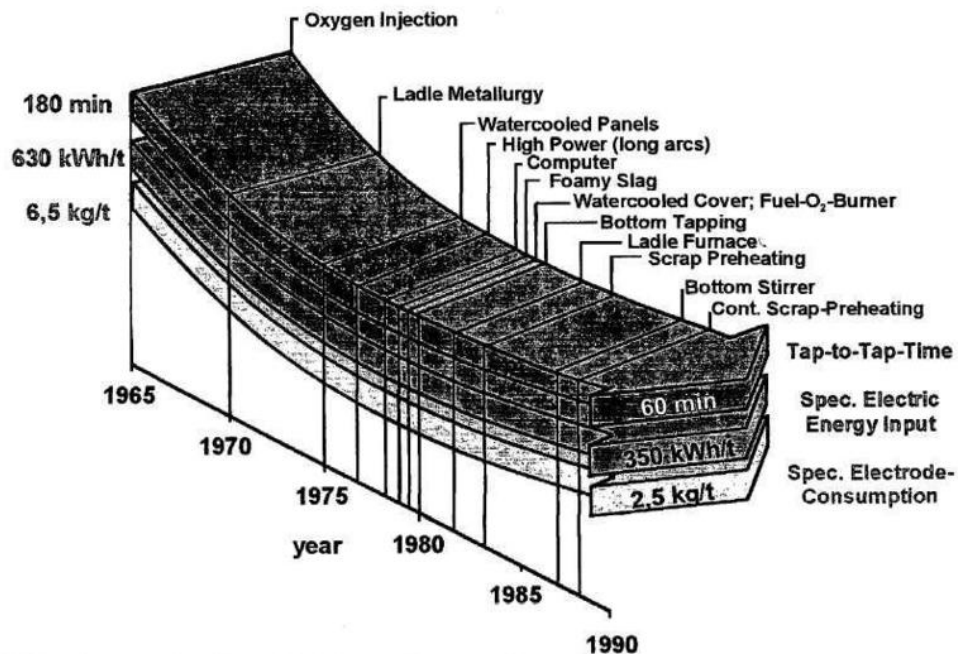


Fig. 1: Developments of the electric arc furnace [1]

Some of this data and its development over the last decades are shown principally in fig. 1 from Szekely and Trapaga [1]. This figure shows on the other hand side, that numerous factors influence the specific electric energy consumption in EAFs. As a result the specific electric energy consumption can vary in a wide range concerning different melting practices or EAF types. It is of practical interest to develop mathematical equations or relationships for the correlation of the specific electric energy consumption with the most important factors influencing this value [2,3]. In this paper the relationships between complete or total energy balances of electric arc furnaces and the factors of the statistical mathematical equations from Köhle [2,4] shall be investigated.

STATISTICAL ENERGY CONSUMPTION FORMULA

In 1992 Köhle [2] developed a first statistical equation (eq. 1) based on the analysis of the average data of 14 furnaces in Germany.

$$\frac{W_R}{\text{kWh/t}} = 300 + 900 \left[\frac{G_E}{G_A} - 1 \right] + 1600 \frac{G_Z}{G_A} + 0.7 \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] + 0.85 \frac{t_S + t_N}{\text{min}} - 8 \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \frac{M_L}{\text{m}^3/\text{t}} \quad (1)$$

W_R	specific electric energy consumption	t_S	power-on time
G_E	weight of ferrous materials furnace	t_N	power-off time
G_A	tapping weight weight of slag	M_G	specific burner gas
G_Z	formers tapping temperature	M_L	specific lance oxygen
T_A			

During the last decade this formula was extended to post-combustion and alternative ferrous materials. Actually a modified version of this formula, based on a large number of single heat data from 5 EAFs, is available [4].

$$\frac{W_R}{\text{kWh/t}} = 375 + 400 \left[\frac{G_E}{G_A} - 1 \right] + 80 \frac{G_{\text{DRI/HBI}}}{G_A} - 50 \frac{G_{\text{Shr}}}{G_A} - 350 \frac{G_{\text{HM}}}{G_A} + 1000 \frac{G_Z}{G_A} + 0.3 \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] + 1 \frac{t_S + t_N}{\text{min}} - 8 \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \frac{M_L}{\text{m}^3/\text{t}} - 2.8 \frac{M_N}{\text{m}^3/\text{t}} + NV \frac{W_V - W_{V_m}}{\text{kWh/t}} \quad (2)$$

G_{DRI}	weight of DRI	W_V	energy losses (if measured)
G_{HBI}	weight of HBI	W_{V_m}	mean value of W_V
G_{Shr}	weight of shredder	NV	furnace specific factor (0.2... 0.4)
G_{HM}	weight of hot metal		

Compared with eq. (1) some of the factors changed and additional parameters affecting the specific electric energy consumption are added. The estimation of the range of such factors from thermodynamic principles is the main topic of this paper.

THERMODYNAMIC ANALYSIS OF EAF ENERGY EFFICIENCY

The experimental and theoretical investigation of mass and energy balances are a main subject of the Institute of Industrial Furnaces and Heat Engineering of RWTH Aachen [5... 8].

MASS BALANCE

The targets of the mass balances are for example the determination of metallurgical reactions (C, Si, Mn, Fe), the mass of infiltrated air and off gas in addition to well known data like metallic input, electrode consumption, productivity, slag, etc. To realise this additional measurements concerning the off gas composition, volume flow and gas temperature are necessary [8]. Fig. 2 shows the average mass balance of 31 heats for a 100t-EAF with a relatively low installed specific power of 450 kVA/t and a relatively high consumption of oxygen, coal and natural gas. This results are based on the mass balances of carbon (off gas measurements), nitrogen (infiltration air) and CaO (slag mass), e. g.

$$x_{\text{CaO,Lime}} \cdot m_{\text{Lime}} + x_{\text{CaO,Refr.}} \cdot m_{\text{Refr.}} = x_{\text{CaO,Slag}} \cdot m_{\text{Slag}} + x_{\text{CaO,Dust}} \cdot m_{\text{Dust}} \quad (3)$$

x mass content of CaO m mass

The data of $m_{\text{CaO,Lime}}$, $m_{\text{CaO,Dust}}$ and $x_{\text{CaO,refr.}}$ are known from chemical analysis of samples. $m_{\text{Refr.}}$ and m_{Dust} are known from statistical data and m_{Lime} is a process parameter. The slag composition $x_{\text{CaO,Slag}}$ is determined of slag probes taken at tapping for each heat.

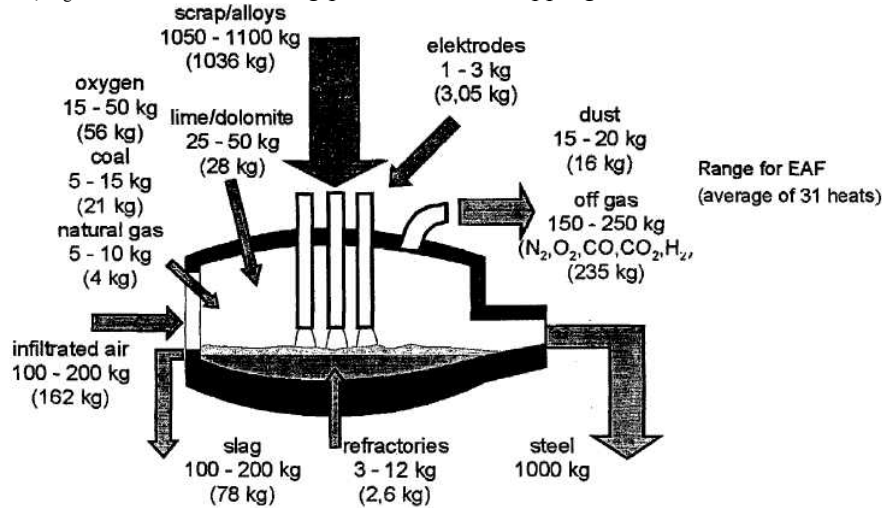


Fig. 2: Averaged mass balance of 31 heats for a 100t-EAF (quality steel grades)

ENERGY BALANCE

Complete or total energy balances are based on the 1st law of thermodynamics. This requires a suitable definition of the system boundary, e. g. shown in fig. 3. Such a definition of the system boundary includes e. g. the electrical losses in the furnace transformer and the high current system. On the other hand, this figure shows that the specific electric energy used for the dedusting system and/or the ladle furnace is not included. This is similar for the case of scrap preheating with additional fuel input for the post combustion of hazard products in off gas system reactors. The energy balance can be written in the form

$$\sum_{i=1}^n \int_{\text{heat}} (Q_i + P + H_i + R_i) dt = 0 \quad (4)$$

Q_i heat flow (e. g. wall and cover cooling)

H_i enthalpy of mass flow (off gas, liquid steel, slag)

P electric power

R_i metallurgical oxidation reaction (C, Si, Mn, Fe)

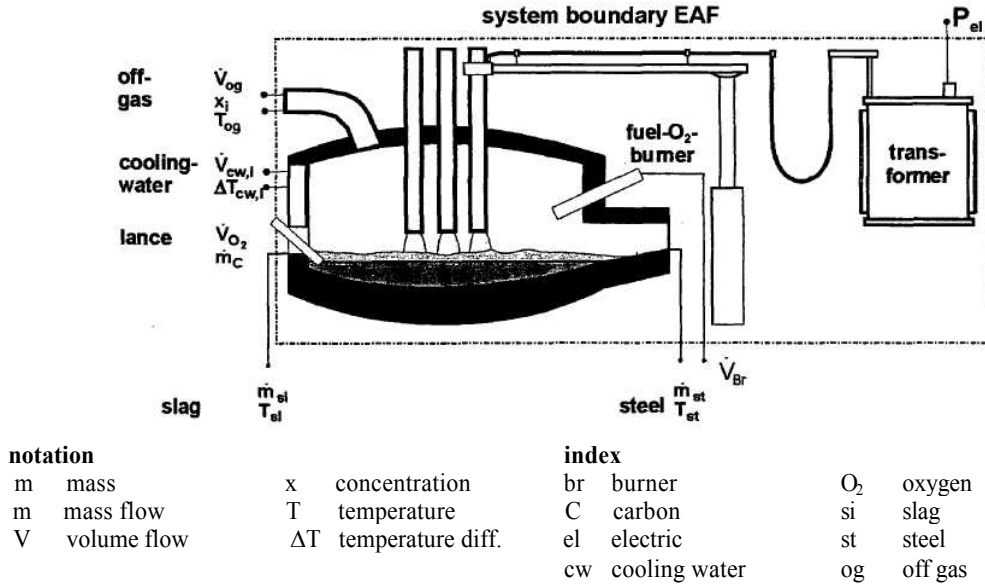


Fig. 3: System boundary for the electric arc furnace

This balance assumes, that the internal energy of the furnace is equal after each heat. For a balance after the 1st law of thermodynamics the EAF itself is analysed as a "black box". This means knowledge is only necessary for the mass- and energy flows over the system boundary. For chemical reactions, e. g. the carbon oxidation reaction $C + O_2 \rightarrow CO_2$ is considered, because CO in the off gas is considered as energy loss. The most important chemical reactions for the EAF process are listed in table 1.

Table 1: Chemical reactions for the energy balance of electric arc furnace

reaction				energy of the reaction	
2Al	+	1.5 O ₂	→ Al ₂ O ₃	- 8.61 kWh/kg _{Al}	-13.86 kWh/m ³ O ₂
Si	+	O ₂	→ SiO ₂	- 8.70 kWh/kg _{Si}	-10.92 kWh/m ³ O ₂
Mn	+	0.5 O ₂	→ MnO	-1.95 kWh/kg _{Mn}	-9.56 kWh/m ³ O ₂
2Cr	+	1.5 O ₂	→ Cr ₂ O ₃	-3.05 kWh/kg _{Cr}	-9.44 kWh/m ³ O ₂
S	+	O ₂	→ SO ₂	-2.75 kWh/kg _S	-3.94 kWh/m ³ O ₂
2Fe	+	1.5 O ₂	→ Fe ₂ O ₃	- 2.03 kWh/kg _{Fe}	-4.74 kWh/m ³ O ₂
Fe	+	0.5 O ₂	→ FeO	-1.32 kWh/kg _{Fe}	-6.58 kWh/m ³ O ₂
C	+	O ₂	→ CO ₂	-9.10 kWh/kg _C	4.88 kWh/m ³ O ₂
C	+	0.5 O ₂	→ CO	-2.55 kWh/kg _C	-2.73 kWh/m ³ O ₂
CO	+	0.5 O ₂	→ CO ₂	-2.81 kWh/kg _{CO}	-7.02 kWh/m ³ O ₂

ENERGY BALANCES OF DIFFERENT ELECTRIC ARC FURNACES

The energy flow diagram (fig. 4) of an 100t-EAF clearly shows mat the energy input consists of electric energy, fuels (gas, oil, coal) and exothermic chemical reactions. The output of energy is the enthalpy of the liquid steel which is taken as energy benefit of the EAF process, the enthalpy of the slag, the heat transported with the cooling water from the water-cooled panels, the off gases as well as radiation losses.

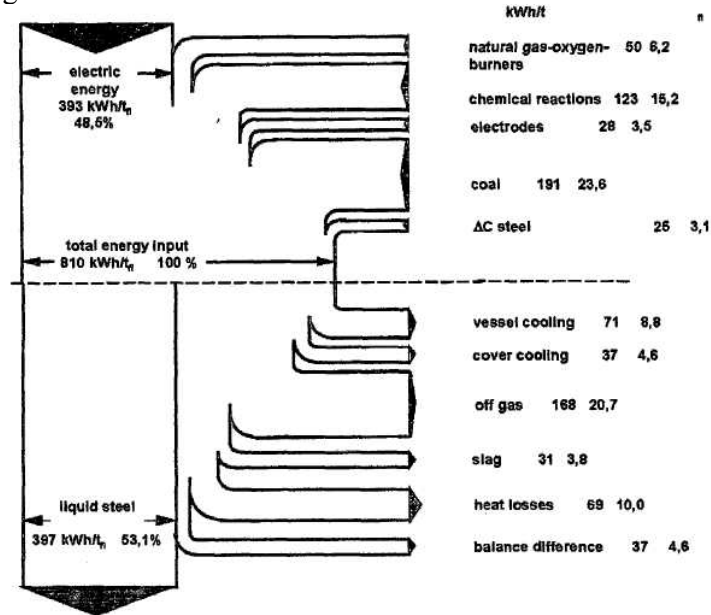


Fig. 4: Energy balance (mean value from 27 heats of a 100t-EAF, 1999)

By definition the efficiency is the ratio of the energy benefit and the energy input.

$$\eta_N = \frac{\text{energy benefit}}{\text{energy input}} \quad (5)$$

The enthalpy of the melt (steel + slag) is designated as energy benefit of the electric steel production. On the basis of a complete energy balances the degree of efficiency is

$$\eta_{\text{EAF}} = \frac{\text{enthalpy steel+slag}}{\text{total energy input}} \quad (6)$$

This definition of the efficiency considers also the other energy inputs (fuel-oxygen-burner, oxygen metallurgy, oxidation of metals, etc.).

Table 2: Efficiencies of EAFs

	year	total energy input [kWh/t]	electric energy input [kWh/t]	steel/slag energy [kWh/t]	η_{EAF} %	
100t-fumace, structural steel	1980	(798)	(541)	(503)	(53.0)	[5]
140t-furnace,	2001	773	497	442	57.2	
120t-furnace, stainless steel	1989	704	487	443	59.2	[9]
150t-fumace, ferritic steel	2001	758	477	449	59.2	[8]
150t-fumace, austenitic steel	2002	807	510	401	49.7	
60t-furnace, scrap preheating	1990	729	427	429	58.8	[10]
conventional furnace	1998	680	400	440	54.7	[11]
100t-fumace	1999	810	393	434	53.5	
average		752	456	434	58.0	

CHARGING OF HOT METAL

The tendencies resulting from increasing hot metal charging in the EAF are given in table 3. The increasing energy input by chemical reactions (C, Si, Mn) results to a lowering of the specific electric energy input related to Kohle [4] to

$$\frac{\Delta w_R}{\text{kWh/t}} = -350 \frac{G_{HM}}{G_A} \quad (7)$$

The comparison of this relationship with collected data from Scheidig [12, 13] shows, that melt shop data are in good agreement with this relationship, fig. 5.

Table 3: Relationship between variation of EAF process parameters and EAF performance data

	Increasing hot metal	Increasing DRI/HBI	Incr. slag formers	Increasing tap. temp.	Increasing burner gas	Incr. lance oxygen	Incr. post-combustion oxygen
specific electric en.	↓	↑	↑	↑	↓	↓	↓
chemical input	↑	↑	→	→	↑	↑	→
electrode consump.	↓	↑	↑	↑	↓	↓	↓
productivity	↑	↓	↓	↓	↑	↑	↑
tap to tap time	↓	↑	↑	↑	↓	↓	↓
slag mass	↑	↑	↑	→	→	↑	→
off gas energy	↑	↑	→	↑	↑	→	↓
cooling energy	→	→	→	↑	→	→	?
enthalpy liquid steel	→	→	→	↑	→	→	→

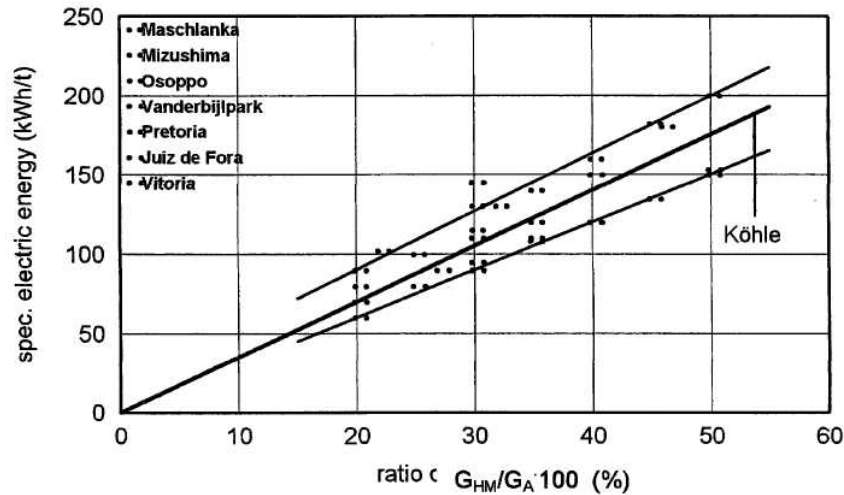


Fig. 5: Variation of specific electric energy consumption vs. ratio of hot metal input

HOT METAL ENERGY INPUT

In a first step the energy input with hot metal is compared with the specific total energy input necessary for 100 % scrap. The sampled data for EAF energy balances given in table 2 show, that the total energy is approximately

$$^{\circ}\text{electric energy} + ^{\circ}\text{reactions} = 725 \dots 775 \text{ kWh/t.} \quad (8)$$

The specific energy of the charged hot metal is plotted in fig. 6 as a function of the carbon content and the hot metal input temperature. Assuming a typical value of 4.1% C of the hot metal and a charging temperature of 1400 °C the energy input is 780 kWh/t. This is equivalent to the typical total energy input for 100% scrap melting.

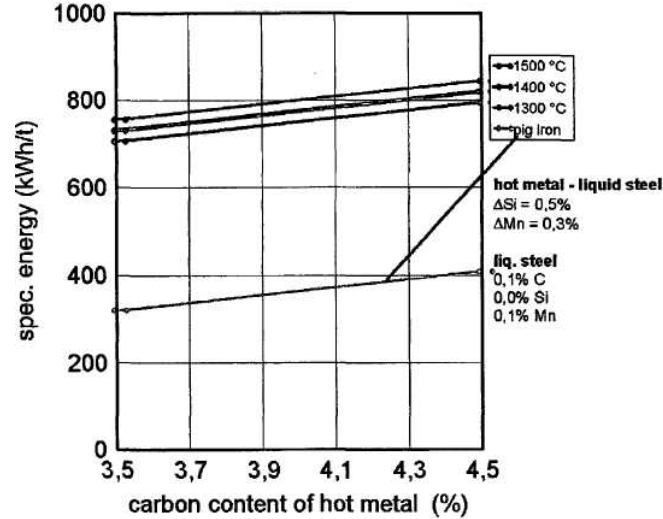


Fig. 6: Specific energy of hot metal including oxidising of C, Si and Mn to the liquid, steel composition (parameters: hot metal charging temperature and carbon content)

HOT METAL ENERGY OUTPUT

The energy output is the sum of the specific enthalpy of steel (390 kWh/t), slag, off gas, vessel/cover cooling. The data are given in table 4.

Table 4: Energy output for hot metal charging

liquid steel	390 - 400 kWh/t	independent from charged ferrous material
vessel/cover cooling	70-80 kWh/t	for the first approx. this term is constant
off gas	250 kWh/t	composition 25 % CO, 25% CO ₂ , 50%N ₂
slag	50 - 70 kWh/t	
	760 - 800 kWh/t	

The estimations for the off-gas calculation are, that the typical off gas composition consists of 25% CO, 25% CO₂ and 50% N₂ with an average temperature of 1500 °C. If 4 % carbon are oxidised 53 kg O₂/t_{HM} (37 m³ O₂/t_{HM}) are necessary if the CO-reaction in the melt is considered. It is assumed, that the O₂ in the gas phase



is from the infiltrated air (26,7 kg O₂/t_{HM})- This means, that 115 kg infiltrated air/t is necessary and a specific off gas mass of approx. 210 kg/t_{HM} is produced. Additional slag formers used in the case of hot metal charging are considered in eq. (2) separately. The energy balance is

$$E_{\text{electric energy}} + E_{\text{reactions}} + E_{\text{HM}} = E_{\text{steel}} + E_{\text{slag}} + E_{\text{off gas}} + E_{\text{cw}} + E_{\text{el. losses}} \quad (10)$$

The variation of the hot metal ratio $AE_{\text{HM}} = ACHMG_{\text{HM}}$ results in the variation of $AE_{\text{electric energy}}$ (ΔW_R), $AE_{\text{reactions}}$, AE_{dag} , $AE_{\text{off gas}}$ and $AE_{\text{el. losses}}$ (ΔAE_{el}), but E_{steel} is independent from this process parameter.

$$\Delta E_{\text{electric energy}} = -\Delta E_{\text{HM}} - \Delta E_{\text{reactions}} + \Delta E_{\text{off gas}} + \Delta E_{\text{slag}} \quad (11)$$

In eq. (2) the variation of AE_{reac} is considered in the O_2 -lancing term and AE_{slag} in the slag formers term. So the result of the data from the given energy balance are

$$\Delta W_R = \frac{\Delta E_{\text{electric energy}}}{G_A} = -\frac{\Delta e_{\text{HM}} G_{\text{HM}}}{G_A} + \frac{\Delta e_{\text{off gas}} G_{\text{HM}}}{G_A} = -530 \frac{\text{kWh}}{t_{\text{HM}}} \frac{G_{\text{HM}}}{G_A} \quad (12)$$

Since the lancing oxygen ($37 \text{ m}^3 O_2/t_{\text{HM}}$) is noted separately in eq. (2) this factor must be "corrected" to

$$\frac{\Delta W_R}{\text{kWh/t}} = -370 \frac{\text{kWh}}{t_{\text{HM}}} \frac{G_{\text{HM}}}{G_A} \quad (13)$$

Slight variations of this factor will occur, if the influence of hot metal temperature and carbon content is considered. If cold pig iron with the same composition is charged the relation is

$$\frac{\Delta W_R}{\text{kWh/t}} = +40 \frac{\text{kWh}}{t_{\text{PI}}} \frac{G_{\text{PI}}}{G_A} \quad (14)$$

CHARGING OF DRI/HBI

The specific electric energy consumption increase with the substitution of scrap with DRI (Direct Reduced Iron) or HBI (Hot Briquetted Iron). The relation after Köhle [4] is

$$\frac{\Delta W_R}{\text{kWh/t}} = 80 \frac{G_{\text{DRI/HBI}}}{G_A} \quad (15)$$

Generally the factor depends from the composition of the DRI/HBI (metallisation rate, carbon content, temperature of charging). The following calculations and assumptions are for the DRI-composition given in table 5.

Table 5: Composition of DRI

			mass in kg	energy in kWh
total iron	Fe_{tot}	93.8 %	882 kg Fe	331 kWh
metallic iron	Fe_{met}	88.2 % ¹⁾	72 kg FeO	101 kWh
gangue		4.4%	44 kg	35 kWh
carbon C		0.2%	2 kg C	-5 kWh
			£ 1000 kg	Σ 462 kWh

1) metallisation rate $x = (Fe_{\text{met}}/Fe_{\text{tot}}) \cdot 100 = 94\%$

Fig. 7 shows the relation between the specific electric energy in kWh/t vs. the ratio of DRI.

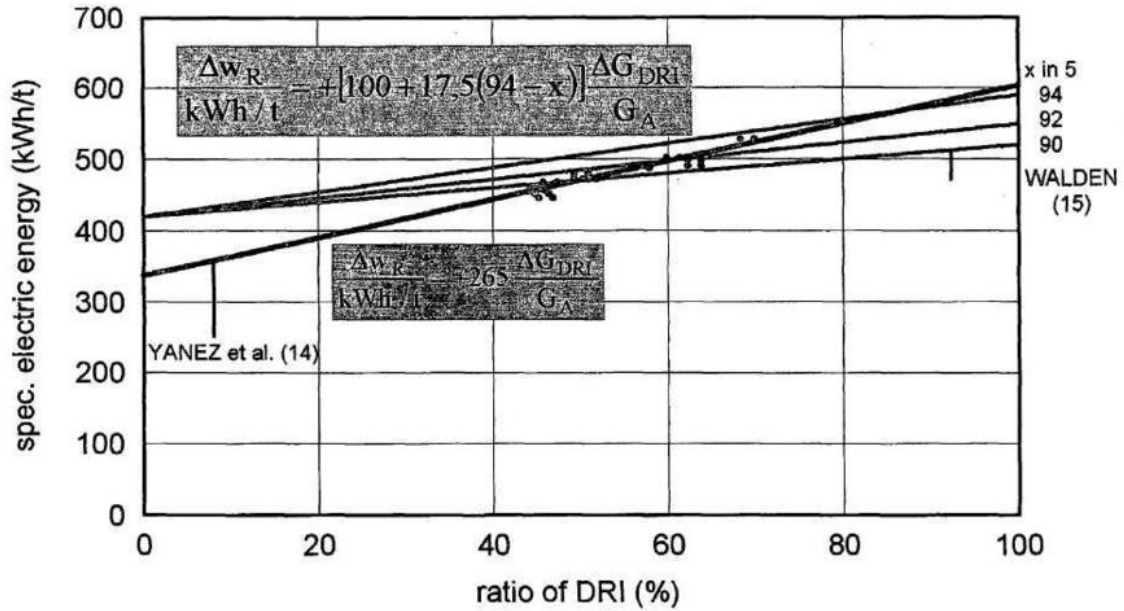


Fig. 7: Specific electric energy vs. ratio of DRI (G_{DRI}/G_A)100

The data from Yanez [14] result in a relation

$$\frac{\Delta w_R}{\text{kWh/t}} = 265 \frac{\Delta G_{DRI}}{G_A} \quad (16)$$

and from Walden [15]

$$\frac{\Delta w_R}{\text{kWh/t}} = [100 + 17.5 \cdot (94 - x)] \frac{\Delta G_{DRI}}{G_A}. \quad (17)$$

The data from table 5 for DRI at 1600 °C indicate a higher energy demand of 77 kWh/t_{DRI} for DRI (462 kWh/t) compared with scrap (385 kWh/t). From the data of table 2 a coefficient ζ can be calculated in the form

$$\zeta = \frac{e_{\text{steel}} + e_{\text{slag}}}{e_{\text{electric energy}}} = 0.9 \dots 1.1. \quad (18)$$

The lower value represents EAFs with lower chemical reactions (e. g. stainless steels) and the higher value EAFs with higher amounts of chemical reactions due to higher carbon and oxygen input (e. g. concrete steels). Under the assumption, that DRI-charging does not influence the relation between electric and chemical energy input, the relation for DRI is

$$\frac{\Delta w_R}{\text{kWh/t}_{\text{steel}}} = \frac{77 \text{ kWh/t}_{DRI}}{\zeta} \frac{G_{DRI}}{G_A} = 70 \dots 86 \frac{\text{kWh}}{t_{DRI}} \frac{G_{DRI}}{G_A}. \quad (19)$$

Additional carbon (FeO reduction) and slag formers are considered in other terms of eq. (2).

SLAG FORMERS

The influence of slag former addition on the specific electric energy consumption has changed in the eq. (1) and (2) from 1600 kWh/t to 1000 kWh/t. The added slag formers are CaO and MgO with a typical relation CaO/MgO = 4...5. Typical compositions of slags from unalloyed steel grades are given in table 6.

Table 6: Typical compositions of EAF slags (unalloyed grades)

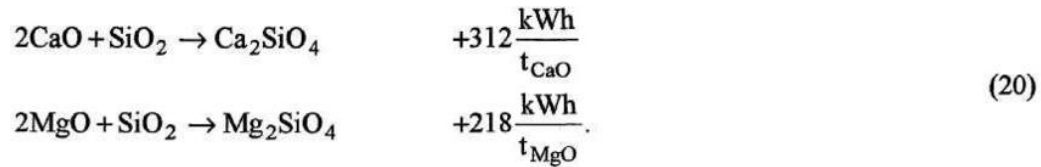
	Al ₂ O ₃	SiO ₂	CaO	MgO	FeO
range [%]	4-6	8-12	20-30	4-6	40-60
average [%]	5	10	25	5	55

The theoretical energies used to heat the slag formers from ambient temperature to the tapping temperature of 1600 °C are

$$\text{CaO: } \Delta h(1600 - 25^\circ\text{C}) = 82\,960 \frac{\text{J}}{\text{mol}} = 410 \frac{\text{kWh}}{t_{\text{CaO}}}$$

$$\text{MgO: } \Delta h(1600 - 25^\circ\text{C}) = 78\,700 \frac{\text{J}}{\text{mol}} = 550 \frac{\text{kWh}}{t_{\text{MgO}}}.$$

The endothermic reactions are



The total energy is

$$\begin{aligned} \Delta h_{\text{CaO}}(15 - 1600^\circ\text{C}) + \Delta h_{\text{Ca}_2\text{SiO}_4} &= 712 \frac{\text{kWh}}{t_{\text{CaO}}} \\ \Delta h_{\text{MgO}}(15 - 1600^\circ\text{C}) + \Delta h_{\text{Mg}_2\text{SiO}_4} &= 768 \frac{\text{kWh}}{t_{\text{MgO}}}. \end{aligned}$$

With the defined coefficient ξ the equation with specific data is

$$\xi e_{\text{electric energy}} = e_{\text{steel}} + \frac{E_{\text{slag}}}{G_A}.$$

The variation of the electric energy is of interest ($\Delta e_{\text{steel}}=0$), so the notation is ($\Delta e_{\text{electric energy}} = \Delta w_R$)

$$\Delta w_R = \frac{e_{\text{slag}}}{\xi} \frac{\Delta G_Z}{G_A}. \quad (22)$$

The specific energy needed for the slag formers is ($\xi = 0.9 \dots 1.1$)

$$\frac{\Delta w_R}{\text{kWh/t}} = \frac{730 \text{ kWh}}{\xi} \frac{\Delta G_Z}{t_Z G_A} = 665 \dots 810 \frac{\text{kWh}}{t_Z} \frac{\Delta G_Z}{G_A}. \quad (23)$$

NATURAL GAS-OXYGEN-BURNERS

The application of natural gas - oxygen burners is to be seen under the following aspects:

- increased productivity of the furnace system in the melting period (additional energy input by fuels)
- increasing the thermal symmetry of the AC-EAF during the melt down period
- energetic improvement of the melting process
- decrease of the specific electrical energy.

With the application of these technologies it is evident that an increase of the specific off gas volume occurs. The operating period of natural gas-oxygen-burners is limited to the start period of the melting process for each bucket when the heat transfer from the flame or the hot combustion gases to the scrap is high. The specific amount of added natural gas is typically in the range from 3,5 to 6 m³/t.

The calorific data of natural gas (ng) varies slightly with the area of origin. Natural gas can be simplified as CH₄ with a net calorific value of $h_u = 10 \text{ kWh/m}^3 \text{ ng}$ (36 000 kJ/m³ ng). For the combustion



2m³ O₂/m³ ng are necessary, if an air ratio of 1.0 is assumed. The combustion efficiency η_f fig. 8,

$$\eta_f = 1 - \frac{\dot{H}_{og}}{\dot{H}_{br}} = 1 - \frac{\dot{H}_{og}}{h_u \dot{V}_{ng,br}} \quad (25)$$

indicates, that in the case of natural gas combustion with air as oxygen source the efficiency is low. If natural gas is burned with pure oxygen the combustion efficiency is obviously higher. 1

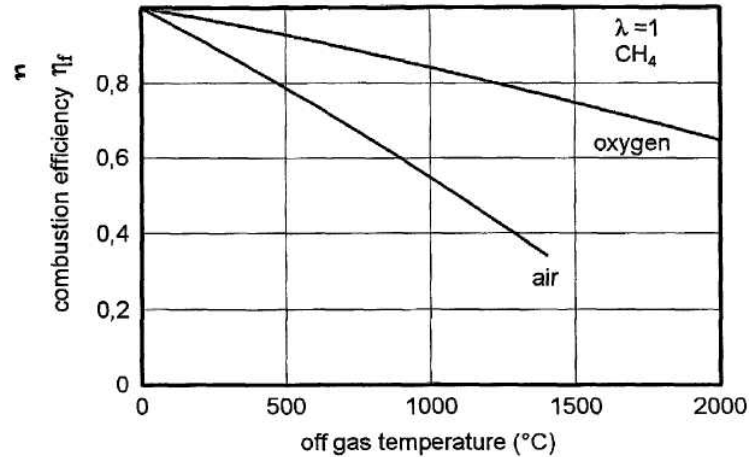


Fig. 8: Combustion efficiency of natural gas (CH₄) vs. off gas temperature for the combustion with air or oxygen

For the determination of the relation between specific electric energy consumption Aw_R and the amount of burner gas MQ the following assumptions are made:

- The efficiency of the heat transfer from the arc to the scrap TW_{scrap} at the beginning of melting (crater) is high (fig. 9).

$$\eta_{\text{arc-scrap}} = \frac{\dot{H}_{\text{scrap}}}{P_{\text{arc}}} = 0.90 \dots 1.0 \quad (26)$$

$\dot{H}$ energy flow from the arc to the scrap P_{arc} power of the arc

- The energy flow from the burner off gas to the scrap is (combustion efficiency)

$$\eta_f = \frac{\text{heating energy} - \text{waste gas energy}}{\text{heating energy}} = \frac{\dot{H}_{\text{scrap}}}{\dot{H}_{\text{br}}}, \quad (27)$$

$$\text{with } \dot{H}_{\text{br}} = \dot{H}_{\text{scrap}} + \dot{H}_{\text{og}}. \quad (28)$$

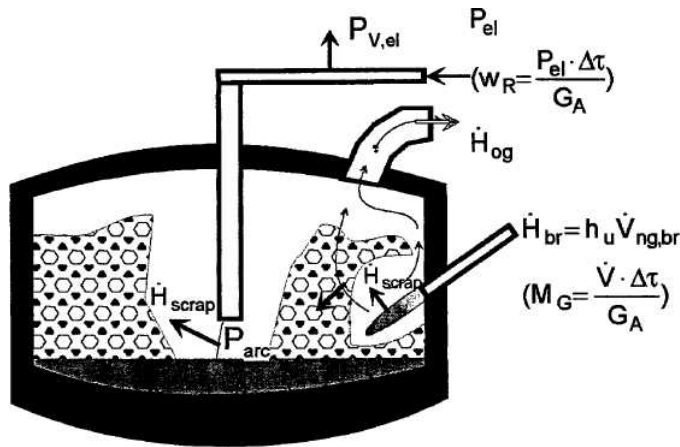


Fig. 9: Energy flows in the EAF with natural gas burners

The same energy flow has to be transferred to the scrap for the calculation of the equivalent parameter

$$\eta_{\text{arc-scrap}} P_{\text{arc}} = \eta_f \dot{H}_{\text{br}} \quad (29)$$

$$\eta_{\text{arc-scrap}} \eta_{\text{el}} P_{\text{el}} = \eta_f \dot{H}_{\text{br}} \quad \eta_{\text{el}} = 0.9 \dots 0.95 \quad (30)$$

$$P_{\text{el}} = \frac{\eta_f}{\eta_{\text{arc-scrap}} \eta_{\text{el}}} \dot{H}_{\text{br}} \quad (31)$$

In terms of energy per ton steel

$$\Delta w_R = \frac{\eta_f}{\eta_{\text{arc-scrap}} \eta_{\text{el}}} h_u M_L = \frac{0.75 \dots 0.85}{0.95 \dots 1.0 \cdot 0.9 \dots 0.95} 10 \frac{\text{kWh}}{\text{m}^3_{\text{ng}}} M_L = 7.8 \dots 10 \cdot M_L \quad (32)$$

The estimated range of the coefficient (7.8 ... 10) includes the given coefficient value from Kohle (8.0). If the calorific value of the natural gas is lower (e.g. 9 kWh/m³), the calculated range of the coefficient is 7.0 to 9.0 kWh/m³.

Studies for the determination of the substitution potential of the electrical energy by fuel oxygen burners at a 100-t UHP EAF showed, that the sum of the specific energy input from elec-

trical energy and fuel energy increases only slight by increasing burner gas input (fig. 10) [17], Thus the necessary electrical energy input is reduced from 13 to 8.4 kWh/m³.

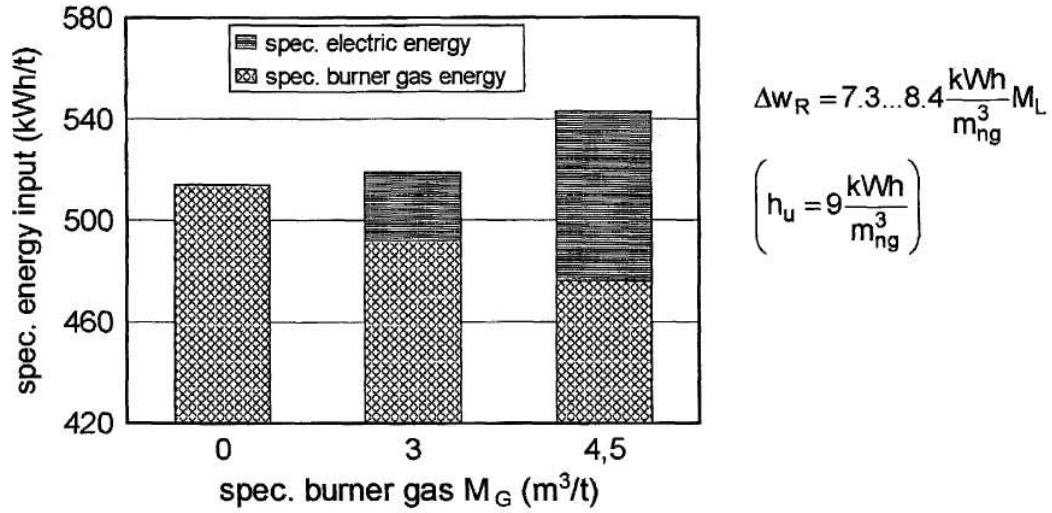


Fig. 10: Substitution of el. energy by chemical energy from natural gas combustion

POST COMBUSTION

Post combustion of CO in the vessel of the EAF is an intensively discussed method to increase EAF efficiency. The reaction enthalpy of the CO-post combustion reaction (eq. 9) is $\Delta h = -7,02 \text{ kWh/m}_{\text{O}_2}^3$ and the "statistical" relation between the specific electric energy and specific oxygen for CO-post combustion is

$$\Delta w_R = -2,8 \frac{\text{kWh}}{\text{m}_{\text{O}_2}^3} M_N \quad (33)$$

$$\Delta w_R \text{ in kWh/t} \quad M_N \text{ in m}_{\text{O}_2}^3 / \text{t}$$

The experimental investigations of the gas atmosphere in EAFs by off gas measurements show, that generally no oxygen in the off gas is detected if larger percentage of CO is available. Complete oxygen balances show, that reactions of CO with O₂ from the infiltrated air occur and the relation CO/CO₂ determine. So the CO-post combustion can be estimated as followed:

- post combustion is effective, if scrap is available to absorb the energy of the reaction (scrap melt down periods),
- the off gas volume flow is not changed for the post combustion period,
- the off gas temperature varies only slight by use of post combustion.

Two energy balances are investigated for the post combustion of 1m³ CO. The balance shown in fig. 11a estimates the heat for the combustion of CO with injected O₂ and balance lib the combustion of CO with infiltrated air.

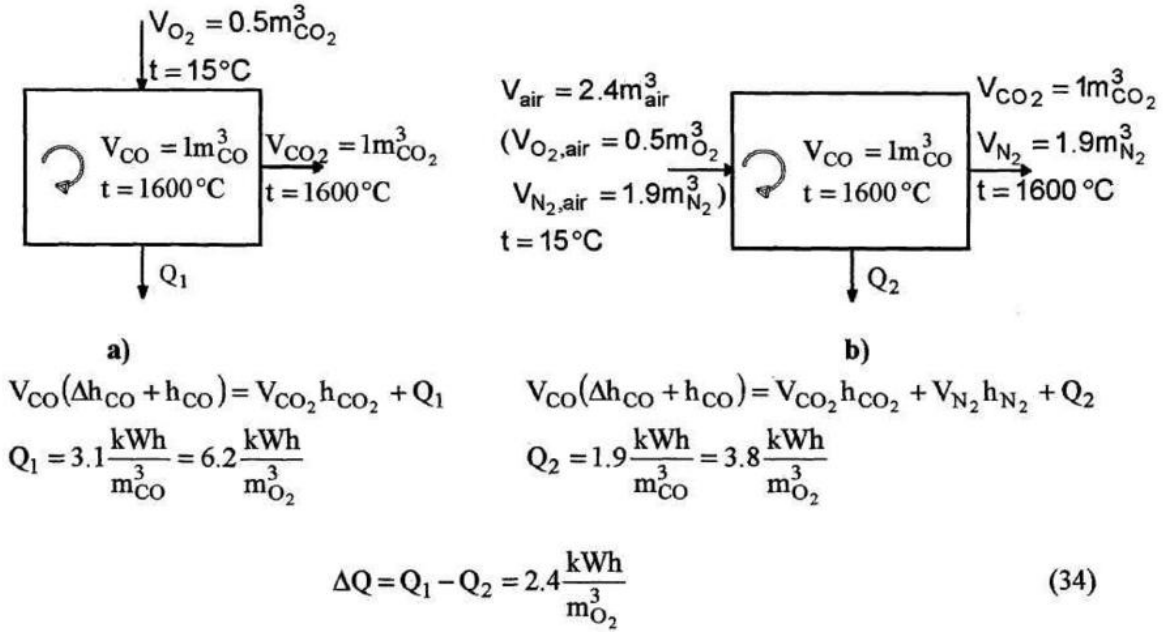


Fig. 11: Post combustion of 1 m³ CO with oxygen (a) and infiltrated air (b)

This valuation gives a coefficient of 2.4 kWh/m³ O₂, which is relative near to the value of Kohle with 2.8 kWh/m³ O₂.

LANCE OXYGEN

The lance oxygen input has the following targets:

- oxidation of oxygen-affine elements like Al, Si, Mn and Fe without increasing the off gas volume
- slag foaming with additional C-input
- decarburisation of the melt in the case of hot metal charging or DRI-charging with higher C-content.

The basic reactions for lance oxygen are listed in table 1. If the typical composition (average) of EAF slags given in table 6 is considered, the energy for oxidation of Al, Si and Fe is 8.6 kWh/m³ O₂. The energy of the complete combustion of carbon to CO₂ is 4.88 kWh/m³ O₂. A number of mass balances for C and O₂ indicates, that approx. 30% of the oxygen is necessary for the metal oxidation and 70% for the carbon oxidation. So the benefit of lance oxygen is 6 kWh/m³ O₂. In [3] the oxygen equivalent factor is estimated to 5.2 kWh/m³ O₂ under consideration of incomplete carbon combustion.

From the data of table 2 a coefficient ξ , can be calculated in the form

$$\xi = \frac{e_{\text{electric energy}} + e_{\text{reactions}}}{e_{\text{electric energy}}} = 1.45 \dots 1.9. \quad (35)$$

The lower value represents EAFs with lower chemical reactions (e. g. stainless steels) and the higher value EAFs with higher amounts of chemical reactions due to higher carbon and oxygen input (e. g. concrete steels).

$$\frac{\Delta w_R}{\text{kWh/t}_{\text{steel}}} = - \frac{6 \text{ kWh/m}^3_{\text{O}_2, \text{L}}}{\xi} \underbrace{\frac{V_{\text{O}_2, \text{L}}}{G_A}}_{M_L} = - \frac{3.1 \dots 4.2 \text{ kWh}_{\text{electric energy}}}{\text{m}^3_{\text{O}_2, \text{L}}} \cdot M_L.$$

The higher value is near to the coefficient calculated from Kohle.

$$\frac{\Delta w_R}{\text{kWh/t}} = -4.3 \frac{\text{kWh}}{\text{m}^3_{\text{O}_2}} M_L.$$

SUMMARY

Six from eleven coefficients of the equation from Kohle [4] have been estimated by mass and energy balances. The results show, that the coefficients are similar from the statistical investigation and typical mass and energy balances. The comparison of complete mass and energy balances from five different EAFs investigated by the Institute of Industrial Furnaces and Heat Engineering in Metallurgy shows, that the correspondence of this data with the modified equation (2) is better than with the original equation (1), fig. 12.

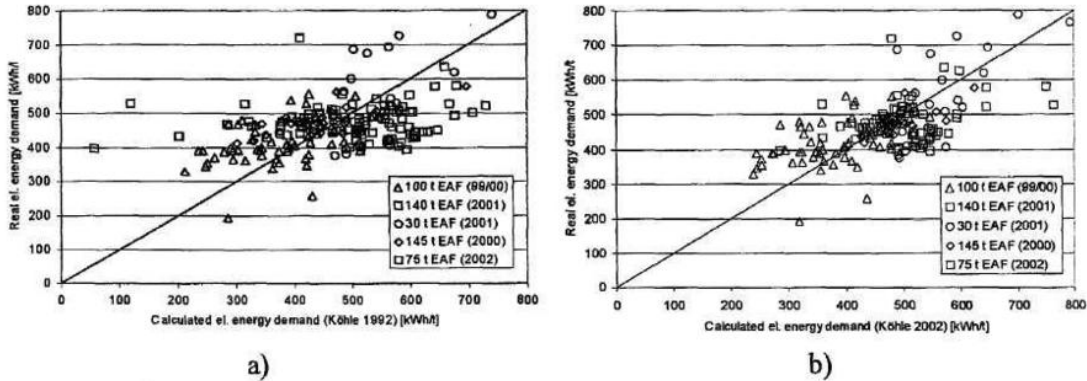


Fig. 12: Comparison of the data from five different EAFs with the specific electric energy consumption after eq. (1) (fig. a) and eq. (2) (fig. b)

REFERENCES

- [1] J. SZEKELY, G. TRAPAGA, Stahl und Eisen, Vol. 114, 1994, No. 9, p. 43-55
- [2] S. KOHLE, Stahl und Eisen, Vol. 112, 1992, No. 11, pp. 59-67
- [3] W. ADAMS, S. ALAMEDDEME, B. BOWMAN, N. LUGO, S. PAEGE, P. STAFFORD, Proc. 59th Electric Arc Furnace Conf., 11-14 Nov. 2001, Phoenix Arizona, pp. 691-702
- [4] S. KOHLE, Proc. 7th Europ. Electric Steelmaking Conf., 26-29 May 2002, Venice, Italy
- [5] F. N. FETT, H. PFEIFER, H. SIEGERT, Stahl und Eisen, Vol. 102, 1982, pp. 461-465
- [6] H. PFEIFER, F. N. FETT, K.-H. HEINEN, elektrowarme int., Vol. 46, 1988, pp. 71-77
- [7] H. PFEIFER, Stoff- und Energiebilanz, in: K.-H. HEINEN (Ed.), Elektrostahl-Erzeugung, Verlag Stahleisen, Dusseldorf, 1997, pp. 112-127
- [8] M. KIRSCHEN, H. PFEIFER, F.-J. WAHLERS, H. MEES, 59th Electric Arc Furnace Conf, 11-14 Nov. 2001, Phoenix, Arizona, pp. 737-748
- [9] H. BROD, F. KEMPKENS, H. STROHSCHNEIN, Stahl und Eisen, Vol. 109, 1989, No. 5, pp. 229-238
- [10] H. GRIPENBERG, M. BRUNNER, M. PETERSSON, Iron and Steel Engineer, 1990, No. 7, pp. 33-37

- [11] J. EHLE, H. KNAPP, H. MOSER, Steel World, Vol. 3, No. 2, pp. 24-32
- [12] K. SCHEIDIG, S.W.G SCHERER, T.B. MARTINS, M. VAN DERPUT, V.K. LAKSMANAN, Proc. 6th Europ. Electric Steelmaking Conf, VDEh, Dusseldorf, 1999, pp. 38-42
- [13] K. SCHEIDIG, Einsatzstoff Roheisen, in: K.-H. HEINEN (Ed.), Elektrostahl-Erzeugung, Verlag Stahleisen, Dusseldorf, 1997, pp. 77-85
- [14] D. YANEZ, M.A. PEDROZA, J. EHLE, H. KNAPP, Proc. 6th Europ. Electric Steelmaking Conf., VDEh, Dusseldorf, 1999, pp. 24-28
- [15] K. WALDEN, Metallurgie bei Eisenschwammeinsatz, in: K.-H. HEINEN (Ed.), Elektrostahl-Erzeugung, Verlag Stahleisen, Dusseldorf, 1997, pp. 503/11
- [16] H. SCHLIEPHAKE, R. STEFFEN, H. B. LUNGEN, Einsatzstoff Eisenschwamm und Eisencarbid, Ed.: K.-H. HEINEN, Elektrostahl-Erzeugung, Verlag Stahleisen, Dusseldorf (1997), p. 65/76
- [17] K.-H. HEINEN, H. SIEGERT, K. POLTHIER, K. TIMM, Stahl und Eisen, Vol. 103, 1983, No. 18, pp. 855-61

Thermodynamic analysis of EAF electrical energy demand.

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Abstract

Empirical models that are applied to calculate the specific electrical energy demand of electric arc furnaces in steel industry are compared to a thermodynamic analysis of the meltdown process. The influence of various process and plant technologies on the specific electrical energy demand is investigated and compared with the regression coefficients of empirical models from Kohle, and Adams and co-workers. For this purpose, thermodynamic analysis of the energy transfer from various sources to scrap and melt of the EAF process is applied. From the complete energy balance of the EAF process ranges of coefficients are derived relating the electrical energy input with process parameters (i.e. input of scrap, coal, hot metal, slag formers, oxygen). These ranges of coefficients correspond to fitting parameters of linear regression models as proposed by Kohle. As a result, hints for further refinements of the Kohle statistical model of electric energy demand are given.

Introduction

Objectives of technical improvements of electric arc furnace (EAF) technology in steelmaking are minimum specific electric energy demand, minimum electrode material consumption, and most important increase of productivity. Significant improvements of the EAF process during the last 4 decades are shown in figure 1. At modern EAF tap-to-tap time arrived 30 minutes at most favourable production conditions, specific electric energy demand below 300 kWh/t, and electrode graphite consumption 0.9 to 1.3 kg/t depending on electrode diameter and AC or DC technology [1, 2]. With these premises the future share of EAF steel making on total steel production is forecasted at 40%.

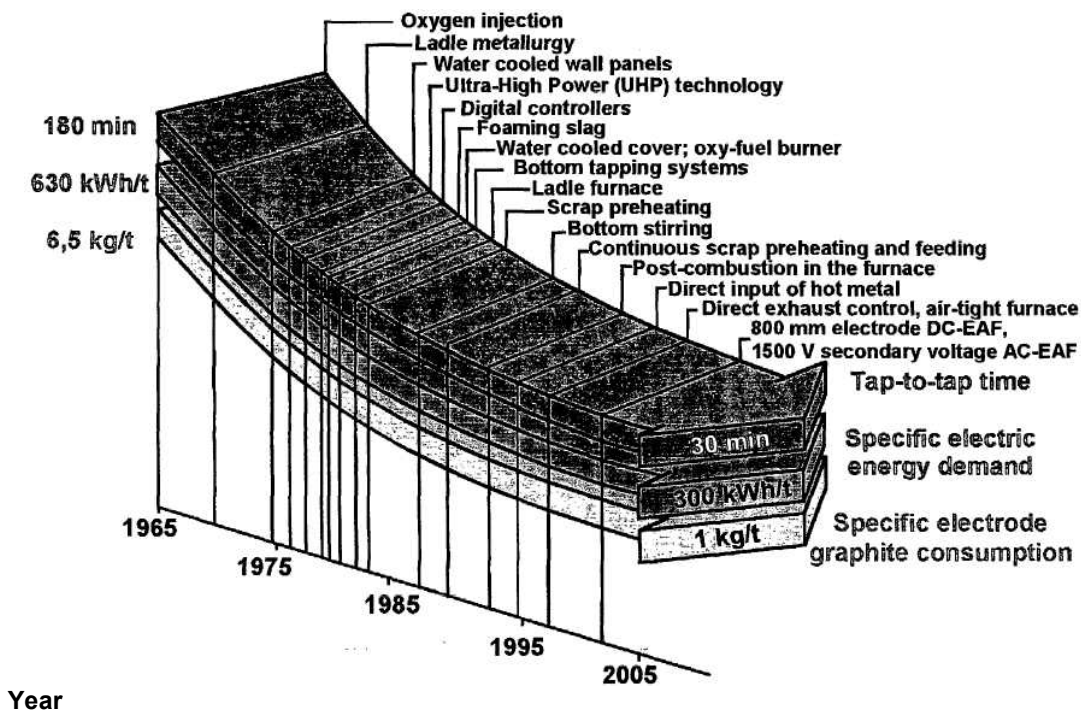


Fig. 1. Influence of various EAF process improvements on characteristic key data: tap-to-tap time, electric energy demand, and electrode graphite consumption [3].

Of special interest for the EAF production process is the impact of mass and energy input to the electric energy demand, the productivity, and the production costs. Recent trends of prices for scrap and energy indicate the importance of models for optimizing the electric energy demand as function of process parameters, e.g. scrap, coal and oxygen input, gas burners, oxygen injectors etc.

The large number of influencing factors to the specific electric energy demand is indicated in fig. 1 and it is shown in more detail in fig. 2. However, user friendly models of the electrical energy demand of the EAF process require the reduction of high complexity of interrelations between electric energy demand and process parameters.

For this purpose, empirical models are based on linear regression of large process data sets. With these models the change of electric energy demand is estimated when process parameter are changed, e.g. substitution of scrap with direct reduced iron (DRI) or the use of gas burners in order to substitute electric energy with chemical energy. Similar models exist to determine the consumption of electrode graphite material [5, 6].

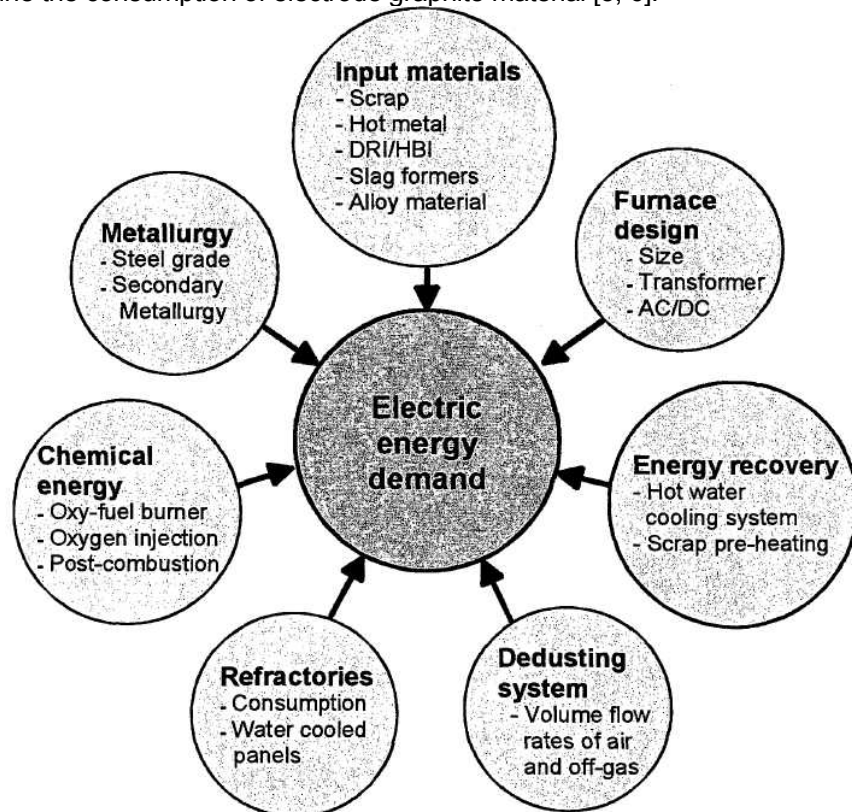


Fig. 2: Influence of various process parameters to the electric energy demand of EAF [4]

In this paper, we investigate empirical models to determine the EAF electric energy demand from Kohle [5-7, 9], Adams et al. [13, 14], Jones [18, 19] and compare these models with a thermodynamic analysis of the meltdown process in the EAF. The study is based on complete mass and energy balances from various R&D projects with steel makers in Germany and on literature data. Feasible ranges for the correlation coefficients in the empirical models are presented.

Empirical models of energy demand

1999 S. Kohle published a linear relation to quantify the influence of various process parameters to the electrical energy demand [8]. The regression analysis of data from 14 AC-EAFs with tapping weights from 64t to 147t without scrap preheating raised a linear equation of electrical energy demand. The comparison with data from AC and DC furnaces indicates,

that the model applies to both EAF types, i.e. concerning the relation between electrical energy demand and process parameters there seems to be no significant difference between these two EAF types [7]. The coefficients were derived with linear regression techniques from process data of various EAFs [8]. The change of model parameters, regression coefficients and additional terms for subsequent refinements of the model is shown in table 1.

Table 1. Development of the Kohle model to determine the electric energy demand

$\frac{W_R}{\text{kWh/t}} = 300 + 900 \cdot \left[\frac{G_E}{G_A} - 1 \right] + 1600 \cdot \frac{G_Z}{G_A} + 0.7 \cdot \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] + 0.85 \cdot \frac{t_s + t_N}{\text{min}} - 8 \cdot \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \cdot \frac{M_L}{\text{m}^3/\text{t}}$		(1) 1992 [8]	
$\frac{W_R}{\text{kWh/t}} = 300 + 900 \cdot \left[\frac{G_E}{G_A} - 1 \right] + 1600 \cdot \frac{G_Z}{G_A} + 0.7 \cdot \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] + 0.85 \cdot \frac{t_s + t_N}{\text{min}} - 8 \cdot \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \cdot \frac{M_L}{\text{m}^3/\text{t}} - 2.8 \cdot \frac{M_N}{\text{m}^3/\text{t}} + 80 \cdot \frac{G_{\text{DRI/HBI}}}{G_A} - 300 \cdot \frac{G_{\text{HM}}}{G_A} - 15 \cdot \text{CON}$		(2) 1999 [7]	
$\frac{W_R}{\text{kWh/t}} = 391 + 450 \cdot \left[\frac{G_E}{G_A} - 1 \right] + 800 \cdot \frac{G_Z}{G_A} + 0.35 \cdot \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] + 0.43 \cdot \frac{t_s + t_N}{\text{min}} - 2.1 \cdot \frac{M_L}{\text{m}^3/\text{t}}$		(3) 2001 [10]	
$\frac{W_R}{\text{kWh/t}} = 375 + 400 \cdot \left[\frac{G_E}{G_A} - 1 \right] + 1000 \cdot \frac{G_Z}{G_A} + 0.3 \cdot \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] + 1.00 \cdot \frac{t_s + t_N}{\text{min}} - 8 \cdot \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \cdot \frac{M_L}{\text{m}^3/\text{t}} - 2.8 \cdot \frac{M_N}{\text{m}^3/\text{t}} + 80 \cdot \frac{G_{\text{DRI/HBI}}}{G_A} - 350 \cdot \frac{G_{\text{HM}}}{G_A} - 50 \cdot \frac{G_{\text{Shr}}}{G_A} + \text{NV} \cdot \frac{W_V - W_{V_m}}{\text{kWh/t}}$		(4) 2002 [9]	
CON	continuous (+1), discontinuous (-1) operation	M _N	Specific post-combustion oxygen [m ³ /t]
G _A	Furnace tap weight [t]	NV	Furnace specific factor (0.2 to 0.4)
G _{DRI}	Weight of DRI (Direct Reduced Iron) [t]	T _A	Tapping temperature [°C]
G _E	Weight of all ferrous materials [t]	t _N	Power-off time [min]
G _{HBI}	Weight of HBI (Hot Briquetted Iron) [t]	t _s	Power-on time [min]
G _{HM}	Weight of hot metal [t]	W _R	Specific electric energy demand (from regression analysis) [kWh/t]
G _{Shr}	Weight of shredder [t]	W _V	Energy losses (if measured) [kWh/t]
G _Z	Weight of slag formers [t]	W _{V_m}	Mean value of W _V [kWh/t]
M _L	Specific lance oxygen [m ³ /t]		
M _G	Specific burner gas [m ³ /t]		

The linear model from 1992 was successively extended, verified and validated with an increasingly comprehensive database comprising various EAF types with and without scrap preheating. The occurrence of process parameters and the regression coefficients change due to the increasing database.

The first version of the regression model (eq. 1) [8] was supplemented with a term for post-combustion of CO and H₂ off-gases in the EAF vessel [11]. The input of hot metal, DRI and HBI was implemented to the model in 1999 (eq. 2) [7]. Also, the impact of the continuous or discontinuous mode of operation, i.e. operation during 24 h a day, on electric energy demand was incorporated with the particular factor CON [7]. For the modelling of the electric energy demand of a single 145t EAF without gas burner the model was modified and adapted to an extensive database of process data for single heats (eq. 3) [10]. At this EAF, scrap and Ni briquettes and Cr alloy material is charged for melting of stainless steel grades. The most recent version of the model (eq. 4) is based on a huge database comprising mean values from 60 EAFs, 5500 heats from 5 EAFs, and monthly mean values of one EAF [9]. In eq. 4 the input of shredder is considered as well as energy loss by furnace cooling system.

Adams and co-workers [13, 14] developed a similar model to estimate the specific total energy demand of the EAF process W_{tot} (table 2). Focus is set on various contributions to total energy demand of 92 furnaces running at more than 80t/h: electric and chemical energy. Process parameters as tapping temperature, tap-to-tap time, input of slag formers and shredder are not accounted for. In contrast to the Kohle model, the Adams model [14] takes into account input of oil and liquefied petrol gas by burners. It has to be noted that the Kohle model is referenced to the tapping weight G_A whereas the Adams model is referenced to the input weight G_E .

Table 2. Development of the Adams model to determine the total energy demand

$\frac{W_{tot}}{\text{kWh/t}} = \frac{W_E}{\text{kWh/t}} + 110 \cdot \frac{G_{PI}}{G_E} - 100 \cdot \frac{G_{DRI/HBI}}{G_E} + 450 \cdot \frac{G_{HM}}{G_E} + 10.5 \cdot \frac{M_G}{\text{m}^3/\text{t}} + 5.2 \cdot \frac{M_{O_2} - 2.0 \cdot M_G}{\text{m}^3/\text{t}}$		(5) 2001 [13]
$\frac{W_{tot}}{\text{kWh/t}} = \frac{W_E}{\text{kWh/t}} + 110 \cdot \frac{G_{PI}}{G_E} - 100 \cdot \frac{G_{DRI/HBI}}{G_E} + 450 \cdot \frac{G_{HM}}{G_E} + 10.5 \cdot \frac{M_G}{\text{m}^3/\text{t}} + 11 \cdot \frac{M_{Oil}}{\text{l/t}} + 8 \cdot \frac{M_{LPG}}{\text{l/t}} + 5.2 \cdot \frac{M_{O_2} - 2.0 \cdot M_G - 2.0 \cdot M_{Oil} - 1.5 \cdot M_{LPG}}{\text{m}^3/\text{t}}$		(6) 2002 [14]
G_E	Weight of input [t]	M_{Oil} Specific volume of oil input [l/t]
G_{PI}	Weight of pig iron [t]	M_{LP} Specific volume of LPG (liquefied petrol gas) [l/t]
M_{O_2}	Specific volume of oxygen [m ³ /t]	W_E Specific electric energy input [kWh/t]

Efficiency factors of energy transfer

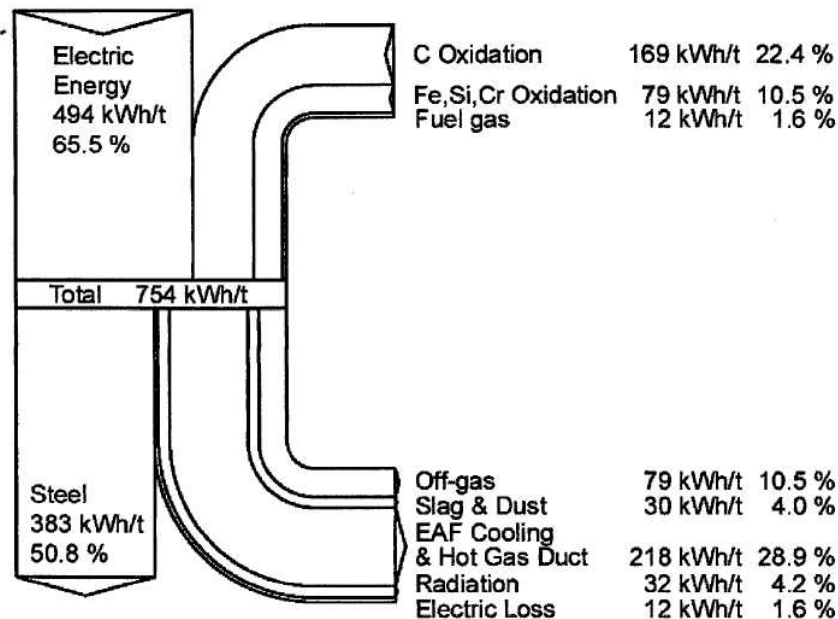
The assessment of energy transfer of the meltdown process requires the definition of an efficiency factor, η_N . The efficiency factor is defined as quotient of useful energy E_{use} to supplied energy E_{sup} for a certain period (eq. 7).

$$\eta_N = \frac{\text{Useful energy}}{\text{supplied energy}} = \frac{E_{use}}{E_{sup}} \quad (7)$$

The considered time interval includes the periods that are characteristic for batch processes: starting time, idle time and ending time. At EAF steelmaking the enthalpy of tapped steel denotes the useful energy in eq. 7 [4]:

$$\eta_{N,EAF} = \frac{\text{Enthalpy of tapped steel}}{\text{Total supplied energy}} = \frac{H_{steel}}{E_{sup}} \quad (8)$$

The proposed definition of the efficiency factor considers various sources of energy: electric energy as well as scrap preheating, gas burners, post-combustion of off-gas in the furnace, combustion of electrode graphite and coal, and energy released from oxidation reactions in the melt and slag. At conventional furnaces, the efficiency factor $\eta_{N,EAF}$ ranges from 50 % to 60 %. The highest value of $\eta_{N,EAF}$ was reported for a finger shaft furnace with integrated scrap preheating [2]: $\eta_{N,EAF} = 67$ %. In this case, the supplemental energy demand for post-combustion and treatment of off-gas is not considered. Fig. 3 shows the energy balance of a 75t EAF based on 24 heats of austenitic stainless steel grade with a efficiency factor of $\eta_{N,EAF} = 50.8\%$ [16].



Fig,3, Energy balance of a 75t EAF based on 24 heats of austenitic stainless steel grade [16]

During the transport of electric energy from the high voltage network to the electric arc ohmic losses occur in the high current system comprising transformer, supply lines and connectors, electrode carriers, and electrodes. The efficiency of transfer of electric energy in the high current system ranges from $\eta_{el} = 90\%$ to 95% [17].

$$\eta_{el} = \frac{\text{Power of electric arc}}{\text{Power of electric arc} + \text{electric losses}} = \frac{P_{arc}}{P_{arc} + P_{el,loss}} \quad (9)$$

The transfer of energy from various sources to the scrap and to the melt depend on time and place of energy supply at the EAF process, on properties of foaming slag and on specific surface of scrap fraction. The corresponding thermal efficiency factor η_{arc} from electric arc to scrap and melt depends on specific surface of scrap fraction and performance of foaming slag.

$$\eta_{arc} = \frac{\text{Energy flow rate Electric arc} \rightarrow \text{scrap}}{\text{Power of electric arc}} = \frac{P_{arc-scrap}}{P_{arc}} \quad (10)$$

At the beginning of the meltdown period, low arc voltage and short electric arcs are used to avoid short circuit to the EAF cover and to the EAF wall panels. After the boring period the electric arc is shielded with scrap. Using high arc voltage and long electric arcs thermal efficiency factors from $\eta_{arc} = 88\%$ to 92% are achieved [18]. After meltdown of the scrap pile, the thermal efficiency factor range from $\eta_{arc} = 36\%$ to 93% depending on efficient shielding of the electric arc by scrap, melt and slag [28]. The total efficiency factor of electric energy transfer to the melt, $\eta_{el} \eta_{arc}$, ranges from 60% to 80% . Fig. 4 illustrates the influence of foaming slag to the efficiency factor of energy transfer from electric arc to melt [28].

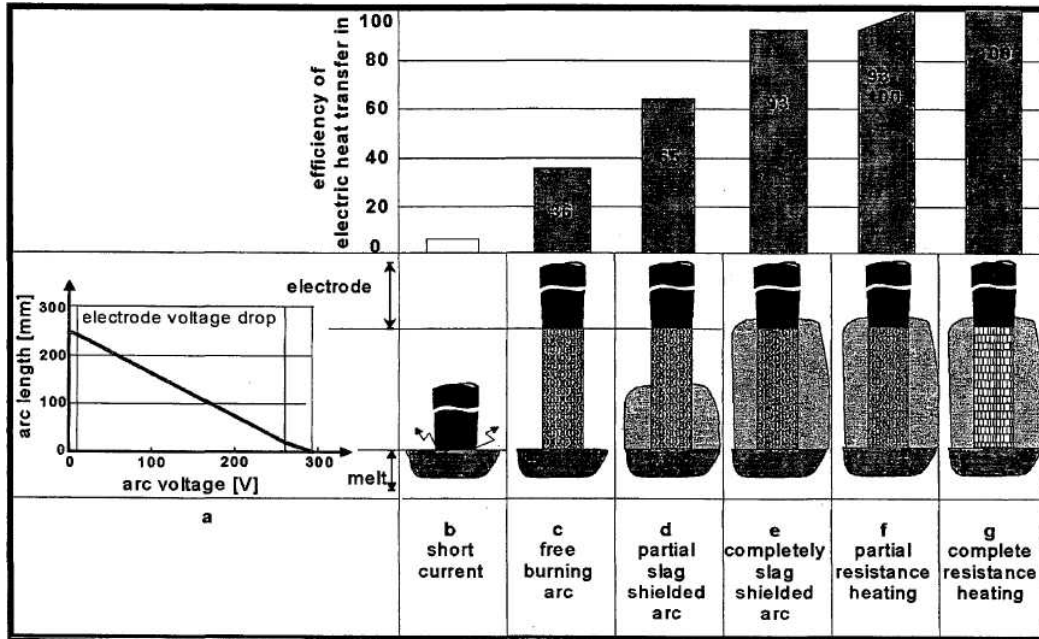


Fig.4. Influence of foaming slag to the efficiency factor of energy transfer from electric arc to melt [28]

The decrease of specific electric energy demand by increase of chemical energy input is usually called "substitution". However, various sources of energy are applied simultaneously. Considering the successive transformation of electric energy from the power supply to the electric arc and to the melt, the amount of effectively transferred electric energy to the scrap and to the melt is $\eta_{el}\eta_{arc} \Delta e_{el}$. The chemical energy Δh_i that substitutes electric energy has to be weighed with a corresponding efficiency factor of energy transfer to the melt, η_i in eq.11:

$$\eta_{el} \cdot \eta_{arc} \cdot \Delta e_{el} = \eta_i \cdot \Delta h_i \quad (11)$$

The right hand side of eq. 11 denotes that the substituting energy Δh_i is bounded in a similar manner as the electric energy to a thermal efficiency factor of the energy transfer to the scrap and melt. The effective substitution of electric energy from different sources Δh_i e.g. oxy-fuel burner, post-combustion of off-gas in the furnace, scrap preheating, exothermal reactions in the melt, is defined by the corresponding thermal efficiency factors η_i :

$$\Delta e_{el} = \frac{\eta_i \cdot \Delta h_i}{\eta_{el} \cdot \eta_{arc}} \quad (12)$$

Ranges for thermal efficiency factors of various energy sources at the electric arc furnace are summarized in table 3. The efficiency factors for gas burners and post-combustion of off-gas in the furnace decrease drastically with decreasing specific surface of the scrap pile below the values that are given in table 3.

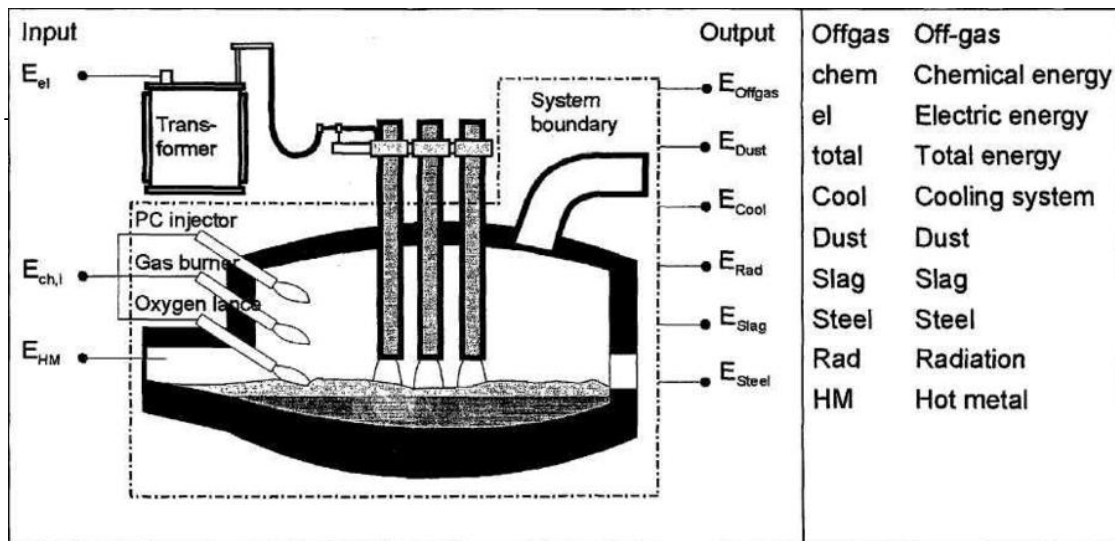
Table 3: Thermal efficiency factors for various sources of energy from the literature

Energy source	Efficiency factor of energy transfer	Abbreviation	[%]	Source
Total energy	Efficiency factor	$\eta_{N.EAF}$	50-67	[2][17]
Electric energy	Efficiency factor of high current system	η_{el}	90-95	[17]
	Thermal efficiency factor of electric arc	η_{arc}	36-93	[29]
	Total efficiency factor of electric energy	$\eta_{el} \eta_{arc}$	60-80	
Oxygen lances	Efficiency factor of oxygen injection	η_L	70-80	[13]
Oxy-fuel burner	Efficiency factor of oxy-fuel burners	η_G	50-60	[19]
Post-combustion of off-gas in EAF	Efficiency factor of post-combustion	η_{PC}	30-50	[13][22]

Choice of system boundary

The energy balance of the meltdown process in the EAF is based on the 1st law of thermodynamics: conservation of energy. With the assumption, that the average energy content of the EAF remains constant, the balance of energy flow to and from the EAF is (eq. 13):

$$E_{total} = \eta_{el} \cdot E_{el} + \sum E_{chem,i} + E_{HM} = E_{Steel} + E_{Slag} + E_{Dust} + E_{Offgas} + E_{Rad} + E_{Cool} \quad (13)$$

**Fig. 5.** System boundary for energy balance of the EAF process

If the system boundary for EAF energy balance is chosen as shown in fig. 5, the required energy for fans of the dedusting system, the energy for subsequent ladle furnace, the energy for scrap preheating, and the energy for post-combustion and heat treatment of off-gas in the dedusting system is not considered. The measurement of the electric energy of a heat is usually carried out before the transformer. Electric losses at the high current system (transformer, power supply line, electrode carriers, and electrodes) lead to an efficiency factor for the transport of electric energy from power supply to the electric arc in eq. 13: $\eta_{el} E_{el}$. Using the system boundary from fig. 5 energy transfer for melting scrap in the EAF is considered with all relevant mass and energy flow paths.

[15] considers off-gas enthalpy before and after post-combustion and cooling of hot off-gas. In the latter case, the system boundary is extended to water cooled hot gas line of primary

dedusting system. After the water cooled hot gas line, the off-gas enthalpy is decreased and the energy flow rate of the cooling system including EAF wall panels, roof, elbow, and hot gas line is increased [15].

Minimum demand of specific electric energy

Using the system boundary no. 1 in fig. 5, the electric energy demand is easily determined from eq. 13:

$$E_{el} = \frac{E_{Steel}}{\eta_{el}} - \frac{\sum E_{chem,i} + E_{HM}}{\eta_{el}} + \frac{E_{Slag} + E_{Dust} + E_{Offgas} + E_{Rad} + E_{Cool}}{\eta_{el}} \quad (14)$$

The electric energy demand is increased with energy losses to slag, off-gas and cooling system, and it is decreased with input of chemical energy and hot metal.

From eq. 14, the minimum value of the electric energy demand for scrap melting is determined, in analogy to the constant factor in the regression models, eq. 1 to eq. 4. A low alloyed steel melt requires a specific enthalpy of $\Delta h_{steel} = 361$ kWh/t for heating from 20 °C to 1600 °C [20], which is used as reference temperature in the regression model (eq. 1 to eq. 4). The specific enthalpy $\Delta h_{steel} = 372$ kWh/t is designated to a high alloyed Cr-Ni stainless steel melt at 1600 °C [20]. The minimum electric energy demand for scrap melting and superheating of melt to 1600 °C without other sources of energy is therefore:

$$\frac{E_{Steel}}{m_{Steel} \cdot \eta_{el}} = \frac{\Delta h_{Steel}}{\eta_{el}} = 380 \text{ to } 413 \frac{\text{kWh}}{\text{t}} \quad (15)$$

where the efficiency factor of the electric system is $\eta_{el} = 0.90$ to 0.95 [17]. Because electric efficiency is high at modern furnaces, $\eta_{el} = 0.95$, $\Delta h_{steel} / \eta_{el} = 380$ kWh/t for low alloyed steel melts and $\Delta h_{steel} / \eta_{el} = 391$ kWh/t for alloyed steel melts. At low electric efficiency factors, $\Delta h_{steel} / \eta_{el}$ increases to 413 kWh/t. The minimum electric energy demand at a reference temperature $T = 1600$ °C corresponds to the constant values K_k in the Kohle models (eq. 1 to eq. 4). The regression coefficient K_k changed from $K_k = 300$ kWh/t (eq. 1) to $K_k = 375$ kWh/t (eq. 4), that is still below the estimated range. At the single furnace model (eq. 3) without oxy-fuel burner $K_k = 391$ kWh/t agrees very well with the estimated value for Cr-Ni stainless steel production.

Specific ferrous material input

Steel scrap is the ideal material for recycling, because it is recycled to arbitrary extend without loss of quality. However, scrap contains non-ferrous metals, oxides, coatings, grease, oil, water and other impurities. The coefficient of specific input of ferrous material considers the amount of specific electric energy that is required for vaporization, oxidation and phase separation of the impurities ($G_E/G_A - 1$) from the ferrous melt. The yield of metallic material usually ranges from 86 % to 92 % [12, 13]. The additional energy, that is required to heat up yield loss to reference temperature, is estimated with a mass and energy balance of the vaporized and oxidized components and the assumption that the average heel remains constant [21].

$$\Delta h_E = \int_{t_c} \sum_i \dot{m}_{Dust,met,i} \Delta h_{Dust,met,i}(T) dt + \sum_i m_{Slag,met,i} \Delta h_{Slag,met,i}(T) + m_{H_2O,met} \Delta h_{H_2O}(T) + m_{Oil,met} \Delta h_{Oil}(T) \quad (16)$$

$m_{Dust,met,i}$ specific mass of component i from metallic input in dust [kg/t]

$m_{Slag,met,i}$ specific mass of component i from metallic input in slag [kg/t]

m_{Oil} specific mass of oil and grease in metallic input [kg/t]

m_{H_2O} specific mass of water in metallic input [kg/t]

The enthalpy of non-ferrous oxide impurities at 1600 °C is determined from slag enthalpies with typical composition. CaO and MgO input from slag formers and erosion of refractory lining is not considered for this term (see chapter about slag formers). The specific mass of dust varies from 10 to 25 kg/t [26]. Analysis of dust composition shows that 80 % to 90 % comes from the non-ferrous gangue of input metallic material. The enthalpy of dust is calculated for a mean off-gas temperature from 900 °C to 1200 °C [20]. The specific mass of water, oil and grease in the metallic input in eq. 9 is neglected due to lack of precise data: $m_{H_2O} = m_{oil} = 0$. Therefore, the specific energy of metallic yield loss at off-gas temperature is estimated to a lower bound of:

$$\Delta h_E = 480 \text{ to } 600 \frac{\text{kWh}}{t} \quad (17)$$

The corresponding specific electric energy demand for metallic yield loss considers the efficiency factors η_{el} and η_{arc} from table 3:

$$e_{el, E} = \frac{\Delta h_E}{\eta_{el} \cdot \eta_{arc}} = 600 \text{ to } 1000 \frac{\text{kWh}}{t} \quad (18)$$

The specific electric energy demand of metallic yield loss is determined by the regression models to:

$$\frac{\Delta W_{R, E}}{\text{kWh}/t} = 400 \cdot \left[\frac{G_E}{G_A} - 1 \right] \quad (19)$$

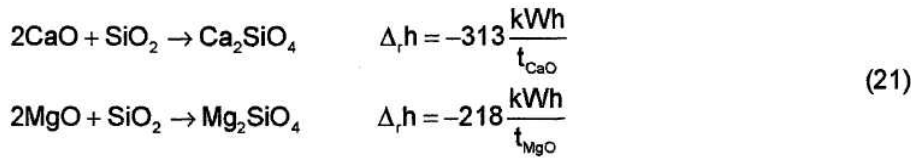
The coefficient of the specific metallic input was adjusted from $KE = 900$ (eq. 1) to $KE = 400$ (eq. 4). In eq. 3 the coefficient is set to $KE = 450$ for stainless steel making with the particular EAR. When compared to the calculated range, only the regression coefficient of eq. 1 is within the estimated range, subsequently refined values are lower. However, precise determination of the specific electric energy demand of metallic yield loss is difficult due to varying mass, composition of impurities (varying values for metallic yield) and due to varying temperature and distribution of the volatiles and oxide losses to gas, slag and dust.

Slag formers

Slag formers are added to the metallic input as 25 kg/t to 50 kg/t lime or lime-dolomite mixture with a ratio CaO to MgO from 4:1 to 5:1 [17]. In rare cases, limestone CaCO_3 is charged in order to increase CO/CO₂ gas production and melt stirring [16]. On the other hand, calcination of limestone requires energy: 500 kWh/t_{CaCO₃} or 890 kWh/t_{CaO}. The specific enthalpy of pure CaO or pure MgO at 1600 °C is $h_{CaO} = 416 \text{ kWh/t}_{CaO}$ and $h_{MgO} = 550 \text{ kWh/t}_{MgO}$, respectively ($\Delta h_{CaCO_3} = 733 \text{ kWh/t}_{CaO}$) [20]. The specific energy that is required to heat slag formers at a CaO : MgO ratio of 5:1 to 1600 °C is $\Delta h_{CaO/MgO} = 438 \text{ kWh/t}_{CaO/MgO}$. When solution enthalpy in the silicate slag phase and formation enthalpy of silicates is not considered, the corresponding specific electric energy is:

$$e_{el, \text{slagformers}} = \frac{h_{CaO/MgO}(T)}{\eta_{el} \cdot \eta_{arc}} = 548 \text{ to } 730 \frac{\text{kWh}}{t_{CaO/MgO}} \quad (20)$$

SiO₂ from oxidation reactions or from refractory linings is bounded as calcium and magnesium silicates. The exothermic reaction enthalpy of silicate formation is considered in complete energy balances only in few cases, e.g. [27].



The reaction enthalpy of silicate formation is $\Delta_r h_{\text{CaO/MgO}} = -297 \text{ kWh}/t_{\text{CaO/MgO}}$ at a CaO : MgO ratio of 5:1. The thermal efficiency factor of the energy transfer from the exothermic silicate formation reaction in the slag phase to liquid steel is estimated to $\eta_r = 50 \%$. When the reaction enthalpy of the silicates is considered, the specific electric energy demand for melting the slag formers is determined to:

$$e_{\text{el,Z}} = \frac{\Delta h_{\text{CaO/MgO}}(T) - \eta_r \cdot \Delta_r h_{\text{CaO/MgO}}(T)}{\eta_{\text{el}} \cdot \eta_{\text{arc}}} = 373 \text{ to } 498 \frac{\text{kWh}}{t_{\text{CaO/MgO}}} \tag{22}$$

The specific electric energy demand that is assigned to the slag formers is considered in the regression models (eq. 1 to eq. 4) with the following term:

$$\frac{\Delta w_R}{\text{kWh/t}} = +1000 \cdot \frac{G_Z}{G_A} \tag{23}$$

The model coefficient of slag formers to the specific electric energy demand decreased from $K_z = 1600$ (eq. 1) to $K_z = 1000$ (eq. 4), $K_z = 800$ in the model of a single EAF (eq. 3). All regression coefficients are remarkably higher than the estimated range of $\Delta e_{\text{el,Z}} = 548 \text{ kWh}/t_{\text{CaO/MgO}}$ to $730 \text{ kWh}/t_{\text{CaO/MgO}}$ and $373 \text{ kWh}/t_{\text{CaO/MgO}}$ to $498 \text{ kWh}/t_{\text{CaO/MgO}}$ when the reaction exothermic enthalpy of the silicates is taken into account.

However, considering the use of a mixture of 70 % limestone, 20% lime and 10% dolomite [16], $\Delta h_{\text{CaCO}_3/\text{CaO/MgO}} = 651 \text{ kWh/t}$ is required for heating the slag formers to 1600°C , and 502 kWh/t if formation enthalpy of silicates is taken into account. The estimated range for the increase of the electric energy demand is: $\Delta h_{\text{CaO/MgO/CaCO}_3} / \eta_{\text{el}} \eta_{\text{arc}} = 628 \text{ to } 837 \text{ kWh/t}$. The estimated range for a mixture of limestone, lime and dolomite is in close agreement to the regression coefficient in eq. 3 for the particular EAF: 800 kWh/t .

Tapping temperature

Tapping temperatures of liquid steel range between 1550°C and 1750°C depending on production specifications and requirements of ladle metallurgy at the steel plants. Fig. 6 shows the specific enthalpy of a non-alloyed steel melt and of a highly alloyed Cr-Ni stainless steel melt as function of tapping temperature [20].

The almost linear development of enthalpies for both steel grades show the constant slope of $\Delta h(T_A) / \Delta T_A = 0.23 \text{ kWh/Kt}$. The change in specific electric energy demand with superheating of the melt above 1600°C is:

$$\Delta e_{\text{el,T}_A} = \frac{1}{\eta_{\text{el}} \cdot \eta_{\text{arc}}} \cdot \frac{\Delta h(T_A)}{\Delta T_A} = 0.29 \text{ to } 0.38 \frac{\text{kWh}}{\text{Kt}} \tag{24}$$

The correlation of specific electric energy demand with tapping temperature is determined by

$$\text{Jones [13] to } \Delta e_{\text{el,T}_A} = 0.24 \frac{\text{kWh}}{\text{Kt}} \text{ and by Memoli et al. [25] to } \Delta e_{\text{el,T}_A} = 0.40 \frac{\text{kWh}}{\text{Kt}}$$

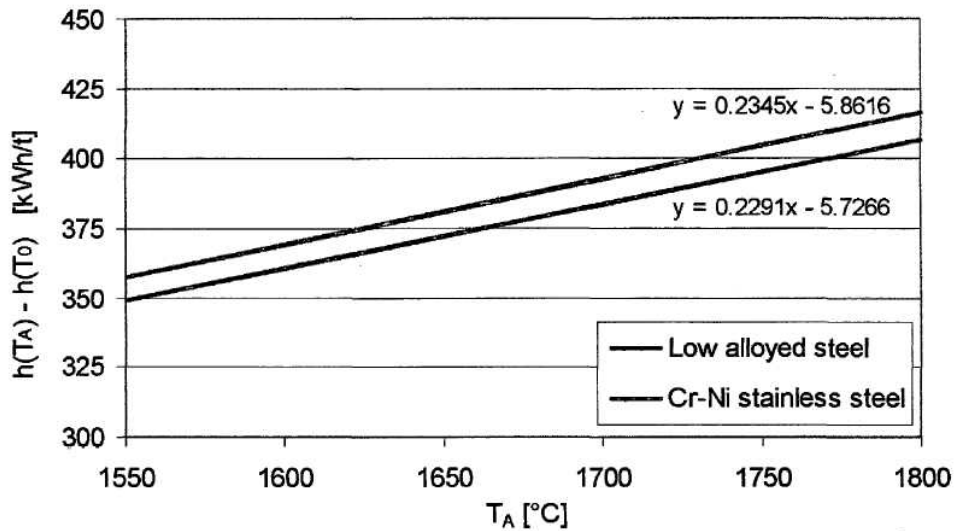


Fig. 6. Specific enthalpies of an unalloyed steel melt and of a Cr-Ni stainless steel melt

The regression coefficients in the statistical models of Kohle are determined to:

$$\frac{\Delta w_{R,T_A}}{\text{kWh/t}} = 0.3 \cdot \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] \quad (25)$$

The regressed values for the influence of the tapping temperature were adjusted from $K_T = 0.7$ (eq. 1) to $K_T = 0.3$ (eq. 4) and to $K_T = 0.35$ in the special model for one stainless steel EAF (eq. 3). The latter values are in good agreement with the estimated ranges of this study (eq. 24). Concerning the adjusted value of $K_T = 0.35$ for single EAF (eq. 3), it is noted that the mean tapping temperature for the corresponding EAF is very close to reference temperature 1600 °C (temperature in ladle after tapping 1550°C [15]), i.e. correlation between the superheating term (eq. 25) and electric energy demand is rather small.

Tap-to-tap time

Tap-to-tap time ($\Delta t_C = t_s + t_N$) has influence on the specific electric energy demand by all energy sinks of the EAF process that depend on time: off-gas volume flow rate, dust mass flow rate, water cooling system of the furnace and heat radiation. The corresponding term applies in eq. 1 to eq. 4 in cases where power-off time t_N decreases overall EAF energy efficiency TIN.EAF but not particular efficiency factors of energy sources in table 3. The time dependency of the electric energy demand is determined by derivation of eq. 7 after time, eq. 26:

$$\frac{d e_{el}(t)}{dt} = \frac{\dot{e}_{\text{Dust}}(t) + \dot{e}_{\text{Offgas}}(t) + \dot{e}_{\text{Rad}}(t) + \dot{e}_{\text{Cool}}(t) - \dot{e}_{\text{HM}}(t) - \sum \dot{e}_{\text{chem},i}(t)}{\eta_{el}} \quad (26)$$

In eq. 26, the time dependency of the specific electric energy demand to incoming energy flow rates as well as to outgoing energy flow rates is obvious. If preheated scrap is continuously charged to the furnace, an additional term applies to eq. 26. By evaluation of measured energy flow rates and energy balances from 4 furnaces with tapping weights between 70 t and 150 t the time dependency of the specific electric energy demand was estimated to $A_{e_{el}\Delta t}/\Delta t_C = 0.8$ to 1.3 kWh/tmin [21]. In [13], the influence of tap-to-tap-time to the specific

electric energy demand is reported as $Ae_{eU}/At = 0.4$ kWh/tmin at the beginning of the melt-down process and to $Ae_{eI}, At/At = 1.7$ kWh/tmin before tapping. This indicates an important difference in the impact of the period of interruption on the electric energy demand, whether the time-out is required at the beginning or at the end of the melting process. The regression models from Kohle (eq. 1 to eq. 4) quantify the influence of tap-to-tap time as:

$$\frac{\Delta w_{R, \Delta t}}{\text{kWh/t}} = +1 \cdot \frac{t_S + t_N}{\text{min}} \quad (27)$$

This value agrees well with the estimated range from 0.8 to 1.3 kWh/tmin [21] in this study and with the range reported in [13]. For the energy model of the single EAF (eq. 3), the refined coefficient is significantly smaller, 0.43 kWh/tmin, indicating smaller effect of heat time to electric energy demand.

Use of gas burner

Oxy-fuel burners are applied at the EAF to achieve a thermal symmetry in the furnace, to reduce the time of scrap melting and to decrease the electric energy demand. Usually, gas burners are active during the first 5 to 15 minutes after charging, because the efficiency of heat transfer to the scrap pile decreases drastically with increasing metal temperature. Chemical energy of commercially available fuel gases ranges from $h_{u,G} = 9.3$ kWh/m³ to $h_{u,G} = 10.7$ kWh/m³ (10.5 kWh/m³ in eqs. 5 and 6). With the thermal efficiency factors in table 3 ($\eta_G = 50\%$ to 60% , $\eta_{el} \eta_{arc} = 60\%$ to 80%), the efficiency of substitution of electric energy by chemical energy released from combustion of fuel gas is computed, eq. 28:

$$\Delta e_{el,G} = \frac{\eta_G \cdot h_{u,G}}{\eta_{el} \cdot \eta_{arc}} = -6.9 \text{ to } -11.5 \frac{\text{kWh}}{\text{m}^3}. \quad (28)$$

Considering higher efficiency factors for energy transfer from burner and electric arc to scrap and melt due to the cold scrap pile after charging, $\eta_G = 75\%$ to 85% , $\eta_{el} \eta_{arc} = 85\%$ to 95% , $\Delta e_{el,G} = 7.3$ to 10.7 kWh/m³ η_G follows [17]. Following the regression models (eq. 1 to eq. 4) the use of oxy-fuel gas burners decreases the specific electric energy demand:

$$\frac{\Delta w_{R,G}}{\text{kWh/t}} = -8 \cdot \frac{M_G}{\text{m}^3/\text{t}}. \quad (29)$$

The regression coefficient $K_G = -8$ agrees well with the computed ranges in eq. 28 and in [17]. The reduction of tap-to-tap-time ($t_S + t_N$) by use of oxy-fuel burners is taken into account with the corresponding term K_t in eq. 1 to eq. 4.

Oxygen injection by lances

Oxygen is injected into the furnace by lances in order to cut the solid scrap, for decarburization of the metal liquid, to generate foaming slag by combustion of coal and for combustion of coal additives. Alloy elements as P, Al, Si are subject to almost complete oxidation; C, Fe, Mn, Cr, Mo are oxidized at higher oxygen partial pressure. The released total energy from exothermal oxidation reactions depends on chemical composition of ferrous input material, on the mass of charged and injected coal, and on the composition of tapped steel. Total chemical energy input from oxidation reactions varies from 50 kWh/t to 300 kWh/t [e.g. 32]. Oxygen is provided by injectors, lances, and inflow of air. Reaction enthalpies of various oxidation reactions in steel making are listed in table 4. Values in table 4 indicate effective reaction enthalpies between 2.73 kWh/m³O₂ (carbon) and 11.2 kWh/m³O₂ (silicon) depending on composition of scrap and steel and lancing conditions. E.g., $Ah_L = 6.6$ kWh/m³O₂ is nominally released when 1% C and 1% Si is oxidised in steel melt. Precise determination of Ah_L is difficult without considering actual chemical composition and temperature of the multi-component melt.

Table 4. Exothermic oxidation reaction at decarburization and refining of the melt [17, 20]

Chemical reactions in the steel melt					Reaction enthalpy	
Si	+	O ₂	→	SiO ₂	- 8.94 kWh/kg _{Si}	- 11.20 kWh/m ³ O ₂
Mn	+	0.5 O ₂	→	MnO	- 1.93 kWh/kg _{Mn}	- 9.48 kWh/m ³ O ₂
2 Cr	+	1.5 O ₂	→	Cr ₂ O ₃	- 3.05 kWh/kg _{Cr}	- 9.42 kWh/m ³ O ₂
2 Fe	+	1.5 O ₂	→	Fe ₂ O ₃	- 2.05 kWh/kg _{Fe}	- 6.80 kWh/m ³ O ₂
Fe	+	0.5 O ₂	→	FeO	- 1.32 kWh/kg _{Fe}	- 6.58 kWh/m ³ O ₂
C	+	0.5 O ₂	→	CO	- 2.55 kWh/kg _C	- 2.73 kWh/m ³ O ₂
2 Al	+	1.5 O ₂	→	Al ₂ O ₃	- 5.29 kWh/kg _{Al}	- 13.84 kWh/m ³ O ₂
Mo	+	O ₂	→	MoO ₂	- 1.70 kWh/kg _{Mo}	- 7.29 kWh/m ³ O ₂
S	+	O ₂	→	SO ₂	- 2.75 kWh/kg _S	- 3.94 kWh/m ³ O ₂
2 P	+	2.5 O ₂	→	P ₂ O ₅	- 5.54 kWh/kg _P	- 8.58 kWh/m ³ O ₂
Chemical reactions in the gas phase					Reaction enthalpy	
C	+	O ₂	→	CO ₂	- 9.10 kWh/kg _C	- 4.88 kWh/m ³ O ₂
CO	+	0.5 O ₂	→	CO ₂		- 7.01 kWh/m ³ O ₂
H ₂	+	0.5 O ₂	→	H ₂ O		- 5.99 kWh/m ³ O ₂

In [13], the chemical energy that is released by injection of 25 m³/t oxygen into a 100 tEAF is estimated with a realistic mean value: $\Delta h_L = 5.2 \text{ kWh/m}^3 \text{O}_2$ (in eqs. 5 and 6). Substitution of electric energy by chemical energy from oxidation reactions, i.e. $\Delta h_L = 5.2 \text{ kWh/m}^3 \text{O}_2$ [13], is controlled with efficiency factors as given in table 3 ($\eta_L = 70\%$ to 80% , $\eta_{el} \eta_{arc} = 60\%$ to 80%)

$$\Delta e_{el,L} = \frac{\eta_L \cdot \Delta h_L}{\eta_{el} \cdot \eta_{arc}} = -4.3 \text{ to } -6.9 \frac{\text{kWh}}{\text{m}^3} \quad (30)$$

A similar study on 20 EAFs in Japan indicated values for substitution of electric energy from $A_{e,i,L} = -4.7 \text{ kWh/m}^3 \text{O}_2$ to $-6.8 \text{ kWh/m}^3 \text{O}_2$ [13]. Memoli et al. [25] determined a substitution capacity of $A_{e,i,L} = 3.2 \text{ kWh/m}^3 \text{O}_2$. Regression models from Kohle discriminates injected oxygen for lances, burner and post combustion injectors (eq. 1 to eq. 4). From the regression analysis of Kohle (eq. 1 to eq. 4), the corresponding value for substituting electric energy by injection of oxygen is:

$$\frac{\Delta w_R}{\text{kWh/t}} = -4.3 \cdot \frac{M_L}{\text{m}^3/\text{t}} \quad (31)$$

The regression coefficient $K_L = -4.3$ is in the given range of our study. $K_L = -2.1$ is remarkably lower for the single EAF (eq. 3) than for the general model (eq. 4) indicating a considerably lower efficiency of oxygen injection (even lower than $K_{p,C} = -2.8$ for post-combustion). There is evidence that the addition and combustion of coal additives with oxygen has very little effect on electric energy demand (probably due to the positive mixing enthalpy of carbon in steel melt).

As carbon dioxide is not stable in liquid steel, chemical energy from the CO to CO₂ oxidation reaction does not contribute to the substitution of electric energy but increases chemical energy flow rate of off-gas. If chemical energy flow rate of CO gas is not considered as energy loss to off-gas, e.g. in [13], chemical energy input from oxidation of carbon and total energy demand is estimated at lower values. However, injection of oxygen for efficient post-combustion in the EAF vessel may decrease electric energy demand.

Injection of oxygen for post-combustion in the EAF

The objective of post-combustion of CO and H₂ gas component inside the furnace is to provide released reaction enthalpy of the oxidation for melting the scrap in the EAF. Reaction enthalpies of the oxidation reactions of CO and H₂ is $\Delta_r h_{\text{CO}} = -7.01 \text{ kWh/m}^3 \text{O}_2$ and $\Delta_r h_{\text{H}_2} = -5.99 \text{ kWh/m}^3 \text{O}_2$, respectively. Besides oxygen input by post-combustion injectors, oxygen in excess from oxy-fuel burners accounts for effective post-combustion in the EAF. The released reaction enthalpy from post-combustion of off-gas containing, e.g., 25% CO and 10% H₂ [15] is:

$$\Delta_r h_{\text{PC}} = \frac{25 \cdot \Delta_r h_{\text{CO}} + 10 \cdot \Delta_r h_{\text{H}_2}}{35} = -6.8 \frac{\text{kWh}}{\text{m}_{\text{O}_2}^3} \quad (32)$$

As most of the post-combustion takes place above the scrap pile and the liquid metal covered with a slag layer, the thermal efficiency factor of the energy transfer from gas phase to scrap and melt is below $\eta_{\text{PC}} = 50 \%$ [13]. In [22] the maximum thermal efficiency factor is estimated to $\eta_{\text{PC}} = 65 \%$ when cold scrap pile is present and down to 20 % to 30 % when post-combustion occurs above foaming slag. We estimate the substitution effect of post-combustion to electric energy with an average thermal efficiency factor between $\eta_{\text{PC}} = 30 \%$ and 50 % and efficiency factors 60 % η_{el} $\eta_{\text{arc}} < 80 \%$ from table 3:

$$\Delta e_{\text{el, PC}} = \frac{\eta_{\text{PC}} \cdot \Delta_r h_{\text{PC}}}{\eta_{\text{el}} \cdot \eta_{\text{arc}}} = -2.5 \text{ to } -5.6 \frac{\text{kWh}}{\text{m}_{\text{O}_2}^3} \quad (33)$$

The decrease of the specific electric energy demand by post-combustion of off-gases in the EAF was reported to $\Delta e_{\text{el, N}} = -3.1 \text{ kWh/m}^3 \text{O}_2$ maximum [14]. The regression coefficient from Kohle (eq.4) is:

$$\frac{\Delta w_{\text{R, N}}}{\text{kWh/t}} = -2.8 \cdot \frac{M_{\text{N}}}{m_{\text{O}_2}^3 / \text{t}} \quad (34)$$

The regression coefficient of the specific oxygen input for post-combustion in the furnace agrees well with the estimated range of this study (eq. 33).

Input of Direct Reduced Iron (DRI) and Hot Briquetted Iron (HBI)

DRI and HBI are increasingly used as input material besides scrap at the EAF. The driving force behind this development is the increase of EAF steel production that increases the demand for high quality scrap. If low quality scrap is used for EAF steel making, unwanted tramp elements in scrap have to be diluted with highly pure input material. Chemical and physical properties of DRI and HBI may significantly vary due to distinct production technologies, due to various resources of ore with different composition, gangue materials, and degrees of metallization. Table 5 shows the ranges of published chemical compositions of DRI.

Table 5. Chemical and physical properties of DRI [21]

Degree of metallization [%]	Fe _{total} [%]	Carbon [%]	Gangue Material	
			acidic [%]	basic [%]
85-96	86-95	0.1	0.7-6.0	0.2 - 4.8

In order to calculate the specific energy demand of DRI and HBI input the reaction enthalpy of the reduction of iron oxide with carbon of DRI/HBI has to be considered as well as the temperature $T_{\text{DRI/HBI}}$ of hot DRI or HBI input (eq. 35). It is assumed that the iron oxides that is not reduced internally with carbon remains in slag decreasing the metallic yield of the DRI/HBI reduction:

$$e_{\text{DRI/HBI}} = \Delta h_{\text{DRI/HBI}}(T) + x_C \Delta_f h_{\text{FeO} \rightarrow \text{Fe}}(T) - h_{\text{T}_{\text{DRI/HBI}}}(T_{\text{DRI/HBI}}), \quad (35)$$

where the enthalpy $\Delta h_{\text{DRI/HBI}}$ of the mixture is computed from the metallic and oxide components of DRI/HBI:

$$\begin{aligned} \Delta h_{\text{DRI/HBI}}(T) = & x_{\text{Fe}} \Delta h_{\text{Fe}}(T) + x_{\text{C}} \Delta h_{\text{C}}(T) + x_{\text{FeO}} \Delta h_{\text{FeO}}(T) + x_{\text{SiO}_2} \Delta h_{\text{SiO}_2}(T) \\ & + x_{\text{Al}_2\text{O}_3} \Delta h_{\text{Al}_2\text{O}_3}(T) + x_{\text{CaO}} \Delta h_{\text{CaO}}(T) + x_{\text{MgO}} \Delta h_{\text{MgO}}(T) \end{aligned} \quad (36)$$

When considering the effects of DRI/HBI addition to the energy balance of the EAF process, it must be noted that with DRI/HBI the addition of slag formers will increase and the yield of ferrous input material will decrease. Basic slag formers are added with a ratio of 2.5 : 1 to the acidic gangue materials of DRI/HBI. The change of specific energy demand with addition of DRI/HBI is calculated as, eq. 37:

$$\Delta e_{\text{el}} = \frac{[e_{\text{DRI/HBI}}(T) + e_{\text{Z,DRI/HBI}}(T)] - [e_{\text{Scrap}}(T) + e_{\text{Z,Scrap}}(T)]}{\eta_{\text{el}} \cdot \eta_{\text{arc}}} \quad (37)$$

The change of electric energy demand when scrap is substituted with DRI/HBI does not only depend on chemical and physical properties of DRI/HBI (i.e. chemical composition, degree of metallization, temperature) but also on chemical and physical properties of the substituted scrap (e.g. size, specific surface, chemical impurities). Low quality of scrap causes low values of metallic yield and higher input of slag formers for compensation. The change of specific electric energy demand with input of DRI/HBI at 25 °C varies according to ranges in table 5 [21]:

$$\Delta e_{\text{el}} = -70 \text{ to } +80 \frac{\text{kWh}}{\text{t}}. \quad (38)$$

This value is compared to the regression coefficient in eq. 4 corresponding to input of DRI/HBI:

$$\frac{\Delta w_{\text{R,DRI/HBI}}}{\text{kWh/t}} = 80 \cdot \frac{G_{\text{DRI/HBI}}}{G_{\text{A}}} \quad (39)$$

The large computed range of values in eq. 38 indicates that the regression coefficient in eq. 39 has to be adjusted to the chemical composition and temperature of DRI/HBI used at the specific EAF.

Input of shredder

The decrease of specific electric energy demand with input of shredder is explained with an increased melting rate of shredder due to the high specific surface. The influence of different sorts of scrap and their mixture on the electric energy demand was studied with a regression model based on 2894 heats [23]. The difference between the average of all sorts of scrap and the shredder ranges from $\Delta e_{\text{Shr}} = -58 \text{ kWh/t}_{\text{Scrap}}$ to $-82 \text{ kWh/t}_{\text{Scrap}}$ [23]. [24] reported a difference of $\Delta e_{\text{Shr}} = -68 \text{ kWh/t}_{\text{Scrap}}$. However, this value depends on purity of shredder, on total input mass of shredder, on the scrap mix, on the distribution of shredder to the charging buckets. [29] assessed the influence of various scrap mixtures on EAF cost balance and reported reduction of electric energy demand from $382 \text{ kWh/t}_{\text{Scrap}}$ for steel scrap to $350 \text{ kWh/t}_{\text{Scrap}}$ for pure shredder or chippings, $\Delta e_{\text{Shr}} = -32 \text{ kWh/t}_{\text{Scrap}}$. Thus, the reduction of electric energy demand by use of shredder ranges from -32 kWh/t to -82 kWh/t . Following the regression model from Kohle (eq.4), the specific electric energy demand decreases with the input of shredder:

$$\frac{\Delta w_{\text{R,Shr}}}{\text{kWh/t}} = -50 \cdot \frac{G_{\text{Shr}}}{G_{\text{A}}} \quad (40)$$

When comparing the regression coefficient in eq. 10 with the reported values electric of energy reduction, it has to be taken into account that the regression coefficient is K_{shr} related to tapping weight. Using values for yield from 86 % to 92 % [12, 13], $K_{shr} = 50 \text{ kWh/t}_{scrap}$ in eq. 40 corresponds to $-54 \text{ kWh/t}_{scrap}$ to $-58 \text{ kWh/t}_{scrap}$. The regression coefficient for the input of shredder in eq. 40 agrees well the reported values from [23], [24] and [29]. By implementation of a more sophisticated model of scrap type input as suggested by [23, 24] the regression model (eq. 4) may be applicable in more detail to EAF steel making.

Input of hot metal

The use of hot metal causes a dilution of unwanted tramp elements from scrap input material and decreases the specific electric energy demand with an increased enthalpy of input material. Hot metal is usually charged to the EAF at 1150°C to 1350°C [14]. At temperatures between 1150°C and 1350°C the enthalpy of hot metal ranges from 255 kWh/t_{HM} to 301 kWh/t_{HM} (Fig. 7). The change of specific electric energy demand with use of hot metal is therefore calculated with efficiency factors $60\% < \eta_{el} \eta_{arc} < 80\%$ from table 3, eq. 41:

$$\Delta e_{el, HM} = \frac{\Delta h_{HM}}{\eta_{arc} \eta_{el}} = -319 \text{ to } -502 \frac{\text{kWh}}{t_{HM}} \quad (41)$$

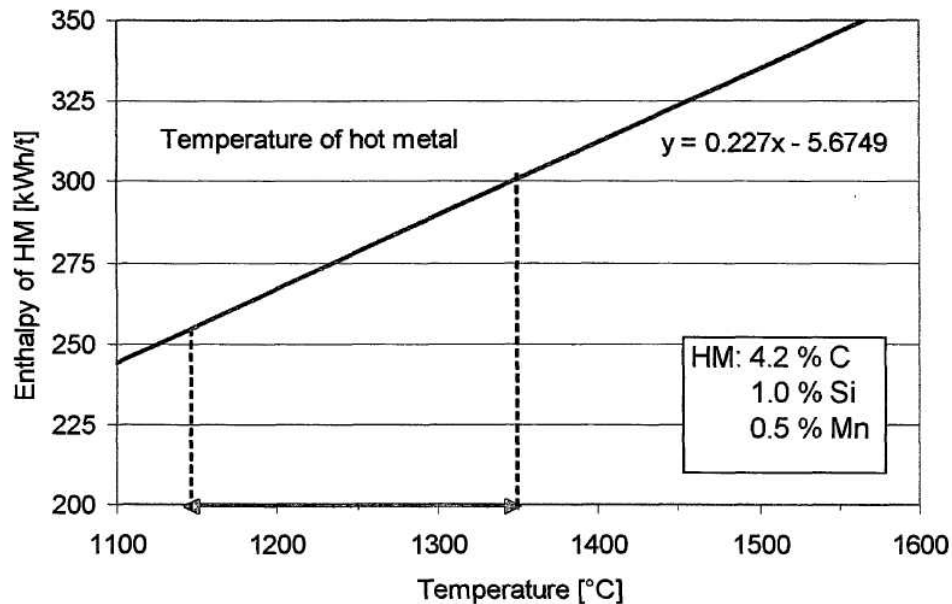


Fig. 7. Enthalpy of hot metal as function of temperature [20]

Because the use of hot metal grants EAF operation with high share of liquid phase, foaming slag technology is always applied and, consequently, $\eta_{el} \eta_{arc}$ close to the upper bound near 0.8 is presumed. Input temperature of hot metal is also important for decrease of electric energy demand. Common input temperatures are near the lower bound of temperature range. The statistical model of Kohle (eq. 4) considers the input of hot metal with the following term, eq. 42:

$$\frac{\Delta w_{R, HM}}{\text{kWh/t}} = -350 \cdot \frac{G_{HM}}{G_A} \quad (42)$$

This regression value $K_{HM} = 350$ is in good agreements with the lower bound of values for substitution of electric energy by use of hot metal (eq. 42), i.e. high efficiency of the energy transfer from arc to melt is indicated. $K_{HM} = 350$ agrees very well with heat data with varying share of hot metal input [17, 31]. The regression model may be applied with higher accuracy if the temperature of hot metal input is included in the model. The additional influence on specific electric energy demand by additional chemical energy of hot metal is taken into account with the corresponding increase of oxygen input und reduction of tap-to-tap time. The input of pig iron is not considered in the model from Kohle [5, 7-9], but in the model from Adams, eq. 5 and eq. 6, [13-14]. Kohle considers pig iron as ferrous input with favourable impact on electric energy demand completely modelled with higher input of oxygen.

Water cooling of the EAF shell

Using measured data of temperature and volume flow rates of cooling water the energy flow rate at EAF wall, EAF cover and at the off-gas cooling system was determined for 4 EAFs. These data lead to the incorporation of an additional term for EAF cooling system into the Kohle regression formula (eq. 4):

$$\frac{\Delta w_R}{\text{kWh/t}} = +NV \cdot \frac{W_v - W_{vm}}{\text{kWh/t}} \quad (43)$$

NV is a specific furnace factor that ranges from 0.2 to 0.4. W_v denotes the measured specific heat flow to the cooling system of the EAF per heat in kWh/t. The concept of this study using weighing efficiency factors of energy transfer to the melt, $\eta_i < 1$, considers a priori all energy losses to off-gas, slag and cooling system. Therefore, the term for water cooling is redundant and must not included to eq. 4 from a thermodynamic point of view of the system as shown in fig. 5. However, differences of process parameters and EAF equipment from EAF to EAF the thermal efficiency values η_i in table 3 may vary to a significant extent. In this case, NV may represent a correcting factor of all other regression coefficients for each furnace.

Conclusion

Based on complete mass and energy balances of the EAF process and data from the literature, the influence of various input materials (scrap, shredder, slag formers, DRI, HBI hot metal) and process parameters (e.g. oxygen injection, tap-to-tap time, tapping temperature) on the specific electric energy demand is studied. Resulting correlation coefficients are compared to regression coefficients that were derived by linear regression of comprehensive datasets of EAF heat data from Kohle, and Adams. The overall good agreements between estimated ranges of values and refined values from regression analysis confirm the linear approach of the models from Kohle and the correct choice of most of the EAF parameters. For some terms, the refined coefficients differ from the thermodynamic estimations. E.g., the influence of slag formers on electric energy demand is estimated to higher values from linear regression to operation data than from thermodynamic calculations. In contrary, the computed influence of yield loss (non-ferrous input with scrap etc.) is lower for the regression analysis than for the thermodynamic calculations. For other terms further refinements are suggested for future adjustments and higher precision of the model, e.g. scrap grades and input temperature of hot metal. As some important factors are related to tapping weight, which is related to the remains and heel, the regression models applies to average values for a number of heats, but not to single heats. On the other hand, the values of regression coefficients depend on the particular entries of the database. Standard deviation for single heats is 25 kWh/t and 10 kWh/t for average values [9]. The comparison of calculated values from a thermodynamic analysis of energy transfer with the regression coefficients is summarized in table 6.

Regression coefficients	1992 (eq. 1)	1999 (eq. 7)	2002 (eq. 4)	(eq. 3)	This work
Constant	+300	+300	+375	+391	+380 to +413
Specific ferrous Input	+900	+900	+400	+450	+600 to +1000
Slag formers	+1600	+1600	+1000	+800	+548 to +730
Tapping temperature	+0.70	0.70	+0.3	+0.35	+0.29 to +0.38
Tap-to-tap time	+0.85	+0.85	+1.00	+0.43	+0.4 to +1.7
Oxy-fuel burner	-8.0	-8.0	-8.0	-	-6.9 to -11.5
Injected lance oxygen	-4.3	-4.3	-4.3	-2.1	-4.3 to -6.9
Oxygen post-combust.	-	-2.8	-2.8	-	-2.5 to -5.6
Input of DRI/HBI	-	+80	+80	-	-70 to +80
Input of hot metal	-	- 300	-350	-	-319 to -512
Input of shredder	-	-	-50	-	-82 to -32
Furnace cooling system	-	-	0.2 to 0.4	-	0

Literature

- [1] Treppschuh, F.; Bandusch, L.; Fuchs, H.; Schubert, M.; Schaefers, K.: Neue Technologien bei der Elektrostahlerzeugung - Einsatz und Ergebnisse, Stahl und Eisen, Vol. 123, 2003, No. 2, pp. 53-57
- [2] Ehle, J.; Knapp, H.; Muller, H.: Produktion, Kosten und Umwelteinflüsse beim Betrieb eines Fingerschachtofens, Stahl und Eisen, Vol. 121, 2001, No. 3, pp. 45-50
- [3] Szekely, J.; Trapaga, G.: Zukunftsperspektiven für neue Technologien in der Stahlindustrie, Stahl und Eisen, Vol. 114, 1994, No. 9, pp. 43-55
- [4] Pfeifer, H.: Energy Balance of the Electric Arc Furnace, VDEh Seminar "Electrical Engineering of Arc Furnaces", Luxemburg, 2001
- [5] Kohle, S.: Improving the productivity of electric arc furnaces, Bericht 2.32.007, Betriebsforschungsinstitut, 2003
- [6] Bowman, B.; Lugo, N.; Wells, T.: Influence of tap carbon and arc voltage on electrode and energy consumption. Proc. 58th Electric Furnace Conference, 2000, Orlando, USA, p. 649-657
- [7] Kohle, S.: Improvements in EAF operating practices over the last decade. Proc. 57th Electric Arc Furnace Conf., 1999, Pittsburgh, USA, pp. 3-14
- [8] Kohle, S.: Einflüsse des elektrischen Energieverbrauchs und des Elektrodenverbrauchs von Lichtbogenöfen, Stahl und Eisen, Vol. 112, 1992, No. 11, pp. 59-67
- [9] Kohle, S.: Recent improvements in modelling energy consumption of electric arc furnaces, Proc. 7th Europ. Electric Steelmaking Conf., 26-29 May 2002, Venice, Italy
- [10] Baker, Briggs, Lewis, Capodilupo, Repeeto, Gonthier, Zbaczyniak, Kleimt, Kohle, Knoop, Mosel, Oberhauser Ecological and economical EAF steelmaking, European Commission Report EUR 19480 EN, 2001
- [11] Kleimt, B.; Kohle, S.: Power consumption of electric arc furnaces with post-combustion, MPT International, 1997, No. 3, pp. 56-57
- [12] Pfeifer, H.: Stoff- und Energiebilanz, in Heinen, K.-H. (Ed.), Elektrostahlerzeugung, Verlag Stahleisen, Düsseldorf, 1997, pp. 112-127
- [13] Adams, W.; Alameddine, S.; Bowman, B.; Lugo, N.; Paege, S.; Stafford, P.: Factors influencing the total energy consumption in arc furnaces, Proc. 59th Electric Arc Furnace

- Conf., 11-14 Nov. 2001, Phoenix Arizona, pp. 691-702
- [14] Adams, W.; Alameddine, S.; Bowman, B.; Lugo, N.; Paege, S.; Stafford, P.: Total energy consumption in arc furnaces, MPT International, 2002, No. 6, pp. 44-50
 - [15] M. Kirschen, V. Velikorodov, H. Pfeifer, R. Kiihn, S. Lenz, J. Loh, K. Schaefer, Off-gas measurements at the EAF primary dedusting system. Proc. 8th Europ. Electric Steelmak-ing Conf., 8-11 May 2005, Birmingham, England
 - [16] Kirschen, M.; Pfeifer, H.; Wahlers, F.-J.: Mass and Energy Balances of Stainless Steel EAF, Proc. 7th Europ. Electric Steelmaking Conf., 26-29 May 2002, Venice, Italy
 - [17] Pfeifer, H.; Kirschen, M.: Thermodynamic analysis of EAF energy and comparison with a statistical model of electric energy demand. Proc. 7th Europ. Electric Steelmaking Conf., 26-29 May 2002, Venice, Italy
 - [18] Jones, J. A. T.: Understanding energy use in the EAF, Proc. 60th Electric Arc Furnace Conf., 10 -13 Nov. 2002, San Antonio Texas, pp. 141 -154
 - [19] Jones, J. A. T.: Understanding energy use in the EAF: Practical considerations and exceptions to theory, ISSTech Conference Proceedings, 27.-30. April 2003, Indianapolis, Indiana, pp. 591-602
 - [20] Knacke, O.; Kubaschewski, O.; Hesselmann, K.: Thermochemical properties of Inorganic Substances, Springer Verlag, 1991 [21] Simoes, J.-P.: Theoretische Untersuchung zum elektrischen Energiebedarf der Lichtbogenofen in derStahlindustrie, Diploma thesis, Institut fur Industrieofehbau undWar-metechnik, RWTH Aachen, April 2003
 - [22] Jones, T.; Oliver, J.F.: A review of post-combustion in the EAF - A theoretical and technical evaluation, Proc. 5th Europ. Electric Steel Congress, 1995, Paris, France, pp. 83-97
 - [23] Maiolo, J.A.; Evenson, E. J.: Statistical Analysis and Optimisation of EAF Operations, 59th Electric Arc Furnace Conf., 11-14 Nov. 2001, Phoenix, Arizona, pp. 105-112
 - [24] Bokan, R.; Jones, J.; Kemeny, F.: Improved Understanding of Feed Materials with Respect to Optimizing EAF Operations, Proc. 60th Electric Arc Furnace Conf., 10-13 Nov. 2002, San Antonio, Texas, pp. 47 - 57
 - [25] Memoli, F.; Koester, V.; Giavani, C: Benchmark study of the EAF plants using KT injection system, Proc. 2nd Conf. New Developments in Metallurgical Process Technology, 19-21. Sept. 2004, Riva del Garda, Italy
 - [26] Kirschen, M.; Velikorodov, V.; Pfeifer, H.; Wahlers, F.-J.: Modelling and optimisation of EAF dedusting system, Proc. 2nd Conf. New Developments in Metallurgical Process Technology, 19-21. Sept. 2004, Riva del Garda, Italy
 - [27] Pujadas, A.; McCauley, J.; Iacuzzi, M.: EAF energy optimisation at Nucor Yamato Steel, ISSTech Conference Proceedings, 27.-30. April 2003, Indianapolis, Indiana, pp. 391-402
 - [28] Ameling, D. u. a.: Untersuchungen zur Schaumslagkebildung im Elektrolichtbogen-ofen, Stahl u. Eisen, Vol. 106, 1986, pp. 625-630
 - [29] Klein, H.H.; Schindler, J.E.: Metallurgie bei Schrotteinsatz, in Heinen, K.-H. (Ed.), Elektrostahlerzeugung, Verlag Stahleisen, Dusseldorf, 1997, pp. 473-477
 - [30] Heard, R.A.; Roth, J.L.: Optimizing energy in electric furnace steelmaking. Iron and Steel Engineer, April 1998, pp. 36-40
 - [31] Scheidig, K.: Einsatzstoff Roheisen. in Heinen, K.-H. (Ed.), Elektrostahlerzeugung, Verlag Stahleisen, Dusseldorf, 1997, pp. 77-85
 - [32] Kuhn, R.: Untersuchungen zum Energieumsatz in einem Gleichstromlichtbogenofen zur Stahlerzeugung. PhD dissertation, Technical University Clausthal, 2003

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Equivalent Circuit-Diagram of AC-Furnaces

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2 Equivalent circuit diagram of AC-furnaces

Prof. Dr.-Ing. Klaus Timm

1 Single-phase equivalent circuit diagram

2 Three-phase equivalent circuit diagram

3 Balanced furnace operation

4 Unbalanced furnace operation

5 Electrical balancing

1 Single-phase equivalent circuit diagram

The electrical behavior of AC furnaces is dependent on the transformer voltages, the geometric arrangement of the high-current conductors and the resulting reactance's. For the purpose of simplification, the equivalent circuit diagram for an AC EAF shall first be derived from a *single-phase electric arc furnace* with an assumed bottom electrode, **figure 1a**. This case is identical with the balanced AC operation that will be dealt with later.

The transformer voltage u_{Str} comprises by the electric arc voltage u_B , the voltage drop u_V , at the ohmic resistance of the circuit R_V and the voltage u_L induced to the self-inductance L of the current loop 1-M by the magnetic alternating field (**figure 1b**). According to Kirchhoffs voltage law, the relationship between the currents and voltages can be described by the following differential equation:

$$u_{Str} = u_V + u_L + u_B = i \cdot R_V + L \frac{di}{dt} + u_B \quad .$$

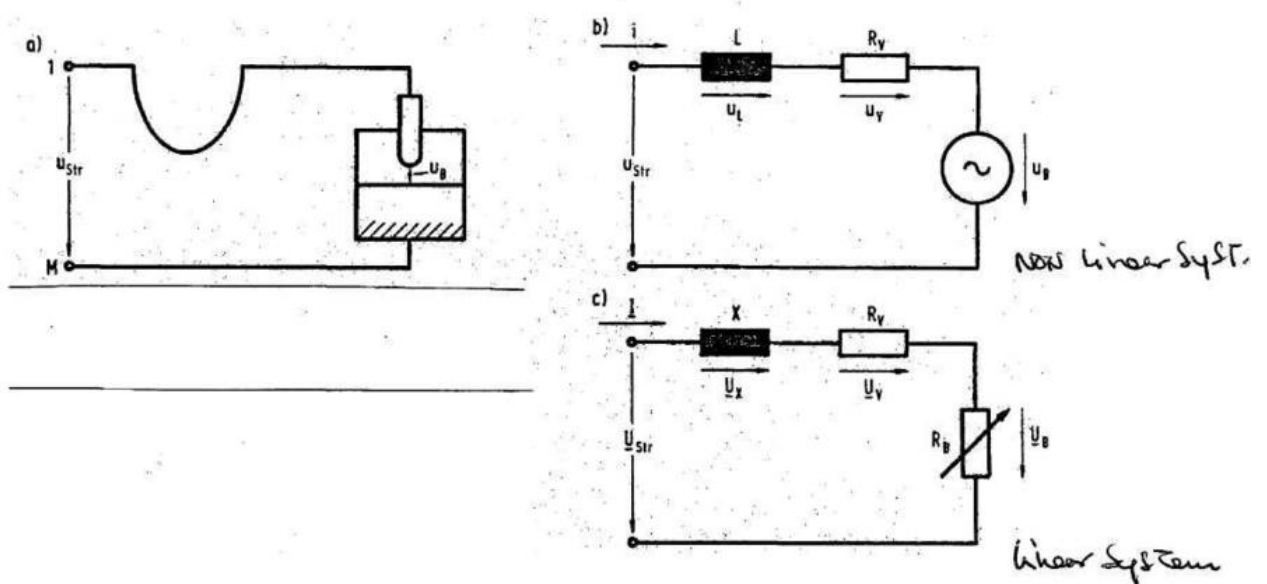


Figure 1: Single-phase AC furnace with bottom electrode. Circuit layout (a), equivalent circuit (b) and simplified linearized equivalent circuit (c)

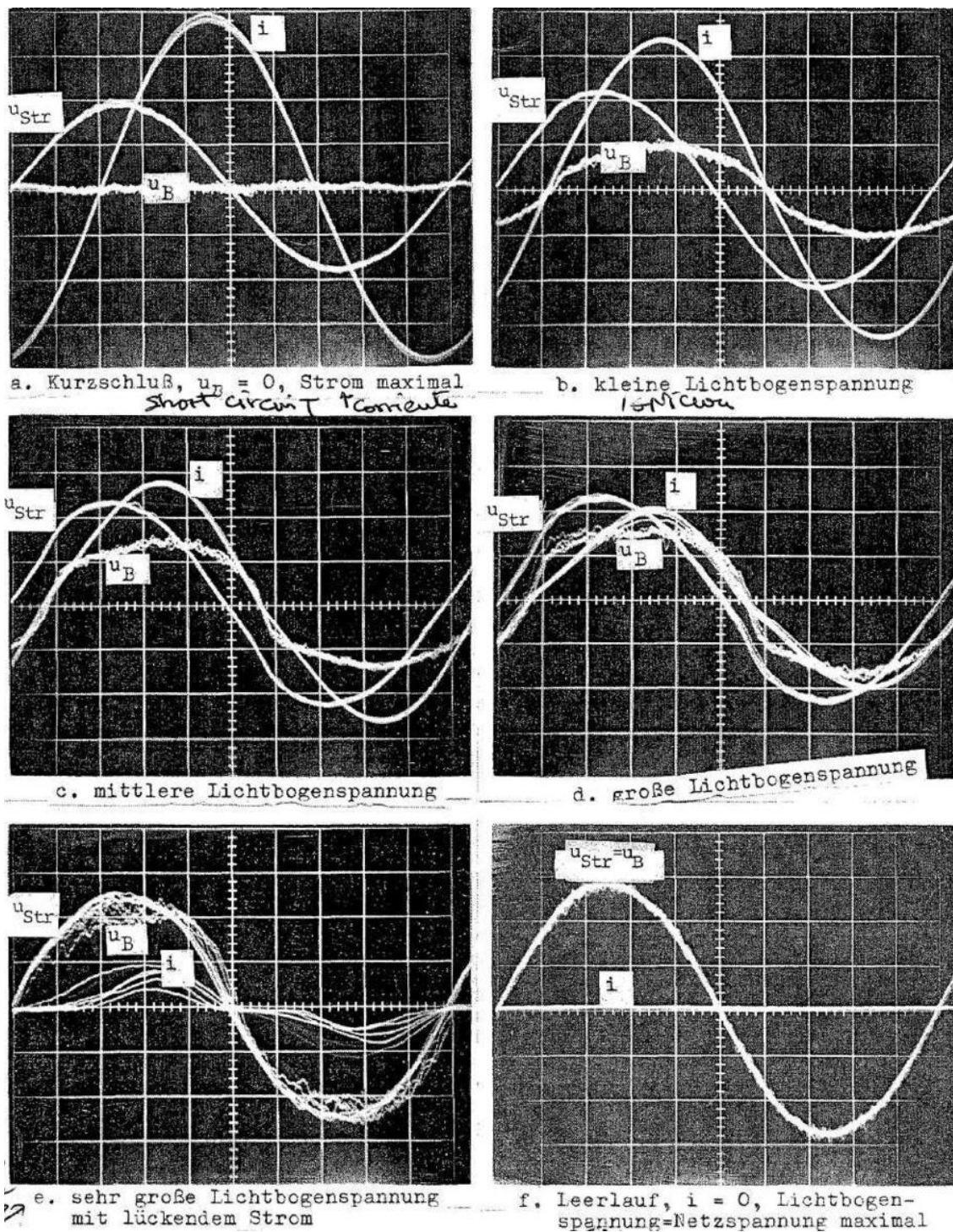


Figure 2: Time records of arc voltage u_B , current i and transformer phase voltage u_{Str} in a single-phase circuit with arc, after moving the electrode

- a. short circuit $u_B = 0$, current maximum
- b. low arc voltage
- c. middle value of arc voltage
- d. high value of arc voltage
- e. stability threshold
- f. idle mode, $i = 0$, maximum arc voltage $u_B = u_{Str}$

Figure 2 shows the development of the arc voltage u_B , current i and phase voltage u_{Str} during different operating stages in a single-phase circuit containing one electric arc:

Figure 2a: Diving the electrode in the molten bath causes a *short circuit* $u_B = 0$. The short-circuit current i is maximum, completely sinusoidal and lags behind the voltage by almost, 90° .

Figure 2b: Upon removal of the electrode from the bath, an electric arc is ignited. The arc voltage is non-sinusoidal and in phase with the current.

Figures 2c, d: The current i and the phase angle (p between the phase voltage u_{Str} and the arc voltage u_B) decrease with increasing arc voltage u_B . At the same time arc voltage fluctuations occur, arcing is becoming more erratic.

Figure 2e: Beyond a certain arc length, stable arcing is no longer possible. Ignition sometimes takes place at a considerable delay. The *stability threshold* is reached.

Figure 2f: If the arc length is further increased, the electric arc extinguishes. As $i = 0$, $u_{Str} = u_B$ The furnace runs in the *idle mode* (power off).

Figure 2 shows that currents and voltages in circuits containing electric arcs are non-sinusoidal and that their representation in the time domain is still quite confusing.

For clarification purposes, in the following we will linearize the equivalent circuit diagram by replacing the non-linear characteristic of the electric arc by a linear, variable resistance R_B (**figure 1c**). In this way the electrical variables can be comfortably calculated by means of the *complex calculation* and represented as complex phasors.

However, for this simplification it must be considered that due to the non-sinusoidal arc voltage the current contains harmonics in addition to the fundamental 50 Hz oscillation. These harmonics cause an additional voltage drop at the inductor of the high-current system. Also the non-stationary behavior of the electric arcs causes variations in the electric parameters. Both effects lead to an *increased operating reactance* of the high-current system, primarily at the start of melting and with long electric arcs. This effect shall be neglected for the moment, but will be dealt with later on.

The electric quantities from the linearized equivalent circuit diagram (**figure 1c**) can be described by means of the symbolic method which transfers the electrical quantities from the time domain to the complex domain, **table 1**.

Time domain	Complex domain
$u_V = i R_V$	$\underline{U}_V = \underline{I} \cdot R_V$
$u_L = L \frac{di}{dt}$	$\underline{U}_L = \underline{I} \cdot j\omega L = \underline{I} \cdot jX$
u_B	$\underline{U}_B = \underline{I} \cdot R_B$

Table 1: Electrical quantities in the time and complex domain

At the same time, the mesh equation - above represented as a differential equation - becomes a complex equation from which the current $\underline{I}$ can be easily calculated:

$$\begin{aligned}\underline{U}_{Str} &= \underline{U}_V + \underline{U}_B + \underline{U}_X , \\ &= \underline{I}(R_V + R_B + jX) = \underline{I} \cdot \underline{Z} . \\ \underline{Z} &= R_V + R_B + jX\end{aligned}$$

$\underline{Z}$ is the impedance of the electric circuit and

$$X = \omega L$$

X the reactance, ω is the angular velocity whose relationship with the frequency f is as follows:

$$\omega = 2 \pi f$$

The value of the impedance is

$$Z = \sqrt{(R_V + R_B)^2 + X^2} ,$$

and its phase is

$$\varphi = \arctan X / (R_V + R_B)$$

For the furnace current $\underline{I}$

$$\underline{I} = U_{Str} / \underline{Z}$$

the value for I is accordingly

$$I = U_{Str} / Z = U_{Str} / \sqrt{(R_V + R_B)^2 + X^2} .$$

It lags behind the phase voltage by the above phase angle

$$\varphi = \arctan X / (R_V + R_B)$$

Figure 3 shows the respective vector diagram for all voltages and currents. This vector diagram is a simpler representation of all voltages and currents than the line diagram in **figure 2**.

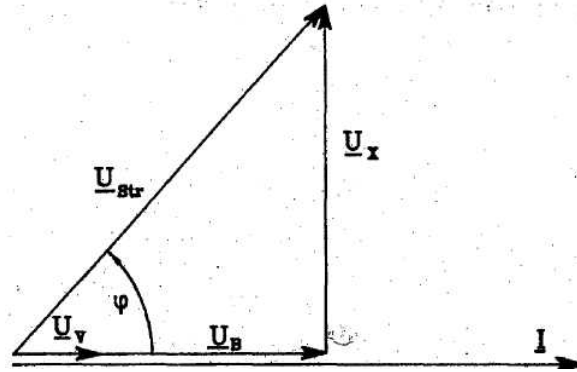


Figure 3: Phasor diagram of voltages and current for a single-phase AC EAF

2 Three-phase equivalent circuit diagram

For the description of the AC electric arc furnaces a three-phase equivalent circuit diagram has proved useful, whose reactance's are defined by the magnetic coupling of the three high-current loops from the outgoing transformer circuit. The equivalent circuit diagram consists of three phases, with the inductance, loss resistance and arc voltage source connected in series and star-connected in the neutral point 0 of the furnace vessel earth (**figure 4a**).

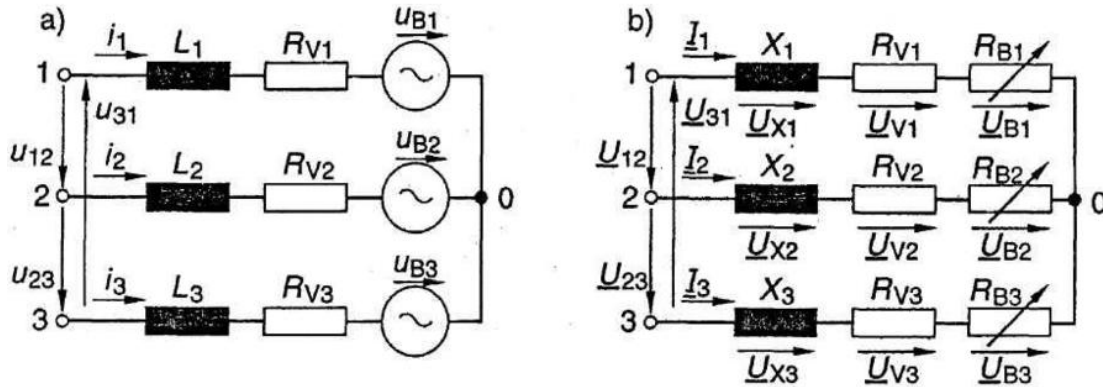


Figure 4: Equivalent circuit (a) and simplified linearized equivalent circuit (b) of the three-phase arc furnace

As in the alternating current furnace there is no bottom electrode, the current coming in through one phase goes out through the other phases. Thus,

$$i_1 + i_2 + i_3 = 0.$$

Changing the electric arc length in one phase thus leads to current changes in all phases. Therefore the currents are coupled. This coupling has negative effects on the electric behavior and the furnace control.

The *effective inductances* of the high-current phases (**figure 4a**) are the mutual inductance's between two high-current loops each:

$$L_1 = M_{12,13}, L_2 = M_{23,21}, L_3 = M_{31,32} \quad .$$

In **figure 5** the term mutual inductance is derived using the magnetic flux linkage between two different electric circuits. The voltage induced into loop 1-2 is made up by two portions caused by the fictitious loop currents i_{13} and i_{23} . The mutual inductance's thus have the same effect as concentrated self-inductance's L_1 and L_2 in phases 1 and 2 (**figure 5c**).

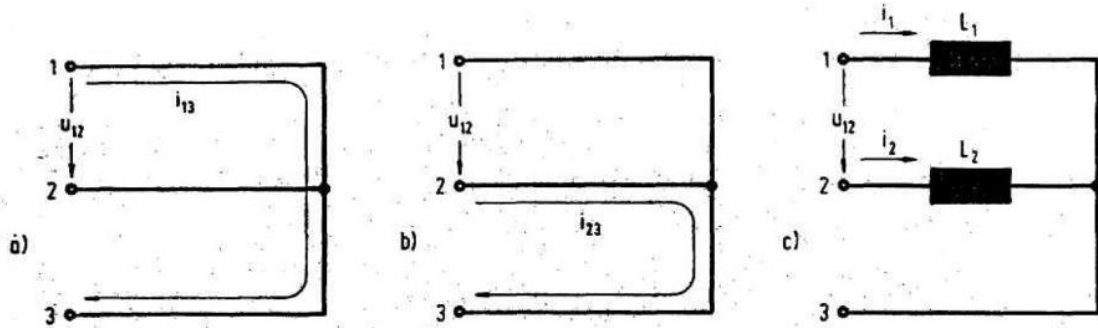


Figure 5: Induced voltages in the loop 1-2, caused by the current loops i_{13} (a), i_{23} (b) and by superposition (c)

By introducing linear arc resistance's R_B and operating reactance's X the equivalent circuit diagram of the AC furnace can be linearized in the same way as in the single-phase example, **figure 4b**. With the phase impedance's being

$$\underline{Z}_1 = R_{V1} + R_{B1} + jX_1$$

$$\underline{Z}_2 = R_{V2} + R_{B2} + jX_2$$

$$\underline{Z}_3 = R_{V3} + R_{B3} + jX_3$$

the following equation system results for the phase-to-phase voltages:

$$\underline{U}_{12} = \underline{I}_1 \underline{Z}_1 - \underline{I}_2 \underline{Z}_2$$

$$\underline{U}_{23} = \underline{I}_2 \underline{Z}_2 - \underline{I}_3 \underline{Z}_3$$

$$\underline{U}_{31} = \underline{I}_3 \underline{Z}_3 - \underline{I}_1 \underline{Z}_1$$

The phase voltages of the furnace are defined as:

$$\underline{U}_{10} = \underline{I}_1 \underline{Z}_1$$

$$\underline{U}_{20} = \underline{I}_2 \underline{Z}_2$$

$$\underline{U}_{30} = \underline{I}_3 \underline{Z}_3$$

3 Balanced furnace operation

The *electrically balanced operation of the furnace* is of utmost importance, therefore this state should be tried to be achieved at all times during furnace operation. It is assumed that the reactance's, loss resistance's, arc lengths - i.e. the electric arc resistance's - are of the same magnitude:

$$\underline{X}_1 = \underline{X}_2 = \underline{X}_3 = X ,$$

$$R_{V1} = R_{V2} = R_{V3} = R_V ,$$

$$R_{B1} = R_{B2} = R_{B3} = R_B ,$$

In this case also the impedance's of all phases are the same:

$$\underline{Z} = R_V + R_B + jX , Z = \sqrt{(R_V + R_B)^2 + X^2} .$$

Furthermore, the phase voltages are identical and smaller than the phase-to-phase voltages U by the factor $\sqrt{3}$:

$$U_{10} = U_{20} = U_{30} = U_{Str} = U / \sqrt{3} .$$

In the case of a balanced state the phase diagram shown in **figure 6** represents the situation in the AC furnace. In all phases it shows the same states as in the single-phase furnace (**figure 3**). The only difference is the position of the potential 0 of the free neutral point in the middle of the triangle.

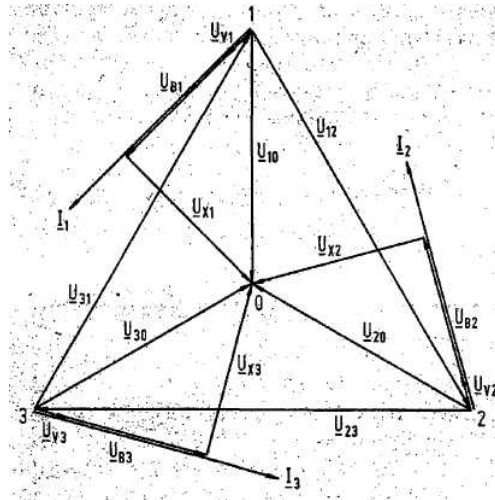


Figure 6: Phasor diagram of the electrically balanced AC arc furnace

In the case of *balanced* state in all phases the currents are

$$I = \frac{U}{\sqrt{3} Z} = \frac{U}{\sqrt{3} \sqrt{(R_V + R_B)^2 + X^2}} .$$

The total *apparent power*

$$S = \sqrt{3} U I$$

consists of the reactive power of the EAF needed for the build-up and removal of the magnetic fields

$$Q = \sqrt{3} U I \sin \varphi = 3 I^2 X$$

and the *active power*

$$P = \sqrt{3} U I \cos \varphi = P_V + P_B .$$

The relationship between these power types is shown in **figure 7**

$$S^2 = P^2 + Q^2 .$$

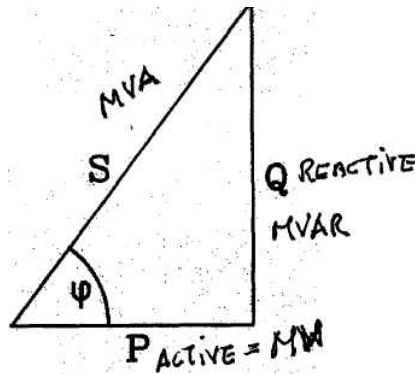


Figure 7: Relationship between P , Q and S

The active power results from the individual loss power values

$$P_V = 3 I^2 R_V$$

and the plasma power of electric arcs

$$P_B = 3 I^2 R_B$$

The power factor of the electric arc furnace

$$\cos \varphi = P / S = \frac{P}{\sqrt{3} U I} .$$

4 Unbalanced furnace operation

The electrically unbalanced operation of the alternating current EAF is much more difficult to handle than the balanced one, see the paper of Dr. *Kohle*. In the following we will discuss two typical operating situations that occur during the start of a heat.

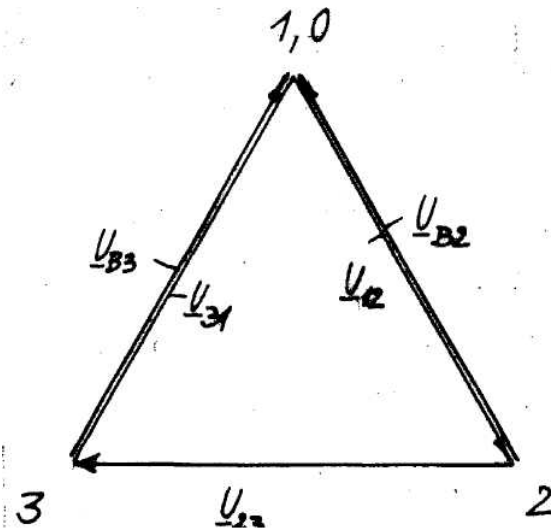


Figure 8: Phasor diagram of the AC EAF without currents, when electrode 1 hits the scrap

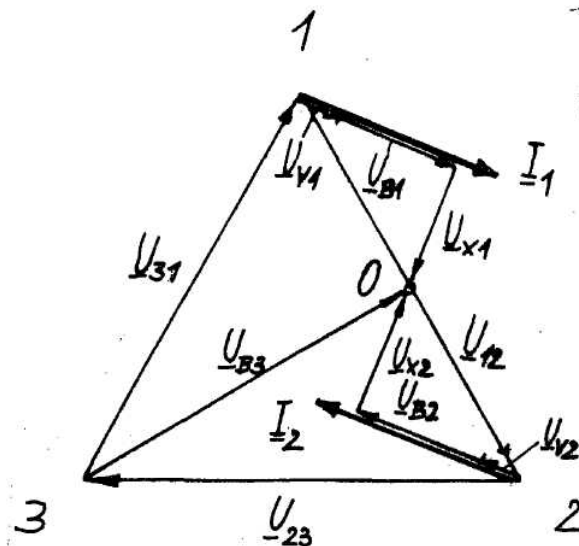


Figure 9: Phasor diagram of the AC EAF in the two phase mode with $I_3 = 0$

The first case describes the situation of the first electrode (phase 1) hitting the scrap when starting the boring period (**figure 8**). As there is no closed circuit, the free neutral point 0 of the furnace moves to the potential of the line conductor 1. As the furnace hearth is earthed, at

the other two phases the line-to-line voltage is available as ignition voltage for the electric arcs. This facilitates the igniting process

$$U_{B1} = 0, U_{B2} = U_{12} = U, U_{B3} = U_{31} = U.$$

As soon as the second electrode (phase 2) hits the scrap, there is a closed circuit. The arcs 1 and 2 ignite. This two-phase operation is illustrated in the phasor diagram in **figure 9**. The neutral point 0 is between the potentials 1 and 2. The phase voltage of each current-conducting phase is half the phase-to-phase voltage. In the third, non-current-conducting phase the arc voltage corresponds to the height of the triangle of the phase-to-phase voltages.

$$U_{B3} = \frac{U}{2} \sqrt{3}.$$

5 Electrical Balancing

For electric arc furnaces with a conventional wall lining the "hot phase", i.e. premature lining wear in the vicinity of the electric arc, is an operating problem (**figure 10**). This is due to the fact that the distribution of the electric power in the furnace is very difficult to measure and the thermal wear pattern is also determined by non-electric effects, e.g. the position of the dust removal aperture in the roof.

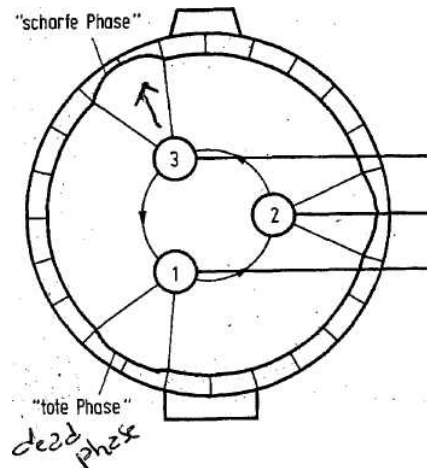


Figure 10: Unbalanced refractory wear with hot and dead phase

Unbalanced states of operation above all occur in electric arc furnaces with unbalanced reactance's, e.g. in the case of a coplanar conductor arrangement. If in such furnaces with balanced line voltages *identical arc resistance's* are set, this will lead to unbalanced phase currents. Whereas in a normal phase sequence 1-2-3, I_1 is minimum (dead phase), I_2 or I_3 - depending on the relationship between the active and reactive power - reach a maximum (sharp phase) (**figure 10**). The currents in the line conductors, I_1 and I_3 , switch values in the case of an inversion of the phase sequence. Of the three variables current, active power and refractory factor only *one* at a time can be balanced through the electric arc length. The other variables inevitably remain unbalanced. Due to the unbalanced refractory factors, e.g. balanced currents inevitably result in unbalanced refractory wear.

The differences in reactance's in coplanar conductor systems can be balanced by rearranging them into a triangular form or installing additional reactance's.

Active balancing entails the removal of the differences in reactance's by unbalanced line voltages and the setting of balanced variables in the electric arcs. An electric balance can only be achieved if the setting of the working point is reliably monitored by high-precision measuring techniques.

With balanced reactance's the electric balance of arc furnaces can be easily achieved: Setting identical furnace currents results in a balanced state of all electric variables. However, also in a state of balanced power unbalanced wear of the wall lining in the vicinity of an electrode can sometimes be observed. This is due to the fact that the thermal pattern of an electric arc furnace does not fully conform with the power distribution.

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Electrical Engineering of Arc Furnaces

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Circle Diagram of AC-Furnaces

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3 Circle diagram of AC-furnaces

Prof. Dr.-Ing. K. Timm

- 1 Current locus diagram
- 2 Power locus diagram
- 3 Example 1: Power locus diagram of an AC EAF (ideal situation)
- 4 Power diagram
- 5 Exercise example: Calculating of a working point

1 Current locus diagram

The relationship between the electric properties of the arc furnace and the arc resistance is described by the so-called circle diagram. Assuming that all phases are balanced the familiar single-phase equivalent circuit diagram can be used here (**figure 1**).

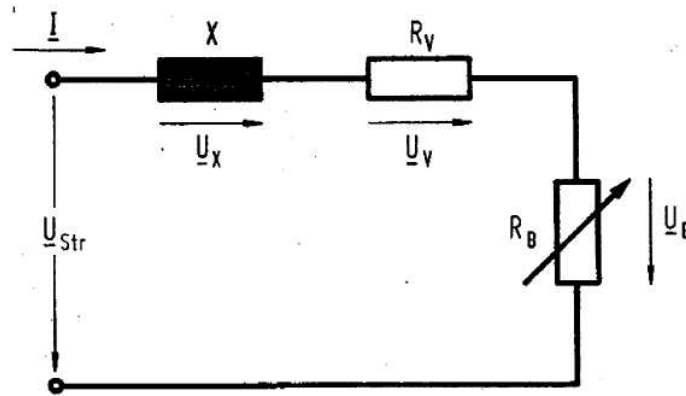


Figure 2: Linearized equivalent circuit of the single phase AC furnace

Changing the arc resistance R_B changes the real part of the phase impedance $\underline{Z}$:

$$\underline{Z} = R_V + R_B + jX.$$

The locus diagram, i.e. the geometric locus of all complex phasors $\underline{Z}$ as a function of the parameter R_B , is thus a parallel line to the real axis (**figure 2a**). In a short circuit ($R_B = 0$) Z is minimum, in the idle run ($R_B = \infty$) it is maximum. The admittance locus diagram results from the inversion of the $\underline{Z}$ locus diagram. It is a semi-circle (**figure 2b**).

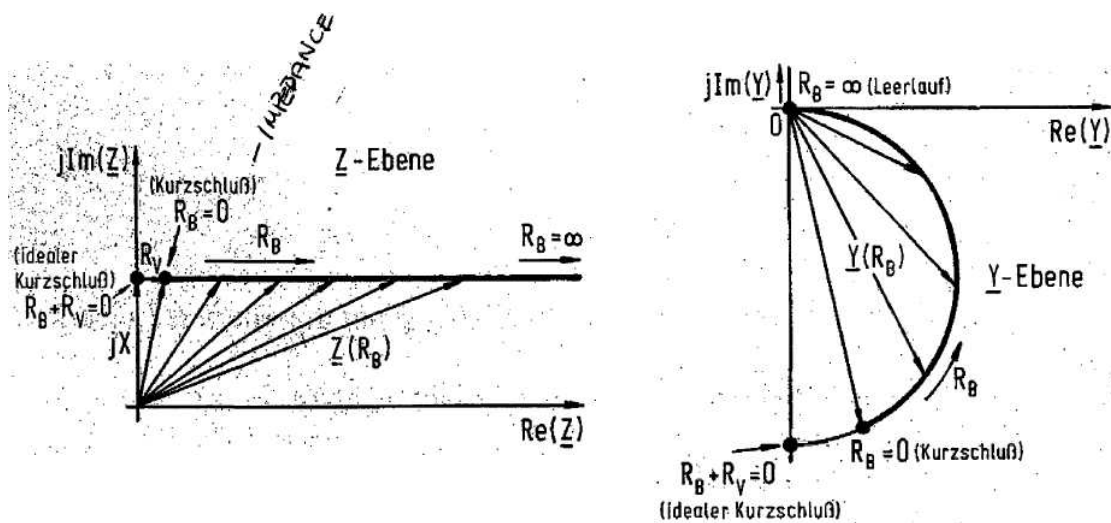


Figure 2: Locus curves of impedance $\underline{Z}$ and admittance $\underline{Y}$

In the case of a constant furnace phase voltage, according to the ohmic law

$$\underline{I} = U_{Str} / \underline{Z} = U_{Str} \cdot \underline{Y}$$

the current locus diagram is identical with the admittance locus diagram. Thus the resulting *current locus diagram* is the familiar circle diagram of the AC electric arc furnace as shown in **figure 3a**, which for graphic reasons has been turned through 90° from the *Y* locus diagram.

According to the circle diagram the value of the furnace current I and its lagging phase angle φ change in relation to the phase voltage when the arc resistance varies between $R_B = 0$ and $R_B = \infty$: In the ideal short circuit ($R_V + R_B = 0$), there is a pure reactive current ($\varphi = 90^\circ$) with a maximum current intensity $I = U_{Str} / X$ *limited by the reactance*. The real short circuit current during the dipping of the electrodes ($R_B = 0$) is slightly lower than that of the ideal short circuit. With increasing arc length, i.e. growing arc resistance, the intensity of the current and the phase displacement between the current and the voltage decrease. At the apex of the circle the active resistance and the reactance arc identical ($\varphi = 45^\circ$). In the idle mode ($R_B = \infty$) the current is zero.

2 Power locus diagram

The current can be split up into an active component $I \cos \varphi$ in the direction of the reference voltage and a reactive component $I \sin \varphi$ (**figure 3b**). Multiplying these components by the phase voltage, the y-axis of the *circle diagram* gives the *progression of the active power P*, the x-axis the *progression of the reactive power Q* and the distance from the origin the progression of the apparent power *S* (**figure 3c**). Multiplication by the factor 3 gives the progression of the power values of the overall three phase system.

The point of *maximum active power input* of the electric arc is at the phase angle $\varphi = 45^\circ$ ($\cos \varphi = 0.707$). In this point both the effective resistance and reactance, and the active and reactive power are equal. The short circuit line in **figure 3c** splits the active power up into the arc power $P\%$ and loss power P_y . The point of maximum arc power P_{max} is thus attained at a power factor of $\cos \varphi > 0.7$. In the ideal short circuit the maximum reactive power corresponds to the circle diameter in **figure 3c**.

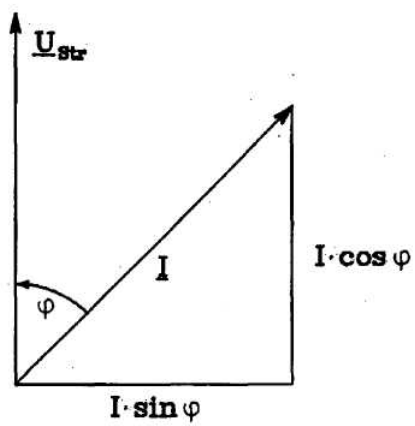
$$Q_{max} = 3 U_{Str}^2 / X = U^2 / X$$

The maximum effective power corresponds to the radius and equals

$$P_{max} = U^2 / 2X$$

According to this equation the maximum furnace power is determined by the furnace voltage U and the reactance X . The parameters of the power locus diagram are given in **figure 4**.

b)



c)

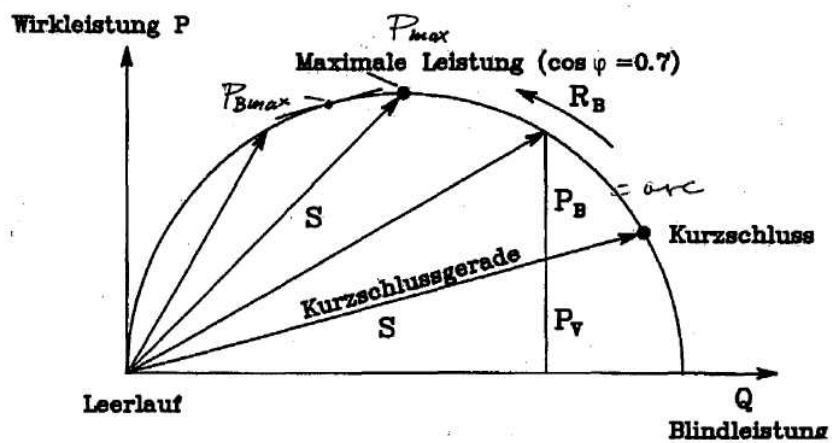


Figure 3: Locus curve for the current (a), components of the current (b) and locus of the power (c) of an AC arc furnace

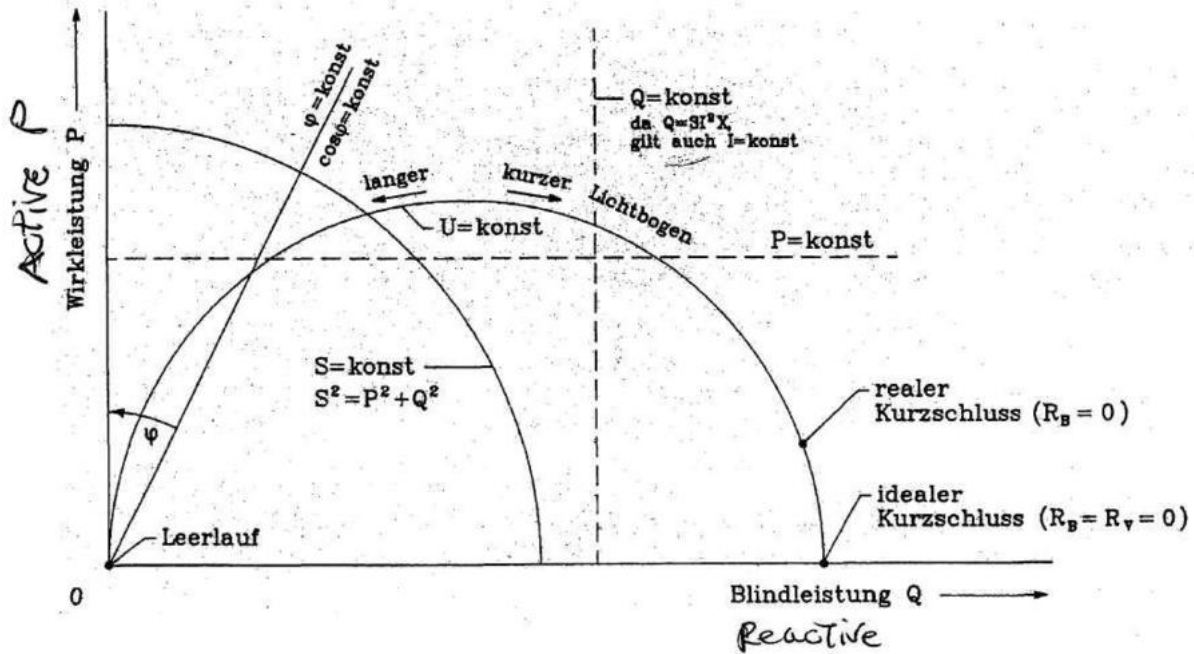


Figure 4: Parameters of the power locus diagram

3 Example 1: Power locus diagram of an AC EAF (ideal situation)

In the following, we will draw a power locus diagram for an ideal furnace. We will first consider an idealized situation which will later on be constantly modified by concrete data.

The following data are given:

Furnace transformer: Rated power		SN = 75 MVA
Phase to phase voltages:	10 steps:	600 V
	Step 9:	560 V
		"
		"
	Step 1:	240 V
Short-circuit reactance of the high-current circuit:		$X = 2.8 \text{ m}\Omega$
Short-circuit resistance of the high-current circuit:		$R_V = 0.45 \text{ m}\Omega$

We first calculate the maximum furnace power for the highest voltage step 10:

$$P_{\max} = \frac{U^2}{2X} = \frac{600^2 \text{ V}^2}{2 \cdot 2.8 \text{ m}\Omega} = 64.29 \text{ MW} .$$

Accordingly, the following data result for all voltage steps:

stufe	10	9	8	7	6	5	4	3	2	1
phase to phase voltage/V	600	560	520	480	440	400	360	320	280	240
max. active power/MW	64.29	56.0	48.29	41.14	34.57	28.57	23.14	18.29	14.0	10.29

We can now draw power locus curves with $P_{\max}$ as the radius for the different voltage steps (figure 5).

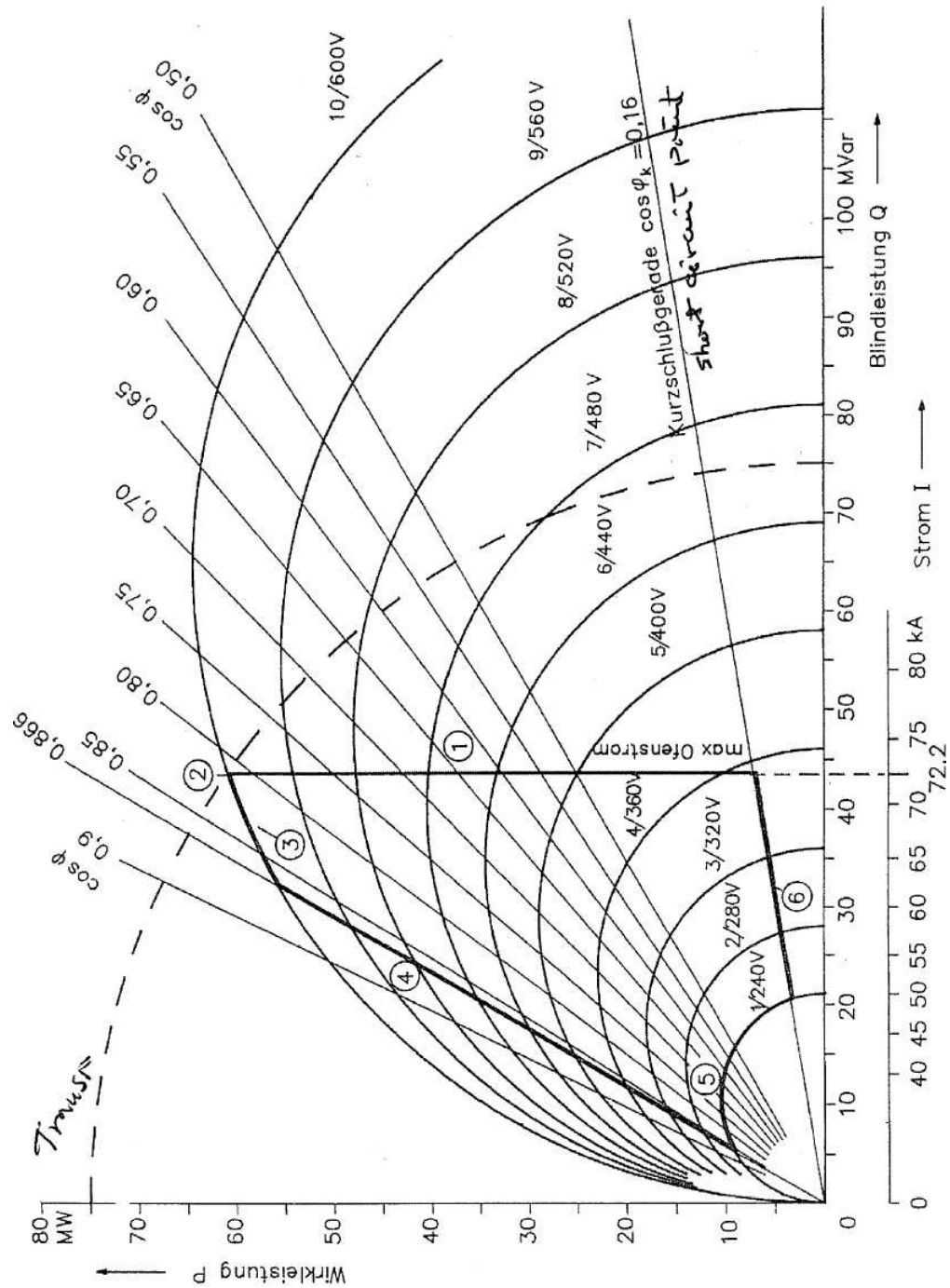


Figure 5: Power locus curves of the AC EAF (example 1)

As at a constant reactance X the reactive power Q is proportional to the square of the current

$$Q = 3 I^2 X \sim I^2 ,$$

to a quadratic scale we can also plot the current along the x-axis.

We also draw the lines $\varphi = \text{const}$ or $\cos \varphi = \text{const}$ for $\cos \varphi = 0.9; 0.85; 0.8 \dots 0.5$. In a three-phase short circuit the working point is on the short-circuit line which can be obtained as follows:

$$\begin{aligned} \tan \varphi_k &= X / R_v = 6.22, \quad \varphi_k = 80.9^\circ \\ \cos \varphi_k &= \cos(\arctan X/R_v) = 0.16 . \end{aligned}$$

Experience has shown that at phase angles $\varphi < 30^\circ$ or $\cos \varphi > 0.87$ stable arc furnace operation is no longer possible.

The working range is determined by 6 *limit curves*, namely:

- 1) by the maximum current, that can be output by the furnace transformer,

$$I_{\max} = \frac{S_N}{\sqrt{3} U_{\max}} = \frac{75 \text{ MVA}}{\sqrt{3} 600 \text{ V}} = 72.2 \text{ kA} ,$$

- 2) by the maximum apparent power of the furnace transformer of $S_N = 75 \text{ MVA}$ (circle around the origin),
- 3) by the maximum secondary phase to phase voltage of 600 V,
- 4) by the stability threshold ($\cos \varphi > 0.87$),
- 5) by the minimum secondary voltage of 240 V and
- 6) by the short-circuit line $\cos \varphi_k = 0.16$.

We see that the maximum furnace power of 64.29 MW cannot be attained without overloading the transformer both in terms of current and apparent power. We can only attain 61 MW in a specific working point with $\cos \varphi = 0.82$. Approximately 10 MW are available as minimum furnace power (for holding the temperature).

Within the allowable working range we now select specific working points for different furnace states. Electrode control uses these working points as target values which are to be approximated during furnace operation.

4 Power diagram

The active power P of the AC electric arc furnace is also frequently expressed in relation to the current / instead of the reactive power Q . The advantage being the fact that, contrary to the reactive power which is difficult to measure and not clearly defined under real operating conditions, the current value / is an easily measurable process variable.

This diagram $P = f(I)$, which in the following will be called *power diagram*, provides practically the same information as the previously described power locus diagram. **Figure 6** shows the power diagram for example 1.

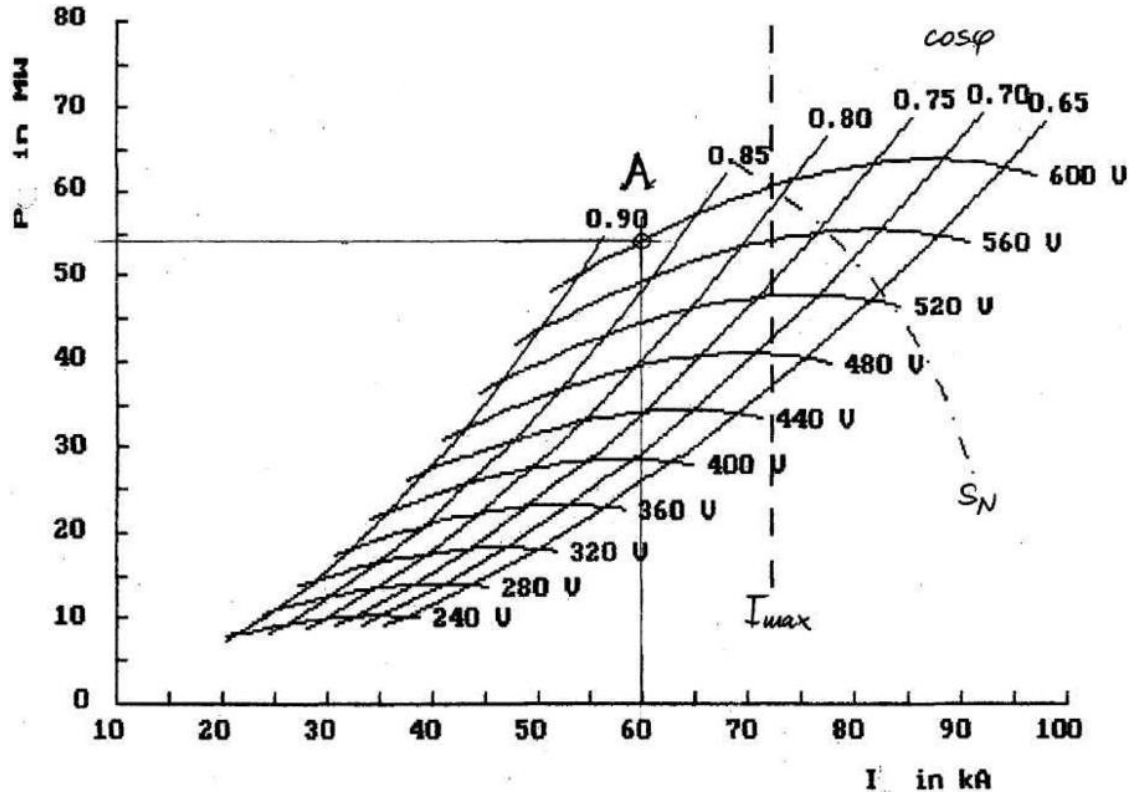


Figure 6: Power diagram for example 1: (ideal situation)

5 Exercise example: Calculation of a working point

We will now calculate the electrical parameters of the working point A in **figure 6**. According to the equivalent circuit diagram of the furnace in **figure 7** we obtain:

for the high-current circuit:	short-circuit reactance	$X = 2.8 \text{ m}\Omega$
	loss resistance	$R_V = 0.45 \text{ m}\Omega$

for the furnace transformer:	line-to-line voltage (step 10)	$U_{\cdot} = 600 \text{ V}$
	phase voltage	$U_{Str} = U / \sqrt{3}$

The ohmic law for the single-phase high-current circuit is:

$$I = \frac{U_{Str}}{Z} = \frac{U}{\sqrt{3} \sqrt{(R_V + R_B)^2 + X^2}} .$$

In this equation two variables are unknown, namely, the current / (effect) and the electric arc resistance R_B (cause). Therefore, we have to assume one of the two values in order to calculate the other:

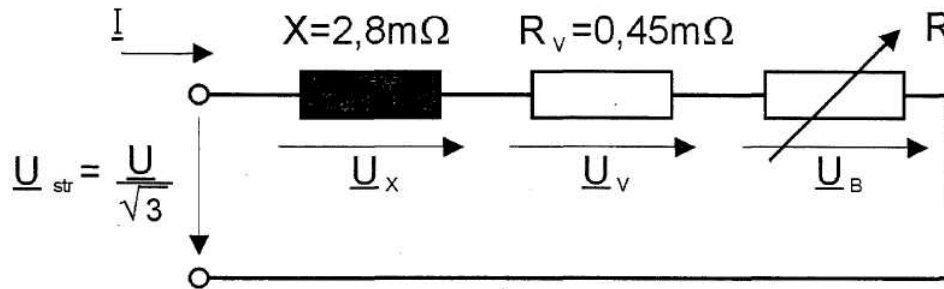


Figure 7: Parameters of a single phase equivalent circuit diagram

1st variant: Assuming the "cause" = electric arc resistance $R_B = 4.6 \text{ m}\Omega$, calculating the "effect" I :

1. phase voltage (cause)	$U_{Str} = U / \sqrt{3} =$
2. impedance (cause)	$Z = \sqrt{X^2 + (R_V + R_B)^2} =$
3. current (effect)	$I = U_{Str} / Z =$
4. arc voltage	$U_B = I \cdot R_B =$
5. voltage at the loss resistance	$U_V = I \cdot R_V =$
6. active voltage	$U_V + U_B =$
7. total arc power	$P_B = 3 I^2 R_B =$
8. total loss power	$P_V = 3 I^2 R_V =$
9. total active power	$P = P_B + P_V =$
10. electrical efficiency	$\eta_{el} = P_B / P =$
11. total apparent power	$S = \sqrt{3} U I =$
12. power factor	$\cos \varphi = P / S =$
13. total reactive power	$Q = \sqrt{S^2 - P^2} =$

2nd variant: Assuming the "effect" (current / = 60 kA), calculating the "cause" $R\%$ etc.

1. phase voltage (cause)	$U_{Str} = U / \sqrt{3} =$
2. impedance	$Z = U_{Str} / I =$
3. arc resistance	$R_B = \sqrt{Z^2 - X^2} - R_V =$

etc.

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Short Circuit and Operational Reactance

Prof. Dr.-Ing. Klaus Timm,
formerly Universität der Bundeswehr, Hamburg

4 Short-circuit reactance and operating reactance

Prof. Dr.-Ing. Klaus Timm

1 Introduction

2 Short-circuit reactance

- 2.1 Reactance of a conductor loop
- 2.2 Balance of reactances
- 2.3 Short-circuit reactance of an AC furnace with current-conducting electrode arms
- 2.4 Optimized reactance
- 2.5 Reactance measuring techniques

3 Operating reactance

- 3.1 Electric variables in real furnace operation
- 3.2 Arc reactance according to *Kohle*
- 3.3 Operating reactance according to *Bowman*

4 Example: Calculation of working points taking into account the operating reactance

5 References

1 Introduction

The parameters phase-to-phase voltage U , reactance X and the working point φ play key roles in the design and operation of alternating current furnaces as they determine the furnace power P , the voltage requirement U and the current I :

$$P = \frac{U^2}{2X} \sin 2\varphi$$

$$U = \sqrt{2 PX / \sin 2\varphi} \quad .$$

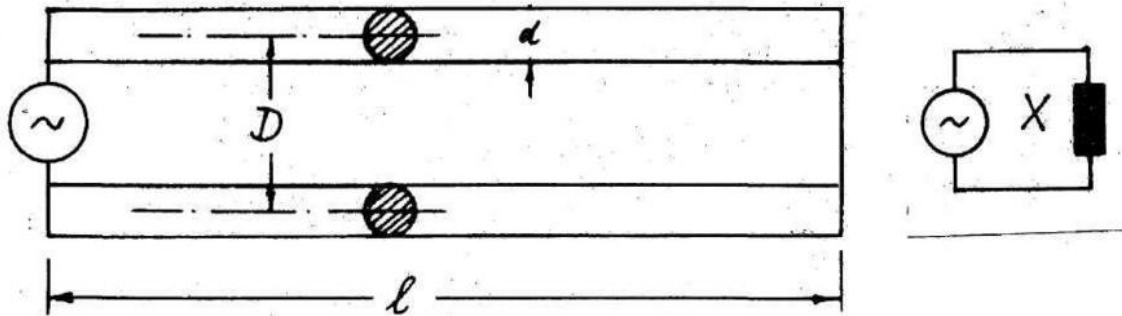
$$I = \sqrt{S \sin \varphi / (3X)}$$

In this context the *short-circuit reactance* X is a very important engineering parameter. In the following we will learn which geometric variables determine the reactance, how to balance the reactance in the three phases, which reactance values are recommendable today for furnace operation and what the term operating reactance means.

2 Short-circuit reactance

2.1 Reactance of a conductor loop

To get an idea of the geometric variables that determine the short-circuit reactance of a high-current conductor we first take a closer look at a straight conductor loop (**figure 1**).



$$\mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}$$

absolute induction coefficient

$$\omega = 2\pi f$$

angular frequency

$$X = \frac{\omega \mu_0}{\pi} \cdot l \cdot \ln \frac{D}{D_{ii}}$$

reactance of the loop, $l \gg D$

$$D_{ii} = \frac{d}{2} \cdot e^{-\frac{1}{4}}$$

mean geometric distance from itself of a cylindrical conductor

Figure 1: Reactance of a conductor loop

The reactance X of this loop is proportional to the conductor length l , increases by growing conductor distance with $\ln D$ and depends on the arrangement of the conductor proper, i.e.

"the mean geometric distance of a conductor from itself". The larger the cross-sectional area, the lower the reactance. This also applies to the division of conductors into multiple lines. The short-circuit reactance is thus determined by the lengths, distances, number and cross-sectional areas of the high-current conductors.

2.2 Balance of reactances

Transferring this knowledge to the three-phase system of the AC furnace means that the foremost engineering objective must be to achieve equal reactances for all three phases. This *balance of reactances* can be obtained when within each section of the high-current system conductors with the same cross-sections and lengths are used. Furthermore, these conductors must be arranged at equal distances.

These layout fundamentals have led to the so-called *triangulation* of high-current conductors, **figure 2b**, which has become common practice since the early 1970s. If for design reasons instead of a triangular a parallel arrangement (**figure 2a**) is chosen, the reactances become unbalanced, leading to a reduction of the reactance of the centre phase. Normally, in an electric arc furnace with unbalanced reactances the electric variables current, active power, arc voltage and radiation value are also unbalanced. Only one of these variables at a time can be balanced by arc length changes.

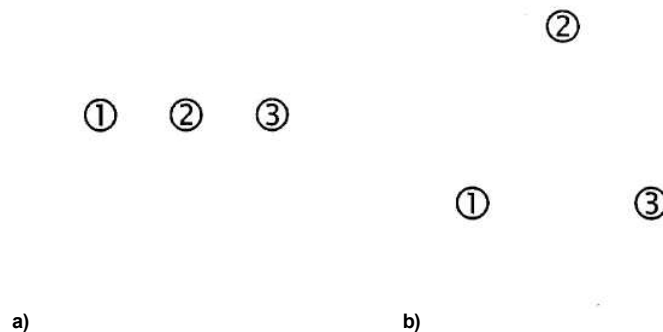


Figure 2: Parallel arrangement (a) and triangular arrangement (b) of high-current conductors

2.3 Short-circuit reactance of an AC furnace with current-conducting electrode arms

In the following we will detail some of the principles of reactance dimensioning in the high-current circuit of an electric arc furnace with current-conducting electrode arms [1], a design feature first introduced in 1984. It is a technological advancement of the previously used tube system installed on the electrode arms. With the new design the electrode arm is used both as a mechanical electrode carrying device and as an electric conductor. **Figure 3** shows the design of the first installation.

Current-conducting electrode arms consist either of carbon steel clad with copper or of pure aluminium.

The high-current line of an AC furnace consists of the segments, **figure 4:**

- Transformer connecting conductors (A-C),
Flexible furnace cables (D-L),
- Electrode arms area (M-Q) and
Electrodes (in this case: water-cooled electrodes with two segments) (R-W).

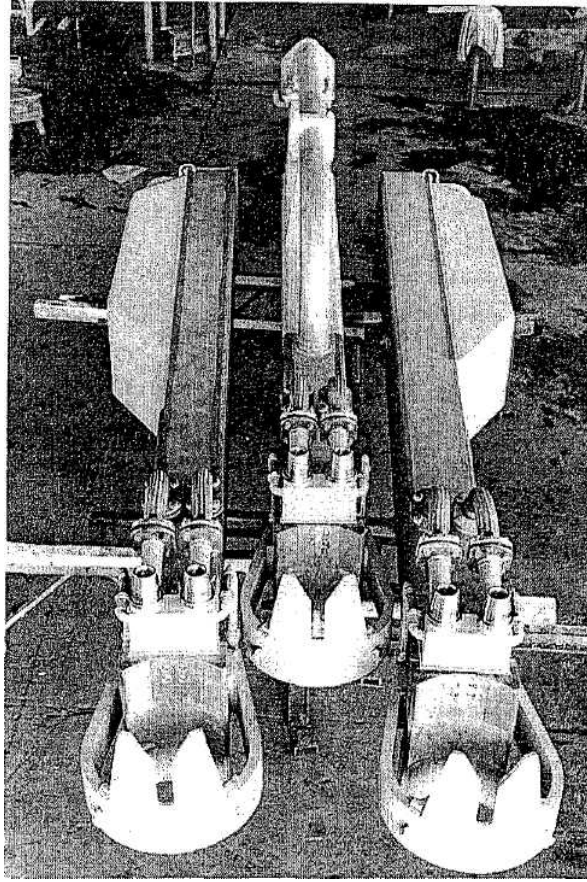


Figure 3: Design of the first installation of current conducting electrode arms at AZMA [1]

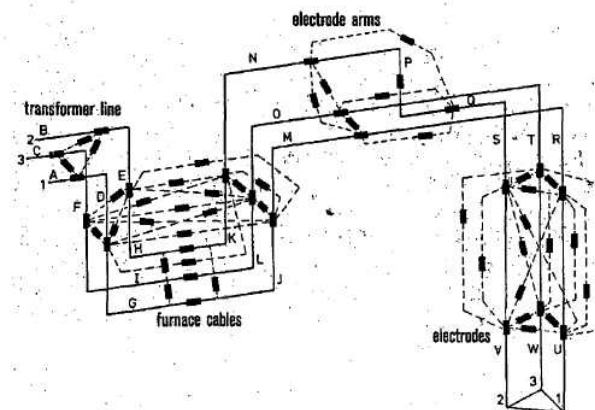


Figure 4: Self and mutual inductance's of the high-current system at AZMA [1]

For the calculation of the phase impedances the self and mutual inductance's of the individual segments must be determined. First the decoupled partial reactances and then the overall system reactance are calculated by means of a reduction procedure [1],

The calculation-based dimensioning of the design components in figures 3 and 4 provided the following reactance values:

$$\begin{aligned} X_1 &= X_3 = 2.22 \text{ m}\Omega \\ X_2 &= 2.41 \text{ m}\Omega \end{aligned}$$

The measurement of the short-circuit impedances by means of two-phase short-circuit tests provided the following results:

Short-circuit reactances: $X_1 = 2.46 \text{ m}\Omega$, $X_2 = 2.52 \text{ m}\Omega$, $X_3 = 2.58 \text{ m}\Omega$.

Loss resistance's: $R_{V1} = 0.41 \text{ m}\Omega$, $R_{V2} = 0.40 \text{ m}\Omega$, $R_{V3} = 0.44 \text{ m}\Omega$.

The results show that the reactances are almost balanced. Today current-conducting electrode arms are state of the art in both direct current and alternating current furnaces. Special attention must be paid to the *balance of reactances*. Several options are possible here:

- In the case of parallel electrode arms the reactance of the centre phase must be increased. This can be achieved by a copper tube with a reduced cross-section, as shown in **figure 3**, or by *reactance loops* in the centre phase installed on the wall of the transformer house or on the middle electrode arm [2].
- A balance can also be achieved by positioning the middle electrode arm at a higher level, which comes very close to a *triangular arrangement*. An example of such a configuration is shown in **figure 5** [3].

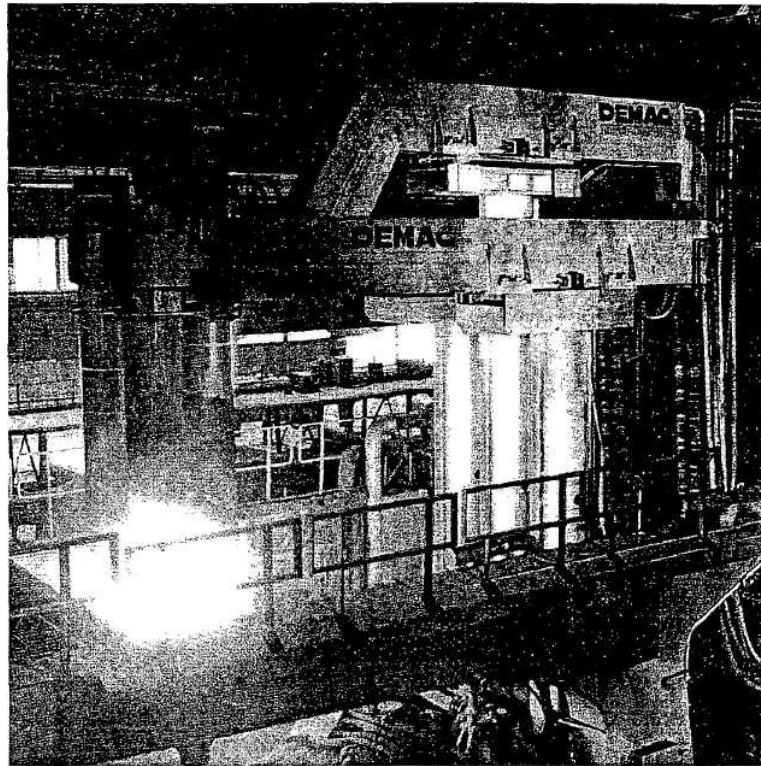


Figure 5: Current conducting electrode arms of aluminium at UES Stocksbridge/Great Britain [3]

2.4 Optimized reactance

At a mains frequency of 50 Hz the short-circuit reactances of AC furnaces range between 2.2 and 3 m Ω .

In the late 1970s installations with *minimum reactances* are preferred, enabling foaming slag operation with long, small-current arcs and low electrode consumption. However, there are limits to the layout of high-reactance high-current systems.

Here it is useful to install a *separate inductor* on the primary of the furnace transformer that is switchable under load. The coil can become effective during the critical boring period and be switched off during the main melting phase in order to avoid power losses [4].

2.5 Reactance measuring techniques

Short-circuit reactances of AC furnaces can either be determined by calculations or by two and three-phase short-circuit measurements at a reduced furnace voltage. The standard which describes the applicable measuring and evaluation methods is currently being revised [5]. The revised version will not deviate much from the methods described in [6].

3 Operating reactance

3.1 Electric variables in real furnace operation

A comparison of the measurements of electric variables with the values obtained from the circle or power diagram shows that the practical operating points are always somewhat below the calculated values, i.e. the actual furnace power is lower than calculated. An example is given in **figure 6**. These are the reasons:

1. Our previous assumption that the arc resistance R_B is linear must be modified. R_B is non linear which causes harmonics in the current as multiples of 50 Hz (100 Hz, 150 Hz, 200 Hz, 250 Hz, etc.).
2. The electric arc variables are not stationary but subject to variations.
3. Non-linearity and variations depend on the state of the melting process.
4. The assumption of balanced load conditions often does not apply. Unbalanced situations reduce the active power.
5. Furnace transformers, step-down transformers and the supply mains feature internal impedances which add to the furnace impedances and must therefore be taken into account.

In the following the effects 1 - 3 on the power diagram will be investigated. Different investigations have shown that *non-linearity* and *variations* of electric arc variables as well as the *increase of the system reactance* have an influence. We therefore use the term *operating reactance*. The operating reactance is higher than the minimum reactance - the short-circuit reactance - by a constant or variable percentage. In this context the following three models will be detailed:

- Operating reactance as a constant factor k ,
- Arc reactance according to *KOHLE* [7, 8],

- Operating reactance according to *BOWMAN* [9].

For simple cases it is sufficient to determine the operating reactance X_{of} of electric arc furnace by increasing the short-circuit reactance X by a constant factor in the range of

$$k = 1,1 \dots 1,2 \quad ,$$

resulting in

$$X_{of} = k \cdot X \quad .$$

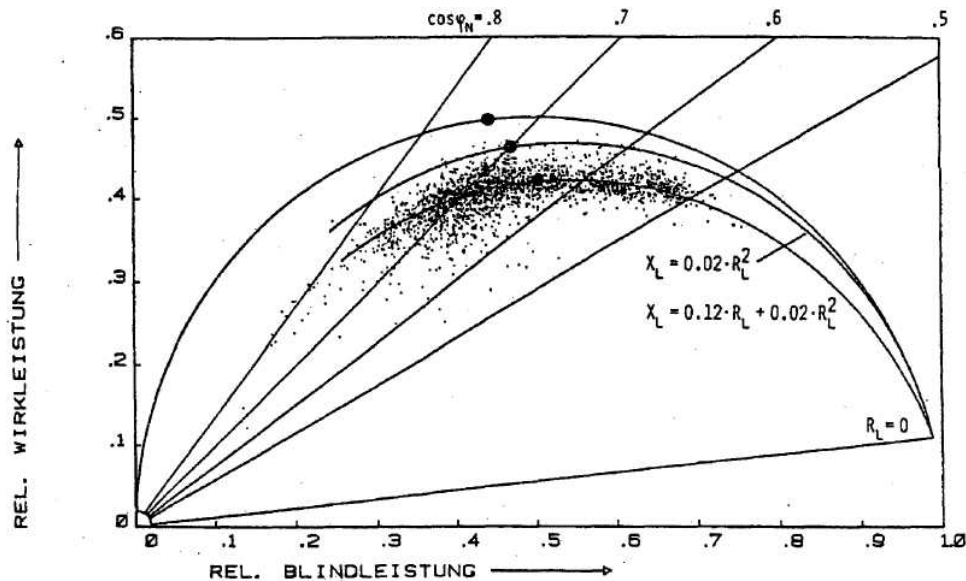


Figure 6: Operating points in the circle diagram

3.2 Arc reactance according to *KOHLE*

KOHLE has shown that the variations and non-linearities of arc variables can be considered in a linear equivalent circuit diagram by assigning a long-term arc reactance X_L to the electric arc. The relationship between the long-term arc reactance X_L and the arc resistance R_L is as follows [7]:

$$X_L = 0,12 \cdot R_L + 0,02 \cdot R_L^2 / m\Omega \quad .$$

The first part considers the variations, the second the harmonics. **Figure 7** shows an equivalent circuit diagram which has been modified accordingly.

The circle diagram in **figure 6** shows that, in contrast to the ideal furnace circle, the modified circle diagram with X_L is a good approximation of the measured operating points.

In a more recent work [8] *KOHLE* considered the influence of the melting time by introducing the factor K_X :

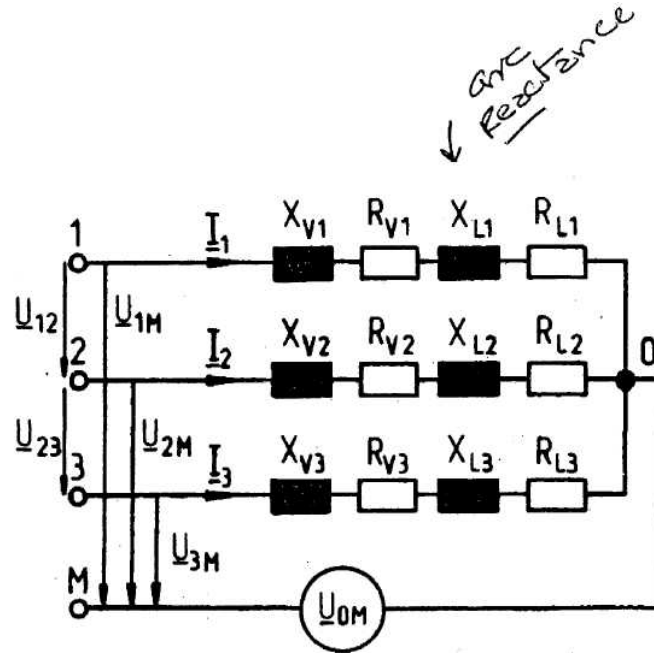


Figure 7: Linearized equivalent circuit with arc reactances X_L

$$\frac{X_L}{X_0} = 0.08 \frac{R_L}{X_0} + K_X \left[0.12 \frac{R_L}{X_0} + 0.08 \frac{R_L^2}{X_0^2} \right],$$

with X_0 being the short-circuit reactance. The factor K_X varies between $K_X = 1$ at the start of melting and $K_X \rightarrow 0$ during foaming slag operation. Measurements on 5 AC furnaces have demonstrated that the factor K_X can be assumed as the following exponential function,

$$K_X = e^{-\frac{t}{T_X}}$$

with the time constant T_X being in the 10 ... 15 min range, **figure 8**.

3.3 Operating reactance according to BOWMAN

Based on a large number of individual investigations, *BOWMAN* [9] has determined a measured operating reactance which is plotted in **figure 9** in relation to the power factor $\cos K\phi$.

This enables the assessment of the operating reactance of an electric arc furnace during different phases of the melting process:

- At the *start* (boring period), arc stability and non-linearity are extremely unfavorable. The operating reactance is up to 50 % higher than the short-circuit reactance.
- During the *main melting period*, this effect is slightly less intensive.
- During *foaming slag operation*, the arcs are largely stable, the arc characteristic is almost linear. The operating reactance is only about 10 % higher than the short-circuit reactance.

The effect of the operating reactance decreases with the shortening of the arc length. In a short circuit these functions should theoretically tend towards the threshold value 1.

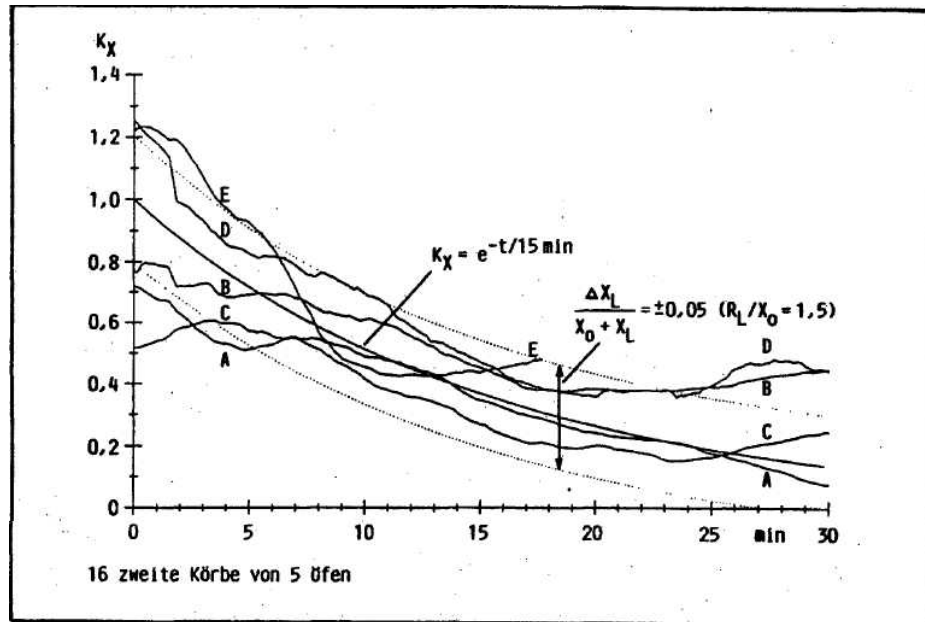


Figure 8: Time behavior of the arc reactance on five AC furnaces, melting the second basket [8]

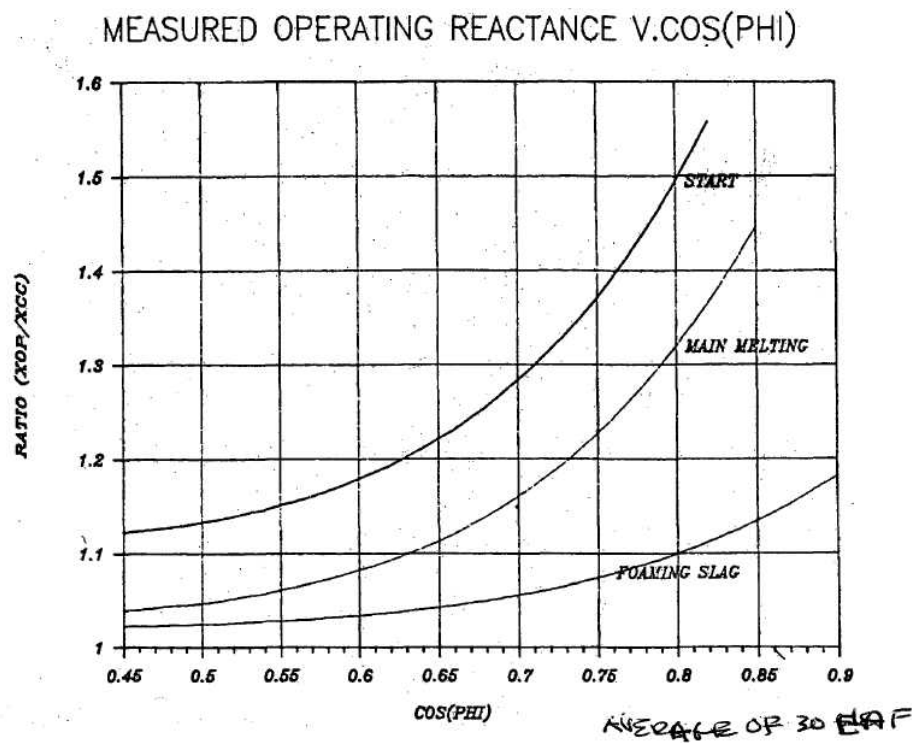


Figure 9: Measured operating reactance versus power factor $\cos \varphi$

KOHLER and BOWMAN found largely the same relationships. There is a close correspondence between the following K_X values:

"Start melting" for $K_X \approx 0.9 \dots 0.7$,

"Main melting" for $K_X \approx 0.5$,

"Foaming slag" for $K_X \approx 0$.

3.4 Effect of the operating reactance on the furnace power

The effect of the operating reactance on the power of an AC EAF is shown in **figure 10**. Power differences of more than 10 MW have been identified between the boring phase and the operation with foaming slag. The figure also shows that when the electrode control is based on a constant impedance control the current values drift away. This phenomenon is, however, only effective in the case of a higher transformer impedance or an additional reactor. This current drift can be avoided by appropriate compensation as part of the furnace control.

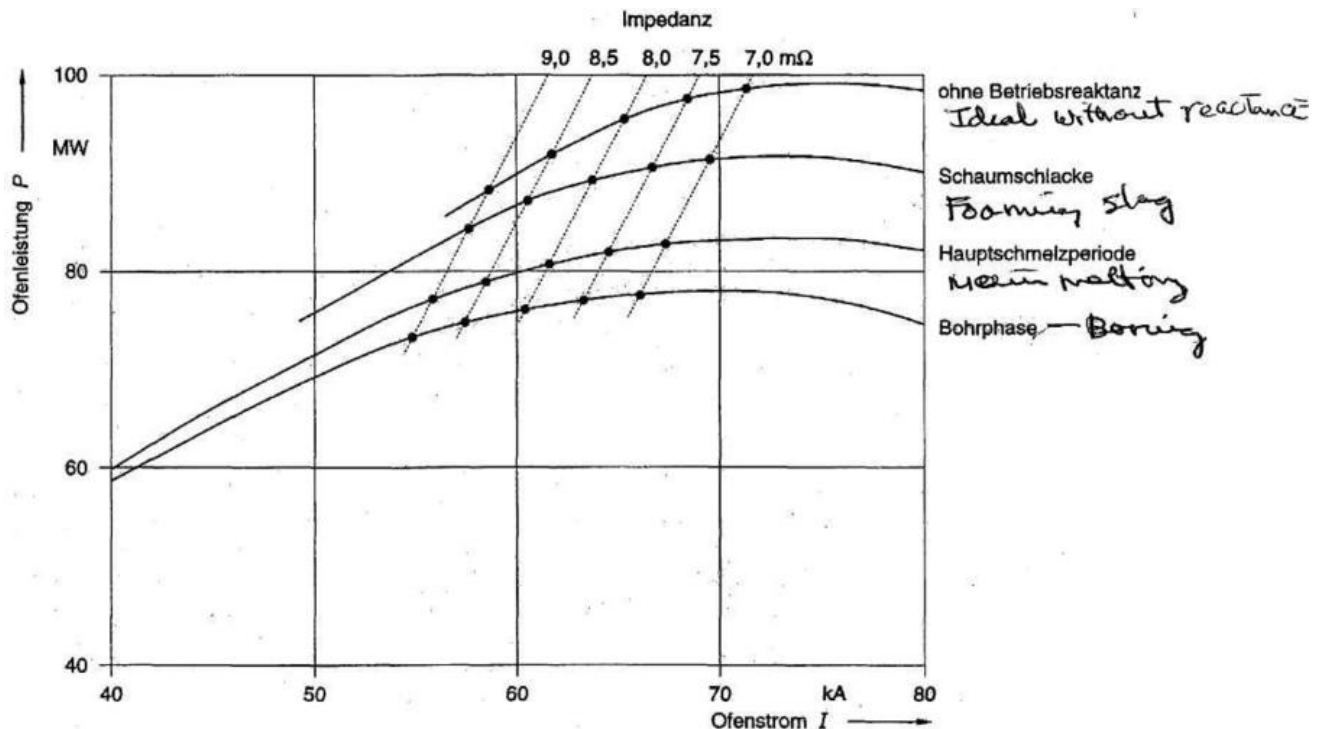


Figure 10: Power diagram of an AC EAF with different operating reactances.

$U = 960$ V. Short circuit reactance of the high-current system:

$X_0 = 2.7$ mΩ, of the transformer and additional reactor: 1.2 mΩ

4 Example: Calculation of working points taking into account the operating reactance

In the following we will investigate how the influence of the operating reactance can be taken into account in the analytical calculation of working points:

- Increasing the short-circuit reactance by a constant factor $k = 1.1 \dots 1.2$ leads to inaccurate results and will therefore be disregarded.
- The operating reactance function according to *BOWMAN* is based on empirical, non-linear functions and is therefore not suitable for analytical solutions.
- The method according to *KOHLE* is suitable for the calculation of "cause" = arc resistance $\rightarrow$ "effect" = current.

We use the familiar example from the chapter on "Circle diagrams", **figure 11**. We add the arc reactance X_L to the single-phase equivalent circuit diagram

$$X_L = 0.12 R_B + 0.02 R_B^2 / \text{m}\Omega = (0.12 \cdot 4.6) + 0.02 \cdot (4.6)^2 = 0.98 \text{ m}\Omega$$

With $R_B = 4.6 \text{ m}\Omega$, the arc reactance is $X_L = 0.98 \text{ m}\Omega$. This value accounts for 21 % of the short-circuit reactance and inevitably leads to a drop in the furnace power:

For the calculation of the operating point we follow the known procedure:

1. phase voltage $U_{\text{Str}} = U / \sqrt{3} = 600 \text{ V} / \sqrt{3} = 346.4 \text{ V}$
2. impedance $Z = \sqrt{(X + X_L)^2 + (R_V + R_B)^2} = \sqrt{(2.8 + 0.98)^2 + 5.05^2} = 6.33$
3. current $I = U_{\text{Str}} / Z = \frac{346.4 \text{ V}}{6.33} = 54.76 \text{ A (ca } 60 \text{ kA)}$

The next calculation steps are the same as described in the chapter on "Circle diagrams". Therefore, here we restrict ourselves to giving the equation for the calculation of the

4. total active power $P = 3I^2(R_V + R_B) =$

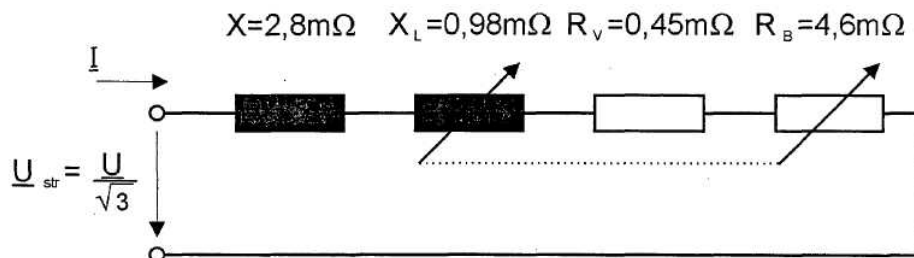


Figure 11: Equivalent diagram of an AC EAF with arc reactance X_L

5 References

- [1] Ehle, J.; Timm, K.; Knapp, H.; Ahlers, H.: Entwurf und Betriebsergebnisse von stromleitenden Tragarmen für Lichtbogenofen. Stahl u. Eisen 105 (1985), S. 26-30.
- [2] Timm, K.: Reaktanzsymmetrierung von Hochstromleitungen für Drehstrom-Lichtbogenofen. elektrowarme international 49 (1991), B3, S. B201-B211.
- [3] Smollong, H.: Der Drehstromlichtbogenofen, reaktanzarm oder reaktanzoptimiert. Sonderdruck MANNESMANN DEMAG, Duisburg.
- [4] Krieger, K.; Timm, K.; Schliephake, H.; Bandusch, K.: Leistungsregelung eines Drehstrom-Lichtbogenofens. Stahl u. Eisen 116 (1996), Nr. 8, S. 95-100.
- [5] IEC 60676: Ed. 2.0 Test methods for direct arc furnaces (being revised).
- [6] Svensson, E.: Das Messen von Impedanzen in Lichtbogenofen. ASEA-Zeitschrift 17 (1972), Heft 4, S. 84-85.
- [7] Kohle, S.: Lineares elektrisches Ersatzschaltbild von Drehstrom-Lichtbogenofen. Bericht Nr. 2.2.14, 10. UIE-Kongress, Stockholm (1984).
- [8] Kohle, S.; Knoop, M.; Lichterbeck, R.: Lichtbogenreaktanzen von Drehstrom-Lichtbogenofen. elektrowarme international 51 (1993), B4, S. B175-B185.
- [9] Bowman, B.: Computer modelling of arc furnace electrical operation. Metallurgia International 1 (1988), S. 286-291.

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International Symposium

Electrical Engineering of Arc Furnaces

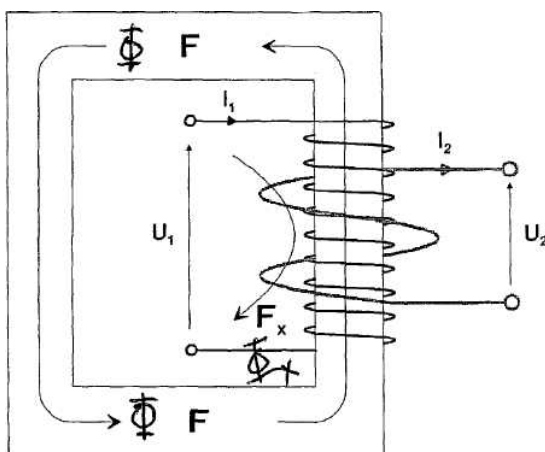
October, 23 - 26, 2006, in Braunschweig, Germany

Furnace Transformers

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Furnace Transformers

1. Mode of Functioning of a Transformer



The mode of functioning will be illustrated based on a simplified single phase model with two windings placed on an iron core. A sinusoidal ac-voltage source U_{01} is connected to the terminals of the inner winding (Which is placed directly on the core). A magnetic flux Φ will then flow through the core. The variation in time of this flux multiplied with the number of turns corresponds to the applied voltage at the terminals:

$d\Phi$

$$U_{01m} = w_1 \times \frac{d\Phi}{dt} \quad (\text{Law of Induction}) \quad (1)$$

If there is no consumer connected to the terminals of the secondary winding, the secondary current will be zero ($I_2=0$) and the transformer is in the so called no load operation. The magnetic flux which flows in this case through the secondary winding is the same as in the primary winding: Φ . The variation in time of this flux induces in the secondary winding the voltage U_{02} :

$d\Phi$

$$U_{02} = w_2 \times \frac{d\Phi}{dt} \quad (\text{Law of Induction}) \quad (1)$$

$d\Phi$

After elimination of $\frac{d\Phi}{dt}$ from the formulae (1)

$d\Phi$

and (2) we come to the conclusion that the ratio of the no load voltages corresponds to the ratio of the turns of the windings:

$$\frac{U_{01}}{U_{02}} = \frac{w_1}{w_2} = \ddot{u}$$

$\ddot{u}$ is the transformation ratio.

Loaded Transformer

Loading the secondary winding with a current I_2 causes a magnetic flux of that winding. This flux is linked also with the primary winding and tends to reduce the total flux seen by the primary winding. Therefore a compensating current I_1 will flow in the primary winding producing a compensating flux. The ampere turns of both windings are nearly equal:

$$I_1 \times w_1 = I_2 \times w_2 \quad \text{and}$$

$$\frac{I_1}{I_2} = \frac{w_2}{w_1} = \frac{1}{\ddot{u}}$$

The flux between both windings is called stray flux Φ_x . The bigger the stray flux is, the weaker is the magnetic coupling between both windings.

The secondary winding is now linked with the main flux Φ and with the stray flux Φ_x

$$U_2 = w_2 \times \frac{d(\Phi - \Phi_x)}{dt} = w_2 \times \frac{d\Phi}{dt} - w_2 \times \frac{d\Phi_x}{dt}$$

Using equation (1):

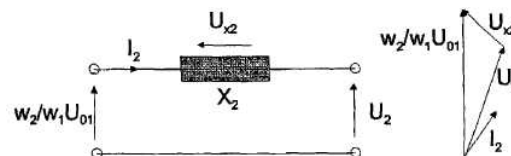
$$U_2 = \frac{w_2}{w_1} \times U_{01} - U_{x2} = U_{02} - I_2 \times \frac{d\Phi_x}{dt} \times \frac{w_2}{w_1} = U_{02} - I_2 \times X_2$$

$$U_{x2} = w_2 \times \frac{d\Phi_x}{dt} \quad \text{is the short circuit voltage}$$

of the transformer related to the secondary winding. This voltage is related normally to the no load voltage and is given in Percent.:

$$u_x = \frac{U_{x2}}{U_{02}} \times 100\% \quad (\text{Impedance of Transformer})$$

Equation (3) can be expressed by an equivalent circuit or by voltage phasors as follows:



The short circuit reactance is calculated based on the short circuit voltage, the no load voltage and the rated power as follows:

$$X = \frac{u_x}{100\%} \times \frac{U_0^2}{S_n} [\Omega]$$

The short circuit resistance is calculated based on the short circuit loss and the corresponding current as follows:

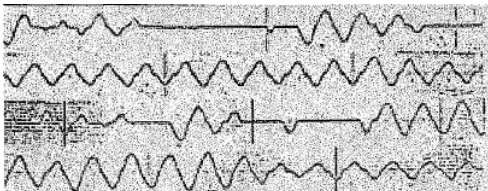
$$R = \frac{P_{Cu}}{3 \times I^2} [\Omega]$$

2. Electrical Characteristics of Furnace Transformers

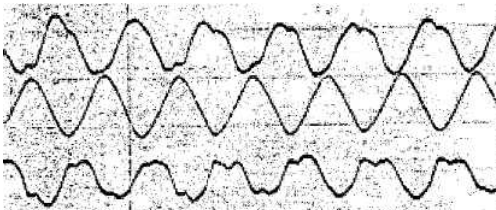
Furnace Transformers have to adapt the electrical energy to the requirements of the electrical furnaces.

The energy will be absorbed normally from a medium voltage system (30, 20 or 10 kV) and transformed to a range of 100 to 1400 V. If a special type of transformer is chosen, it can be connected also directly to the 110 kV or even to the 220 kV system.

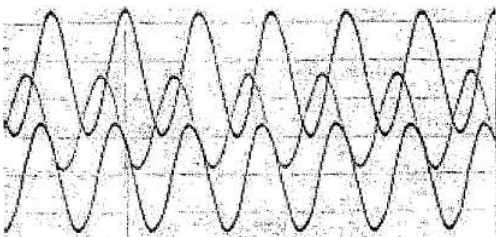
The variation in time of the currents is influenced by the mode of operation of the arc furnace. The variation of power covers the whole range between no load and short circuit of the electrodes including a superimposed inrush current:



Current at different moments of time within the first seconds after the first ignition of the arc in a new batch.



Currents in the three phases, two minutes after the first arc ignition in a new batch.

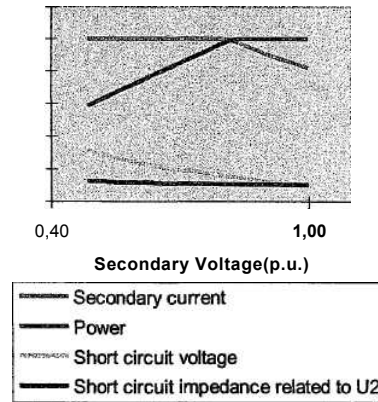


Currents in the three phases, 40 minutes after the first arc ignition in a new batch.

Furnace Transformers are characterised by a typical definition of power, a great tapping range and very high currents on the low voltage side.

Usually, a range of constant power and a range of constant current are defined, while the secondary voltage decreases and the primary (applied) voltage remains unchanged. In some cases the range of constant power is omitted. In those cases the rating is defined by a range of constant secondary current only. Furnace transformers show a typical

variation of short circuit voltage and short circuit impedance with the tapping range:



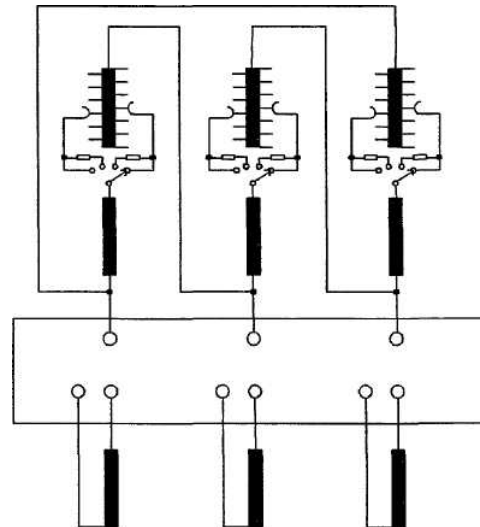
The secondary voltage can be regulated in a ratio of 2:1 to 3:1 or even more. As higher the power of a furnace transformer, as higher is normally the maximum value of the secondary voltage.

3. Types of Furnace Transformers

3.1. AC-Furnace Transformers

3.1.1. Variable-Flux Voltage Regulation

The furnace transformer contains in this case one active part. The voltage regulation is done by changing the number of turns in the high voltage winding by means of a tap changer. As the supplying voltage on the high voltage side remains unchanged, the flux density will change with changing numbers of turns.(Variable-Flux voltage regulation).



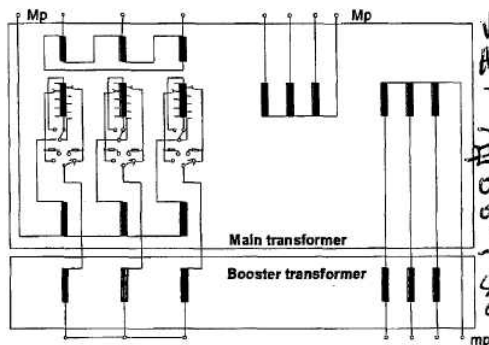
The high voltage winding can be star or delta connected. The low voltage winding can have a star-, delta- or open-circuit connection.

This type of furnace transformer has the most economic design, as only one active part is required, (see also 3.1.4). The range of application is limited due to the maximum height of the primary voltage as the transient over-voltages in the tapping winding increase considerably with higher system voltages.

The voltage regulation is normally done in unequal steps due to the variable flux regulation. A coarse equalisation can be achieved in some cases using different numbers of turns per step.

3.1.2.Regulation With Intermediate Circuit

This type of furnace transformer consists of two active parts enclosed normally in the same tank: a main transformer and a booster transformer. The main transformer contains the high voltage winding, a part of the low voltage winding and the regulating winding. The booster transformer contains the second part of the low voltage winding (connected in series with the first part) and a high voltage winding, fed by the regulating winding of the main transformer. The regulating winding of the main transformer and the high voltage winding of the booster transformer form the intermediate circuit.



This type is normally connected to high voltage systems. Furnace transformers made by Siemens which are connectable to the 110 kV system as well as to the 220 kV system are in service since decades.

The voltage of the intermediate circuit can be chosen by the designer. As higher it is, as more sophisticated is the insulation system. But as the current is lower at higher voltages, a less expensive tap changer can be chosen. It is up to the designer to find the optimum.

The switchgear can be included in the intermediate circuit. Due to the reduced voltage of the intermediate circuit, a less expensive switchgear can be chosen. If the switchgear is open, the booster transformer will be magnetised from its low voltage winding. This implies, that the booster transformer is designed for the voltage level of the low voltage

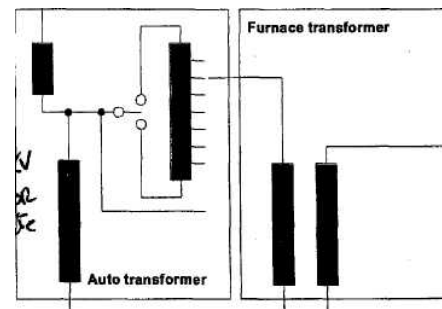
winding of the main transformer. Therefore the power of the booster transformer has to be increased. The opened contacts of the switchgear are stressed by double the voltage of the intermediate circuit. All these effects have to be considered in the design stage.

An additional advantage of this type is that equal voltage steps can be achieved along the whole tapping range. There are also no limitations in choosing the size of the tapping range.

The example given above contains also a tertiary winding which is suitable for connecting an external filter or power factor correction equipment. This leads to cost optimisation of such equipment especially in the case of high system voltages.

3.1.3.Regulation With an Auto Transformer

This type contains two active parts, an auto transformer with regulating winding and a furnace transformer which are located normally in a common tank.



This type can be connected directly to a high voltage system.

In this case, an intermediate circuit is formed by the common winding and the regulating winding of the auto transformer and the high voltage winding of the furnace transformer. The voltage of this intermediate circuit can be chosen by the designer. As higher this voltage is, as lower is the current, which determines the size and cost of the tap changer. The built in power of the auto transformer decreases with a lower transformation ratio but the cost of the insulation system increases.

A tertiary winding can be foreseen to connect a filter or a power factor correction equipment.

3.1.4.Comparison of the Three Types

The possible range of application of the three types has been described above. The following comparison is done from an economical point of view.

The built in power of a furnace transformer is normally much higher than the rated power. This is determined by the special power demand of such a

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transformer and by the chosen concept. The comparison is done based on the same tapping range for all three types e.g.: $U_{max}/U_{constant}/U_{min} = 1 / 0,8 / 0,5$. The ratio between built in power and rated power for the given tapping range is as follows:

Variable flux regulation:	1,63
Intermediate circuit regulation:	1,44
Regulation with auto transformer:	1,56

The best ratio is achieved in the case of Intermediate circuit regulation, followed by the regulation with auto transformer. As these types consist of two active parts, the manufacturing effort is much higher than in the case of the variable flux regulation. If the transformer is connected to the medium voltage system, the variable flux regulation leads to the most economical design. If the transformer is connected to the high voltage system, the available manufacturing facilities and the figures given above will determine the chosen type.

3.1.5. Other Characteristics

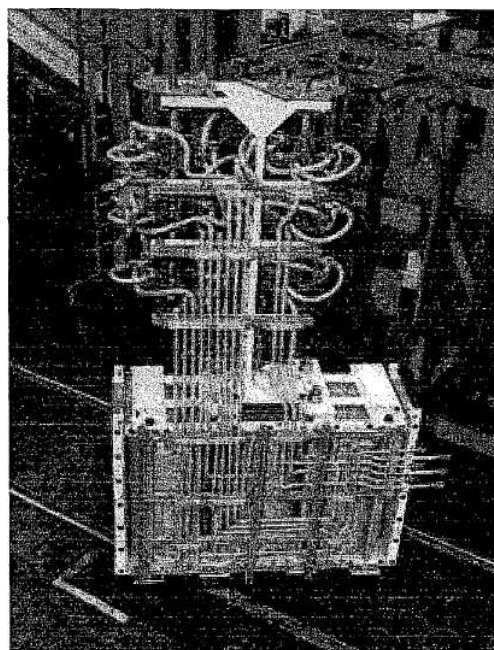
Other characteristics of some special types of furnace transformers are given below:

No load star delta switchover of the high voltage winding of furnace transformers with variable flux voltage regulation is used to reduce the built in power in cases where big tapping ranges are required. If for instance a voltage range $U_{max}/U_{min} = 1 / 0,33$ is foreseen, the built in power is only 1,49 times the rated power if such a switchover connection is used, (compare also 3.1.4).

An individual regulation of each phase can be realised. In this case, a zero sequence flux can occur. Special measures have to be taken in this case.

Furnace transformers for ac-furnaces can be built also as single phase units. In the case of the so called Knappsack-connection, three single phase units are arranged symmetrically around the furnace. Due to the geometrical symmetry the impedance of the three phases is nearly the same. This leads to a uniform load of the three phases. This advantage is compensated by higher manufacturing cost and greater content of material of the single phase units compared with a three phase unit.

Furnace reactors are used mainly in connection with furnace transformers of high rating to regulate the impedance of the plant (in order to achieve a more stable arc). The reactance of such reactors can be changed in 3 to 7 steps with the use of a no load tap changer. The more expensive solution with an onload tap changer can also be chosen. The reactor can normally be included in the transformer tank.

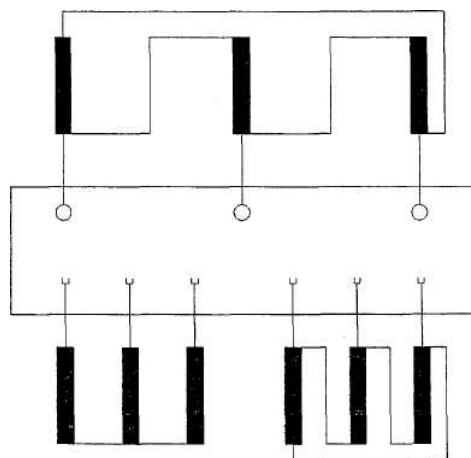


Furnace reactor with attached tap changer to be included in the main transformer tank.

3.2. Transformers for DC-Furnaces

This type of transformer contains some elements from conventional rectifier transformers (used in electrolysis plants or dc-drives) and other elements from ac-furnace transformers.

Transformers for dc-furnaces can be built to be connected to medium voltage systems and to high voltage systems. All kinds of voltage regulation mentioned above can be foreseen in principle for this type of transformer too. In many cases rectifiers with thyristors are used. In this case the voltage regulation can be done via thyristors and there is only a small tap changing equipment necessary or it can be even omitted. If a tap changer is foreseen, it is normally a no load tap changer.



The both low voltage windings are connected to the rectifier. They are connected in star and delta re-

spectively. A special 6 pulse connection has been developed by Siemens in order to minimise the flicker phenomenon. This connection requires two low voltage windings, both connected in star or both connected in delta.

The amount of harmonics caused by the arc are less in the case of dc-furnaces, as the dc-arc burns smoother than the ac-arc. But in this case the additional harmonics produced by the rectifier have to be considered in the design of the transformer (see also 4.2.1). The influence of the harmonics generated by the rectifier can be reduced by increasing the pulse order. In the case of a bridge connection of the rectifier, a 12 pulse system can be achieved by using one low voltage winding in star connection and one other in delta connection. By the use of phase shifting windings 24 pulse-, 36 pulse- and even higher pulse order connections can be realised.

The short circuit current is lower than in the case of ac-furnaces, because of the current limiting properties of the rectifier.

4. Mechanical Design of Furnace Transformers

4.1. Transformer Core

The core carries the main magnetic flux of the transformer. The form of the core is the same as used in regular power transformers. The core consists nowadays of grain oriented magnetic steel of the H1B class. A favourable distribution of loss and temperature in the core is achieved by using the so called step lap stacking of the core sheets. The maximum flux density has to be chosen taking into account the voltage harmonics produced by the rectifier, which can lead to an increase of the loss and temperatures of the core.

If the voltages of each phase are regulated individually, a zero sequence flux can occur. If there is no delta winding on the core, a return path for the zero sequence flux has to be foreseen.

Due to the currents and forces produced in the windings of furnace transformers, vibrations are transmitted from the windings to the core. Core sheets and other parts of the core have to be secured against movement.

The core of furnace transformers for dc-furnaces can be built in double tier form. The differential flux can be carried by intermediate yokes which are placed between the middle of the core legs.

4.2. Windings of Furnace Transformers

4.2.1 .Stresses

Frequent short circuits of the electrodes produce high magnitudes of the load currents (about 2.5 times the rated current). The shape of the currents can be distorted due to the nonlinearity of the arc resistance. The frequent reignition of the arc can lead to inrush currents with high magnitudes.

High forces are generated in the windings due to the high magnitude of these currents. Many measures are required in the design stage, during manufacturing and in the winding treatment process in order to control these forces.

Some keywords for this are: detailed calculation of stresses and forces, careful selection of the materials used, proper dimensioning of all supports inside and outside the windings, securing all parts against movement, manufacturing with very small tolerances, proper drying and pressing of the windings in order to eliminate the plastic component of the windings, excellent symmetry of the windings.

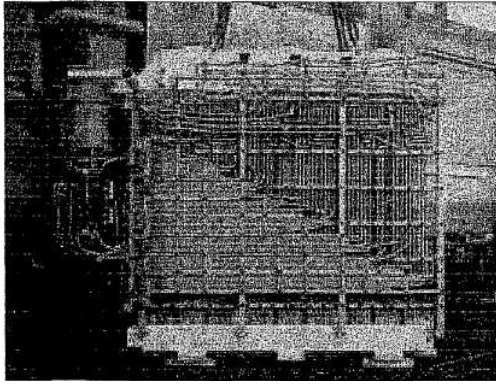
The influence of the harmonics of the current has to be considered in the thermal design of the windings. This applies especially in the case of dc-furnace transformers, where the stray losses can be doubled or even tripled by the harmonics of the current.

Traditionally loss evaluation has not the same importance for furnace transformers than for power transformers. Therefore higher current densities are chosen in the case of furnace transformers. Therefore a very effective cooling is required. In many cases the OD-cooling (oil-directed) is used, where the oil is directly pumped through the windings.

4.2.2.Design of the Windings

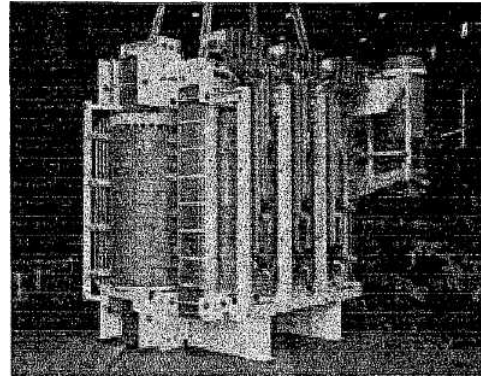
The conductors used for high voltage windings are bare conductors or continuously transposed conductors for higher ratings. Layer windings are used in the case of lower voltage levels, otherwise disc windings are used. Disc windings can be interleaved at the line end of the windings in order to control the impulse voltage distribution inside the windings.

The conductors used for regulating windings can be also bare conductors or continuously transposed conductors. The control of impulse voltages and resonant voltages is of major importance for regulating windings. Especially switching operations can cause resonant frequencies, which can be in the range of the resonant frequencies of tapping windings. The voltages which can occur in this case have to be controlled in order to assure the reliability of the transformer.



The leads of the regulating winding are connected to the tap changer.

The types of conductors used in the low voltage windings are mainly continuously transposed conductors, cylinders of copper, or clamps of copper. In the past also bare conductors have been used.



If clamps of copper are used, they can be connected in parallel and in series.

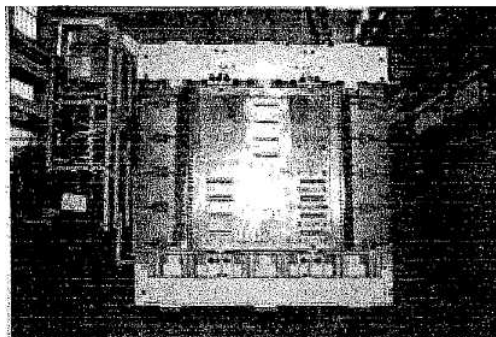
Low voltage leads can carry currents up to 100 kA. Therefore special measures are required to assure a proper current distribution within the windings and leads.

4.3. Low Voltage Connections of Furnace Transformers

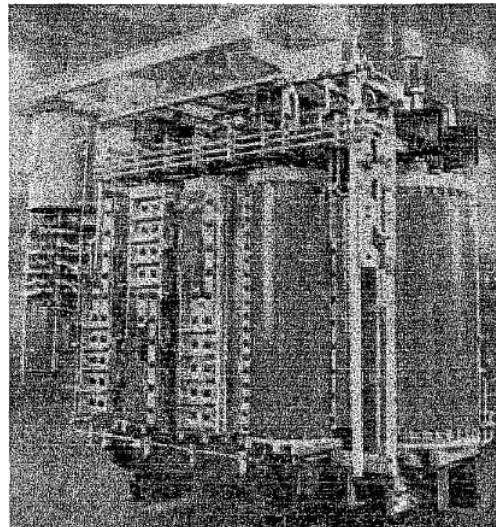
Bushings consisting of flat bars of copper can be used up to currents of 60 kA.. A transformer with such bushings arranged on the top of the active part (cover of the tank) can be seen in the figure above.

For higher currents water cooled bushings consisting of bent copper tubes are used (see the picture below).

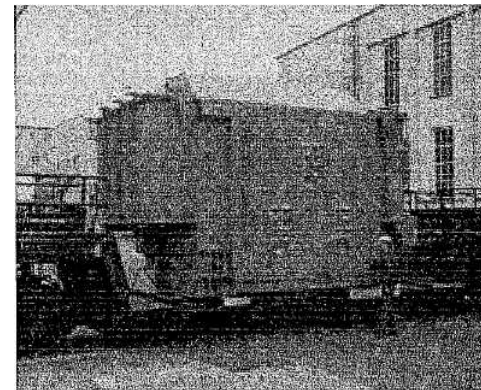
Bushings can be placed on the tank wall or on the cover of the tank. The bushings are arranged very often in the form of a triangle. This makes it possible that the leads to the furnace can be arranged symmetrically in order to achieve nearly equal impedances and currents in all the phases.



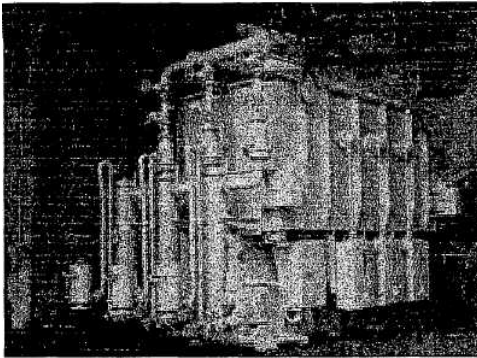
If continuously transposed cables are used, the low voltage windings consist normally of many groups of transposed cables which are connected in parallel by the use of huge bars of copper.



One or two turns can be realised by the use of cylinders of copper.



4.4. Cooling



The outer cooling system consists normally of oil-water coolers by which the heat can be led away in a space saving manner.

4.5. Tap Changing Equipment

The voltage can be regulated normally by an on-load tap changer or by a no load tap changer. The contacts of tap changers for furnace transformers are made normally of material of higher quality. The contacts may have bigger diameters than normally. The special circumstances of furnace operation have to be considered for the selection of the switching capacity.

Due to the increased number of switching operations and due to the fact that high amplitudes of current have to be switched, the oil in the switching compartment of on-load tap changers will be deteriorated faster. Therefore it is advisable to use oil filters.

4.6. Screening

The stray field of the windings and of the leads which carry high currents can induce eddy currents in metallic parts. These eddy currents can cause high losses and temperatures. These losses and temperatures can be controlled by the use of magnetic and nonmagnetic screens.

4.7. Protection Against Overvoltages

Switching overvoltages can be generated when switching-off furnace transformers. They can be high when loads are switched off but can be relevant also when the unloaded transformer is switched-off.

Resonant events are of major importance. If frequencies are generated which correspond to the resonant frequencies of the transformer, high overvoltages can be generated inside the transformer. Resonant events can be started by reignitions of switches during load-switch-off or by arc interruptions in service.

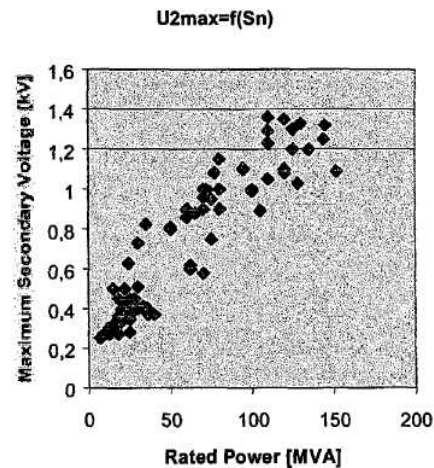
The protection of transformers against resonant overvoltages can be done as follows: choosing different resonant frequencies for the system and for the transformer, using R-C damping elements,

protection of terminals with surge arresters and protecting parts of the transformer windings by voltage limiting elements.

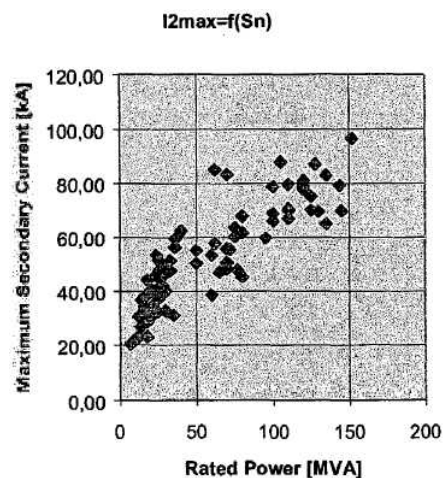
5. Limitations of the Rated Power

Furnace transformers have been built up to a maximum power of 150 MVA and up to maximum low voltage currents of 100 kA.

The following chart shows which secondary voltages are normally chosen for transformers of different power ratings. The graph is based on data of transformers manufactured in the Siemens Factory in Nürnberg. The range of the ladle furnace transformers with rated power up to 50 MVA can be recognised in the graph.



The r.m.s value of the secondary currents is in the range of 20 to 100 kA. The current is limited due to the maximum load of the electrodes used in furnaces. The dependence of secondary currents from the rated power is shown in the following chart, which is based on transformers manufactured in the Siemens Factory in Nürnberg.



It is possible, from our point of view to build furnace transformers of higher rated power in the future.

The secondary current of furnace transformers is limited due to the following factors:

- The width of transformer windings is limited due to the losses produced by the stray field.
- Available space for the low voltage bushings
- Current distribution in the low voltage bushings

A maximum secondary current of 120 kA can be reached based on the limitations given above if a conventional design is used.

The primary current is limited by the tap changers which are available. Tap changers for furnace transformers are available up to a maximum current of 3000 A. The rated power of furnace transformers is limited based on this consideration as follows:

Primary Voltage [kV]	Rated Power [MVA]	
	HV-Delta	HV Star
10	90	50
20	180	100
30	270	150

This consideration is not valid for transformers with intermediate circuit because the current of the intermediate circuit can be chosen individually.

If a rated secondary voltage of 1500 V and a maximum secondary current of 80 kA would be chosen, the rated power of the transformer would be:

$$S_n = 1500V \times 80kA \times \sqrt{3} = 210MVA$$

Such a transformer could be built with a primary voltage of 30 kV. Also if the primary voltage would be 110 kV or 220 kV the transformer could be built with intermediate circuit or with directly connected autotransformer.

Other limitations can be:

- Maximum dimensions and weight with regard to the transportation possibilities
- Production capabilities of the manufacturers

6. Example of a Furnace Transformer

The technical data of a furnace transformer with variable flux voltage regulation will be discussed below, based on the data of the rating plate (see Appendix 1 and 2).

Rated Power	105 MVA
constant up to	837 V
Vector group	DdO
Rated primary voltage	30 kV
Secondary voltage	
maximum	960 V
minimum	550 V
steps	18
Secondary current	73 kA

Furnace Transformers

Short circuit voltage

Tap position 18	7%
Tap position 13	10,5%
Tap position 1	18,2%

The short circuit reactance can be calculated based on the short circuit voltage. It will be related to the secondary voltage:

At tap position 18:

$$X_2 \approx \frac{u_k}{100\%} \cdot \frac{U_{02}^2}{S} = \frac{7\%}{100\%} \cdot \frac{(0,96kV)^2}{105MVA} = 0,61m\Omega$$

$$X_2(Tap_position_13) = 0,67m\Omega$$

$$X_2(Tap_position_1) = 0,79m\Omega$$

Although the short circuit voltage increases with higher tap positions, the reactance seen from the secondary terminals remains nearly unchanged.

The resistance related to the secondary terminals can be derived from the short circuit loss (approx. 520 kW on tap position 18):

$$R_2 = \frac{P_{cu}}{3 \times I^2} = \frac{520kW}{3 \times (63kA)^2} = 0,044m\Omega$$

The transformer is equipped with a reactor connected in series to the high voltage winding, with an onload tap changer. The reactance of this reactor related to the primary terminals as well as to the secondary terminals (reduced by the square of the transformation rate u) is given in the table below:

Tap pos. reactor:	10	9	5	1
Primary side delta	0Ω	0,56 Ω	2,63 Ω	4,93 Ω
Primary side, star	0 Ω	0,19 Ω	0,88 Ω	1,64 Ω
Secondary side		0,19 m Ω	0,90 m Ω	1,68 m Ω
Tap position 18	0 Ω			
Secondary side		0,064 m Ω	0,29 m Ω	0,55 m Ω
Tap position 1	0 Ω			

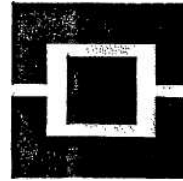
The effect of the reactor on the secondary side is greater if the transformation ratio is lower, i.e. if the secondary voltage is higher.

Bibliography

- [1] Feyertag, H.: Transformatoren für Lichtbogenöfen, Klepzig Fachberichte 82 (1974) Heft 4
- [2] Heindl, H.: Ofen- und Gleichrichtertransformatoren, ETZ-A, Heft 3, 1977
- [3] Timm, K.: Elektrotechnik des Lichtbogenofens, Seminar vom 19. Bis 22. Oktober 1999 in Saalfeld

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Trafo - Union

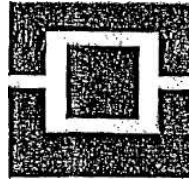


Typ	TWPW 8246	FTNR	N 407 912	Baujahr	1993	VDE	0532 / 03.82
Bemessungsleistung	105 000 ¹⁾ kVA	Art Type	LT / S			Isolationspegel:	LI 170 AC 70 / LI - AC 3
Schaltgruppe	Dd0	Betrieb	DB	Bem. - Frequenz	50 Hz	Kühlungsart	ODWF
Stellung	Bemessungsspannung <i>Tap Voltage</i>		Bemessungsstrom <i>Tap current</i>		u_z ²⁾		
18	30 000 V	960 V	2 021 A	63 148 A	7,0 %		
13	30 000 V	808 V	1 966 A	73 038 A	10,5 %		
1	30 000 V	550 V	1 338 A	73 038 A	18,2 %		
Dauerkurzschlußstrom OS	15,5 kA	Kurzschlußdauer max.	2 s		Umgebungstemperatur max.	<i>Temp</i> 40°C	
Kessel und Ausdehnungsgefäß	vakuumfest <i>Tauche</i>			Gesamtgewicht	135 t	Ölgewicht / -sorte	36,5 t / DEA GK 2 / 1
Transport auf Fwb 272	<i>Transport über die Fwb</i>			Heraushebbarer Teil	22 + 59,5 t	Transportgewicht	97 t
Stufenschalter (Transformator) Typ	3 x MI 1 500 - 60 / B 18 180			Nennstrom	1 500 A	U_m	72,5 kV
Stufenschalter (Drosselspule) Typ	3 x MI 1 500 - 60 / B 10 100			Nennstrom	1 500 A	U_m	72,5 kV
Kühlleistung je Kühlkreis bei zulässiger Ölbertemperatur	410 kW			Übertemp. Öl/Wicklung	42 / 60 K	Anzahl der Kühlkreise	3
Höchstzulässige Eintrittstemperatur des Kühlwassers	30°C			Öldurchsatz je Kühlkreis	105 m³/h	Eigenverbrauch je Kühlkreis (+25°C)	3,9 kW
Wasserdurchsatz je Kühlkreis	33,9 ³⁾ m³/h			Erforderliche Anzahl der Kühlkreise bei Betrieb mit Bemessungsleistung	2		

- 1) Leistung konstant bis sek. 830 Volt, dann sinkend mit der Unterspannung.
 2) ohne Reihendrosselspule
 3) plus 2 m³/h für die Sekundärableitungen

Terminale Oberspannung / <i>Tap</i>					Unterspannung		
Schaltung Anschluß	Spannung V	Strom A	Feinwähler-Verbindung	Stellg.	Schaltung Anschluß	Spannung V	Strom A
	30 000	2 021	2	18		960	63 148
			30	17		925	65 529
			29	16		894	67 839
			28	15		864	70 148
			27	14		837	72 457
		1 966	26	13		808	73 038
			25	12		781	
			24	11		755	
			23	10		732	
			22	9		709	
			21	8		686	
			20	7		665	
			19	6		642	
			18	5		621	
			17	4		602	
			16	3		583	
			15	2		566	
			14	1		550	

Eingebaute Drehstrom - Reihen - Drosselspule		
FTNR	N 407 913	
Typ	DWPW 7346	
Kühlungsart (Type Cooling)	ODWF	
Bemessungsleistung	kVA	19 600
Netzspannung	V	30 000
Bemessungsstrom	A	2 021 / $\sqrt{3}$
Schaltung	Vector Group	III
Bem. - Frequenz	Hz	50
<i>Rated Frequency Tap Selector</i>		
Reaktanz / Phase Ω	Feinwähler-Verbindung	Stellg.
0	1	10
0,56	3	9
1,07	4	8
1,76	5	7
2,17	6	6
2,63	7	5
3,12	8	4
3,68	9	3
4,28	10	2
4,93	11	1



Ofentransformatorensatz

Typ TWPW 8246 + DWPW 7346

FTNR

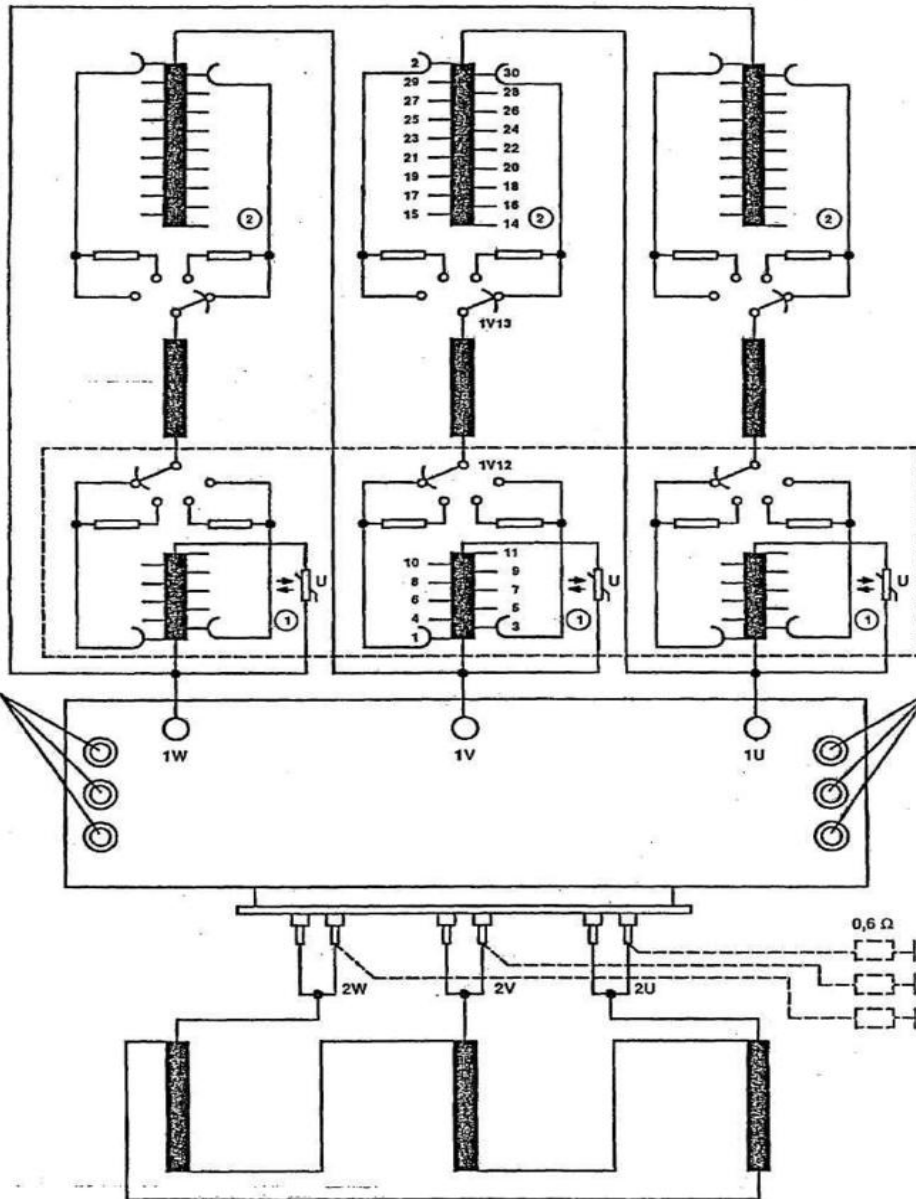
N 407 912 - 913

RC - Beschaltung
der Stufenwicklungen
siehe Betriebsanleitung

Reihen - Drosselspule

Stufenschalter für
Reihen - Drosselspule

Stufenschalter für
Transformator



US - Seite

- ① Parallel zur Wicklung der Reihen - Drosselspule sind 14 ZNO - Elemente geschaltet.
- ② Überspannungsschutz der Stufenwicklung durch Parallelschalten eines RC - Elements ($R = 63 \Omega$, $C = 185 \text{ nF}$) zwischen Anzapfung 14 und 16.

Calculation of the Short Circuit Impedance of the Transformer

$$X_2(\text{pos.18}) \approx \frac{u_k}{100\%} \cdot \frac{U_{02}^2}{S} = \frac{7\%}{100\%} \cdot \frac{(0.16 \text{ kV})^2}{105 \text{ MVA}} = \dots\dots\dots m\Omega$$

$$X_2(\text{pos.13}) \approx \frac{u_k}{100\%} \cdot \frac{U_{02}^2}{S} = \frac{10.5\%}{100\%} \cdot \frac{(0.81 \text{ kV})^2}{102 \text{ MVA}} = \dots\dots\dots m\Omega$$

$$X_2(\text{pos.1}) \approx \frac{u_k}{100\%} \cdot \frac{U_{02}^2}{S} = \frac{18.2\%}{100\%} \cdot \frac{(55 \text{ kV})^2}{64.5 \text{ MVA}} = \dots\dots\dots m\Omega$$

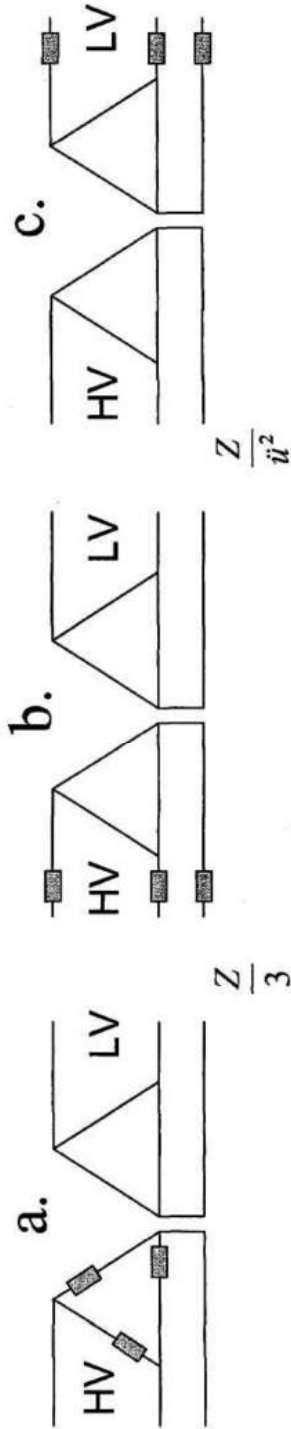
$$R_2 = \frac{P_{Cu}}{3 \times I^2} = \frac{\dots\dots\dots kW}{3 \times (.63 \text{ kA})^2} = \dots\dots\dots m\Omega$$

Consideration of the Impedance of the Reactor

Tap Position of the Reactor:	10	9	5	1
a.) Impedance of the Reactor	0..... Ω	0.54..... Ω	2.63..... Ω	4.93..... Ω
b.) HV-Side Star	0..... Ω	0.19..... Ω	0.88..... Ω	1.64..... Ω
c.) LV-Side Tap position 18	0..... $m\Omega$	0.19..... $m\Omega$	0.90..... $m\Omega$	1.68..... $m\Omega$
c.) LV-Side Tap Position 1	6..... $m\Omega$	2.064..... $m\Omega$	0.29..... $m\Omega$	0.55..... $m\Omega$

31.3

54.5



Main Data of the Rating Plate

Annex 3

Type TWPW 8246		FTNR N 4 7912		Year of Manuf. 1993		VDE 532/ 3.82	
Rated Power 1 5 kVA 1)		Type PT/T		-		Insulation Level: L117 AC 7 / LI - AC 3	
Vector Group Dd		Continuous Operation		Rated Frequency 5 Hz		Type of Cooling OFWF	
Tap	TapVoltage			Tap Current		zu 2)	
18	3 V	96 V		2 21 A	63 148 A	7%	
13	3 V	88V		1 966 A	73 38 A	1.5 %	
1	3 V	55 V		1 338 A	73 38 A	18.2 %	
Short Circuit Current (r.m.s) 15.5 kA		Duration of s.c. max. 2 s				Max. Ambient Temperature 4 °C	
Tank and Conservator Vacuum Proof				Total Mass 1351		Mass/Type of Oil 36.5t DEA GK 2/1	
Transportation on Fwb 272				Untanking Mass 22 +59.51		Transportation Mass 97 t	
Tap Changer (Transformer) Type 3xMI 15 -6 /B 18 18				Rated Current 15 A		Urn 72.5 kV	Revol. of Drive Shaft/Step 16.5
Tap Changer (Reactor) Type 3xM11 5 -6 /B 1 1				Rated Current 15 A		Um 72.5 kV	Revol. of Drive Shaft/Step 16.5
Cooling Capacity per Circuit at Max. Top Oil Temp. 41 kW				Temp. Rise Oil/Winding 42/6 K		Number of Cooling Circuits 3	
Maximum Temperature of Inflowing Cooling Water 3 °C				Oilflow per System 1 5 m ³ /h		Consumption per Circuit (+25°C) 3.9kW	
Required Cooling Water per Circuit 33.9 m ³ /h 3)				Number of Cooling Circuits required at Rated Power 2			

1) Power constant up to 83 Volt, then decreasing with secondary voltage

2) Series reactor not included

3) plus 2 m³/h for secondary bushings

High Voltage					Low Voltage			Built in 3 Phase Series Reactor		
Terminals	Voltage V	Current A	Position Selector	Tap Position	Terminals	Voltage V	Current A	FTNR	N 4 7 913	
	3	2 21	2	18		96	63 148	Type	DWPW 7346	
			3	17		925	65 529	Type of Cooling	OFWF	
			29	16		894	67 839	Rated Power	19 6 kVA	
			28	15		864	7 148	System Voltage	3 kV	
			27	14		837	72 457	Rated Current	2 21 / √3A	
		1966	26	13		88	73 38	Vector Group	III	
		1 91	25	12		781		Rated Frequency	5 Hz	
		1 839	24	11		755		Reactance/ Phase Ohm	Tap Selector	Tap Position
		1 781	23	1		732			1	1
		1 727	22	9		79		,56	3	9
		1 671	21	8		686		1,7	4	8
		1 618	2	7		665		1,76	5	7
		1 564	19	6		642		2,17	6	6
		1 513	18	5		621		2,63	7	5
		1465	17	4		62		3,12	8	4
		142	16	3		583		3,68	9	3
		1378	15	2		566		4,28	1	2
		1 338	14	1		55		4,93	11	1

Steel Academy

International Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Energy Balance of the Electric Arc Furnace

Univ.-Prof. Dr.-Ing. Herbert Pfeifer,
RWTH Aachen

Energy Balance of the Electric Arc Furnace

Development of the steelmaking processes

During the production of metallic materials a high degree of recycling of scraps from production and fabrication already exists, In addition the mostly long life products are fed to the material circuit again after the service life.

Considering the development of the steelmaking processes before this background in Germany (fig. 1), the available process mix should be able to recycle all the available scrap.

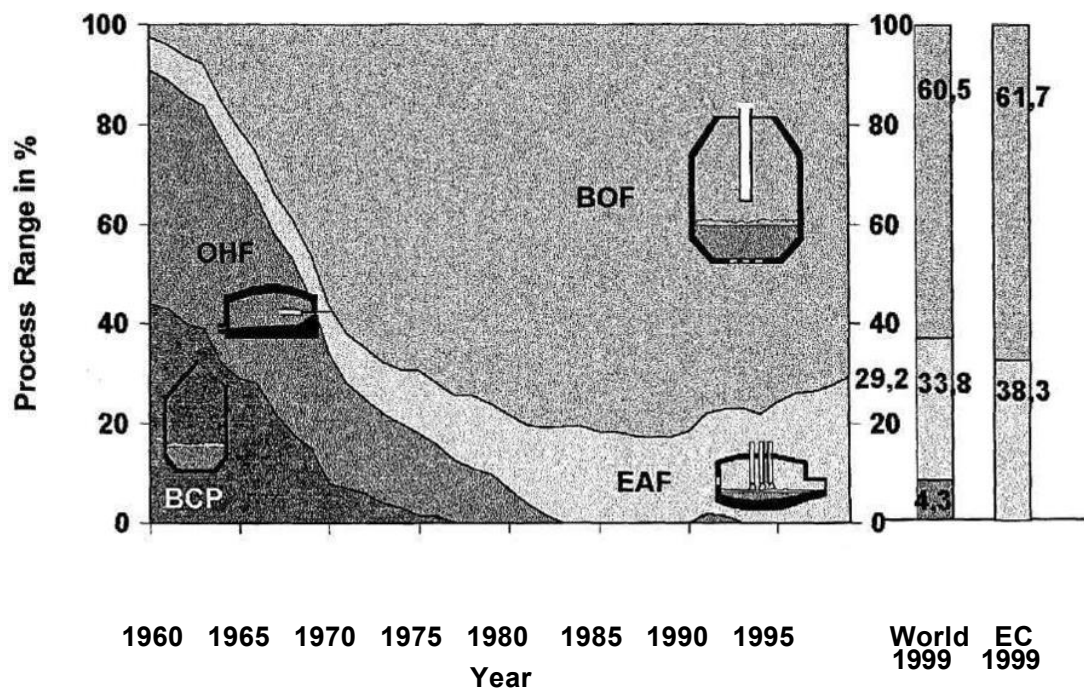


Fig. 1: Change of the steelmaking processes in Germany

In the year 1960 the percentage of the open hearth furnace (OHF) and electric arc furnace (EAF) operating on scrap base was 50 % . The blast oxygen furnace (BOF) developed in the fifties began the technological victory train in the sixties and replaced the bottom blowing Thomas converter (Basic Converter Process BCP) working with air, in which due to the high nitrogen content only steels grades with lower qualities could be produced, as well as the gas fired open hearth furnace working on scrap base. In this time the integrated steel mills with typical converter sizes of 300 t were build up. In the blast oxygen converters can be inserted approx. 25 to 30 % of the metallic input as scrap due to the energy surplus of the exothermic reactions of the oxygen with the elements C, Si, Mn, P and S and in part also iron.

The part of the electric steel production increased in this time from 8 % in the year 1960 to 26,4 % in the year 1997 *III*. With that the part of the electric steel production is by far lower in Germany than in the world wide or European average of 34 % *III*. From the open hearth fur-

nace process the product spectrum of the stainless steels and the structural steels, for example for the automotive industry, was taken over. The reasons for the change of the technology were the higher productivity, the improved quality of the products and the reduced costs.

The most important reason for the comparably small percentage of electric steel production in Germany compared with the world wide percentage is to be seen in the high costs which are to be paid in Germany for the electric energy.

A further reason is to be seen in the production range of the steel industry in Germany. Ultra clean steel grades for automotive, shipbuilding, off-shore-plants and the package industry determine the production programme to about 2/3. Here the production route with ore as raw material and BOF process is clearly held over the electric steel process with steel scrap as raw material with regard to low contents of tramp elements. The product spectrum of the electric steel plants contains basically long products in the form of concrete and wire steels and structural steels for the automotive industry. Stainless steels are produced mainly as flat products and in smaller circumference also as long products [21].

Scrap

Fig. 2 clarifies, that the specific scrap mass was small for the basic converter process. The available scrap from the open hearth process was used as raw material partially in the BOF process and mainly in the electric arc furnace process. It becomes, however, clear that Germany developed to a scrap export country due to the lower electric steel ratio since the mid eighties.

If one considers the scrap import/export of Germany to countries (fig. 3), so it becomes clear, that the highest exports occur to the Netherlands, Belgium/Luxembourg, France and to Italy. The scrap imports are small. In 1999 there were imports of approx. 2,7 Mio. t scrap and exports of approx. 7 Mio. t scrap. With that Germany is a scrap exporting country which has basic recourses for an expansion of the electric steel production.

The remelting of scrap is also reasonable from energetic viewpoint. The specific primary energy consumption of steelmaking processes is dependent from the inserted raw materials. In fig. 4 the specific primary energy consumption of different steelmaking processes is given depending on the charged scrap ratio [3]. At the determination of the primary energy consumption all energies were considered, that will be needed for the production of the raw materials, surcharges and supplements as also the operating and consumption materials, that is for

cooling water, electrodes and refractory materials. For the transformation and distribution of the electrical energy an efficiency of 34,5 % is estimated. The scrap is evaluated energetically with the value 0.

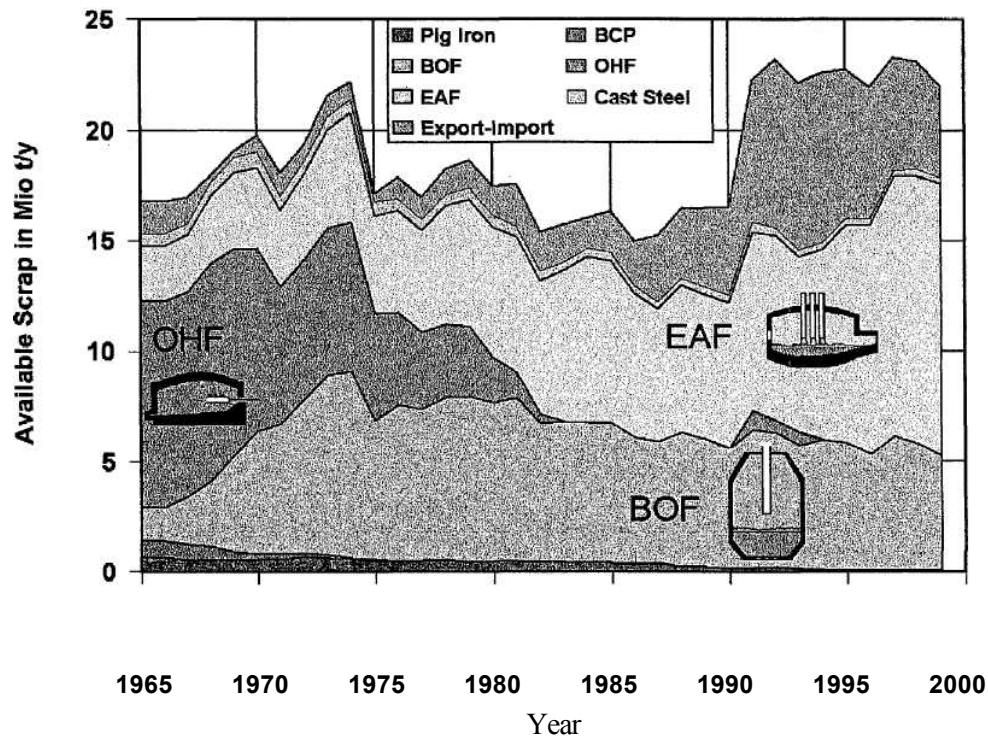
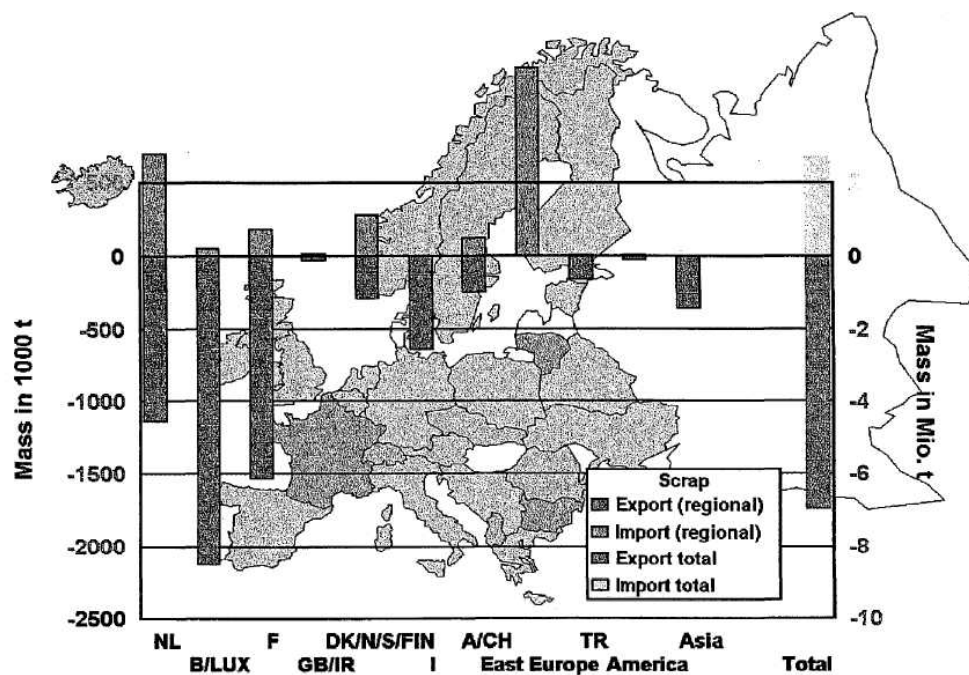


Fig. 2: Statistic of scrap in Germany



Quelle: Statistisches Jahrbuch der Stahlindustrie 2000/2001

Fig. 3: Scrap import/export of Germany (1999)

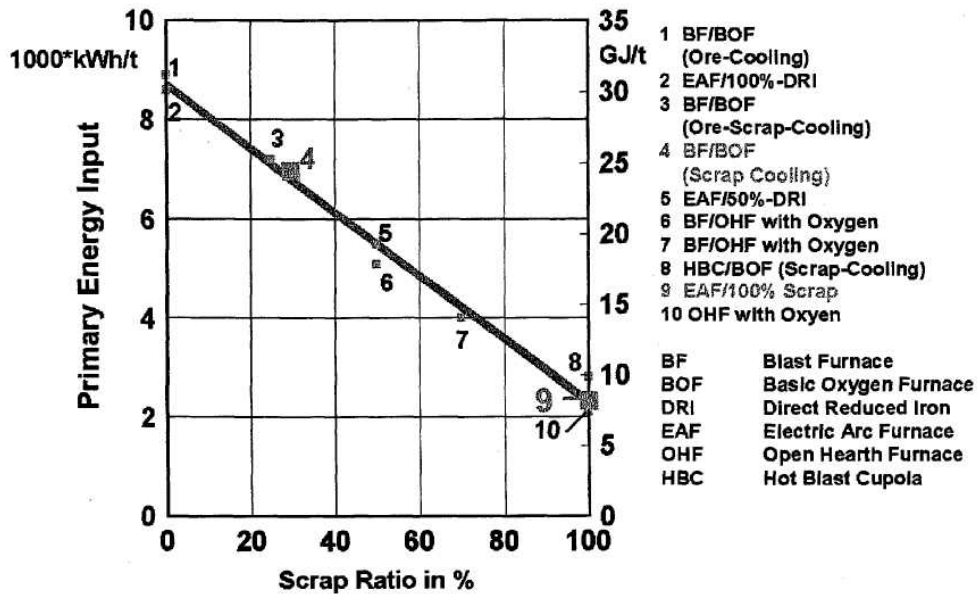


Fig. 4: Specific primary energy consumption for different steel production routes /3/

Development of the electric steel process

The economical steel production in electric arc furnaces was enabled by an enormous development of the electric arc furnace in the last three decades (fig. 5) /4/. Technological developments decreased the specific energy consumption, tap to tap-time and specific electrode consumption clearly and increased with that the efficiency and productivity of the arc furnaces very considerably.

Through that mini mills with electric arc furnaces are suitable to produce economically standard steels as long and flat products, latter in connection with the thin slab technology. The effects of different measures onto the energy balance and the change of the specific energy input are essential content of this lecture.

The number of the electric arc furnaces decreased in the last years. For that the furnaces became, however, higher-performance. Fig. 6 shows the decreasing number of the furnaces beginning in the year 1970 up to the year 1999 *III*, the increasing electric steel production of 5 Mio. t/y on approx. 12 Mio. t/y and the enlargement of the average production per furnace of 50000 t/y on almost 425 0000 t/y. Some electric arc furnaces achieve a productivity of up to 1 Mio. t/y.

If one compares the statistically electric energy input (melting current, operating current) with the annual electric steel production and considers the specific electric energy input, so three typical developments are detectable (fig. 7):

- Reduction of the specific energy consumption of approx. 7 kWh/ty from 1960 to 1970 (reasons: for example larger furnace units).
- Increase from 550 kWh/t on 620 kWh/t from 1970 to 1975
(reasons: dedusting of the electric arc furnaces
higher tapping temperatures due to higher rate of secondary metallurgy
water cooling of furnace components - cover, wall)
- Reduction of the specific energy consumption of approx. 5 kWh/ty since 1975
(reasons: development of the process engineering
oxygen metallurgy
foamy slag metallurgy)

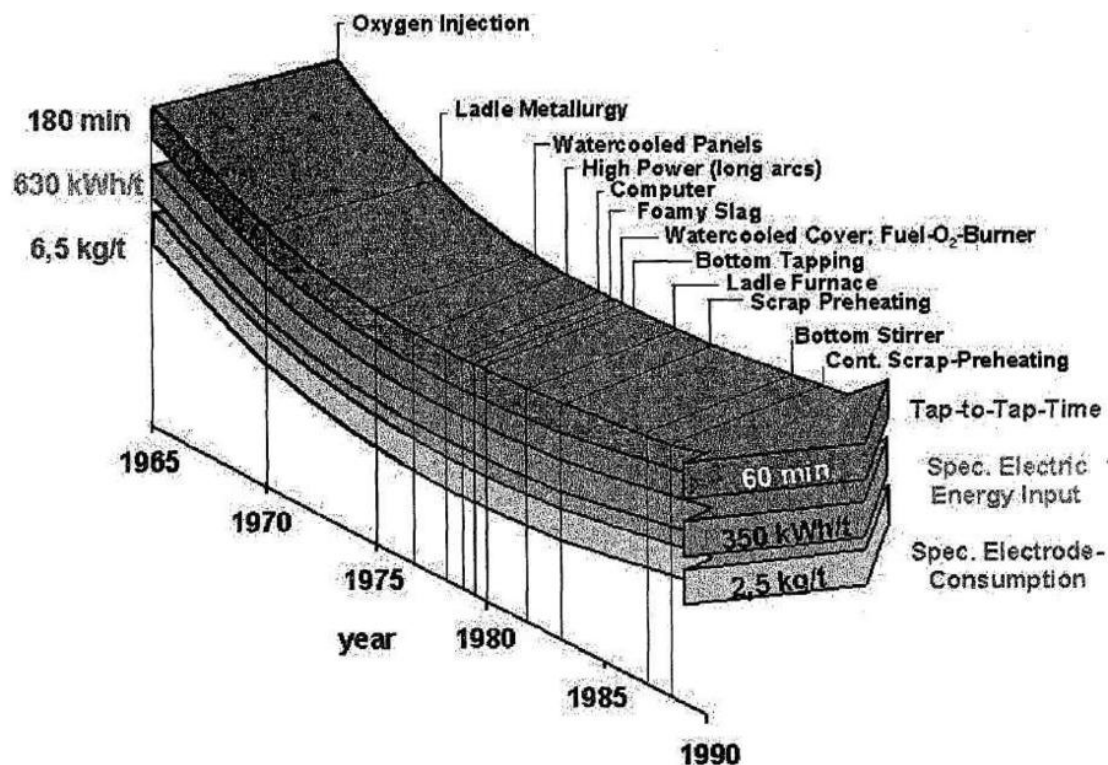


Fig. 5: Developments of the electric arc furnace

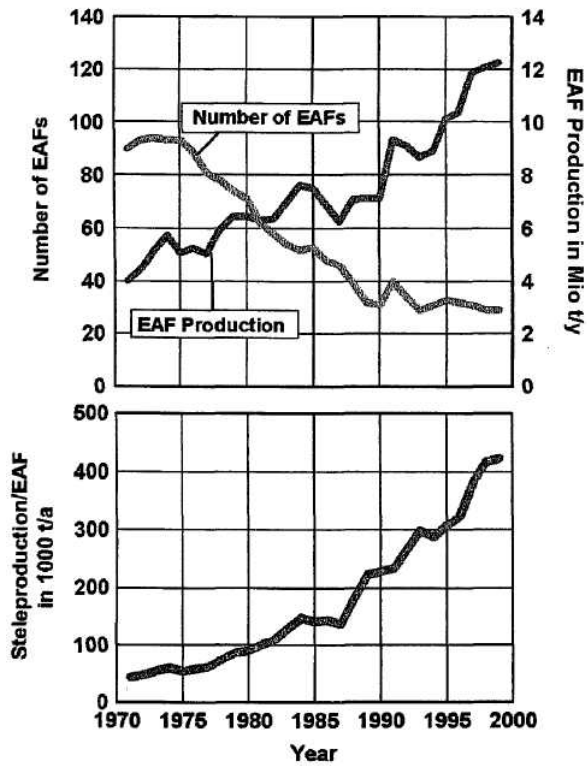


Fig. 6: Development of the electric steel production in Germany

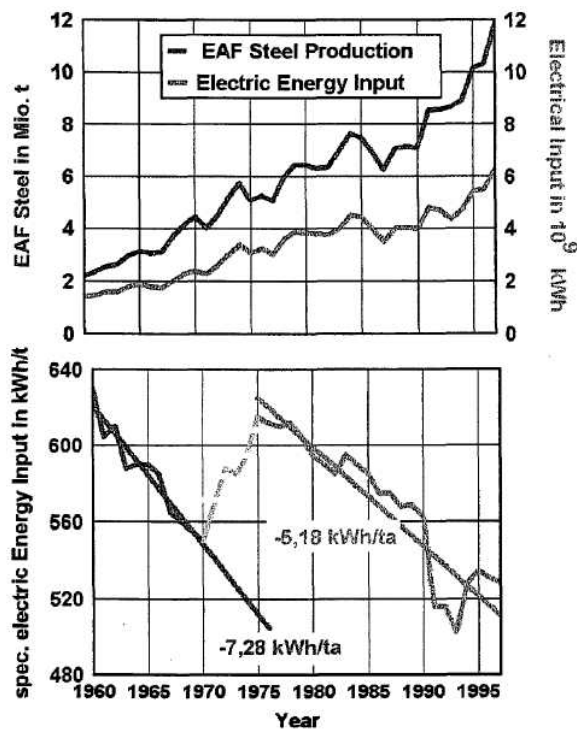


Fig. 7: Development of the production and the absolute as well as the specific energy input for the electric steel production

Mass and energy balance

The mass and energy balances are necessary for the evaluation of processes under each other, for the comparison of concurrent technologies as well as for the energetic optimisation of processes. In particular in processes with metallurgical reactions the mass- and energy balance are closely coupled with each other.

Mass balance of the electric arc furnace

The material or mass balances are the precondition for the preparation of energy balances and in addition the basis for material flow considerations of an EAF steel mill. Fig. 8 gives an general view of the data for the input and output data of discrete masses m_i or mass flows m_j for the electric arc furnace. The average data of 27 heats of a 100t-EAF are given additionally in brackets. The mass balance can be noted by

$$\sum_i m_i + \sum_j \int_{\tau_A}^{\tau_E} \dot{m}_j(\tau) d\tau = 0, \quad (1)$$

by integration from the start (TA) to the end of the heat (TE) concerning that the liquid heel is constant from heat to heat /5/.

The data for specific values of masses, e. g. dust or electrode consumption are available from statistical data.

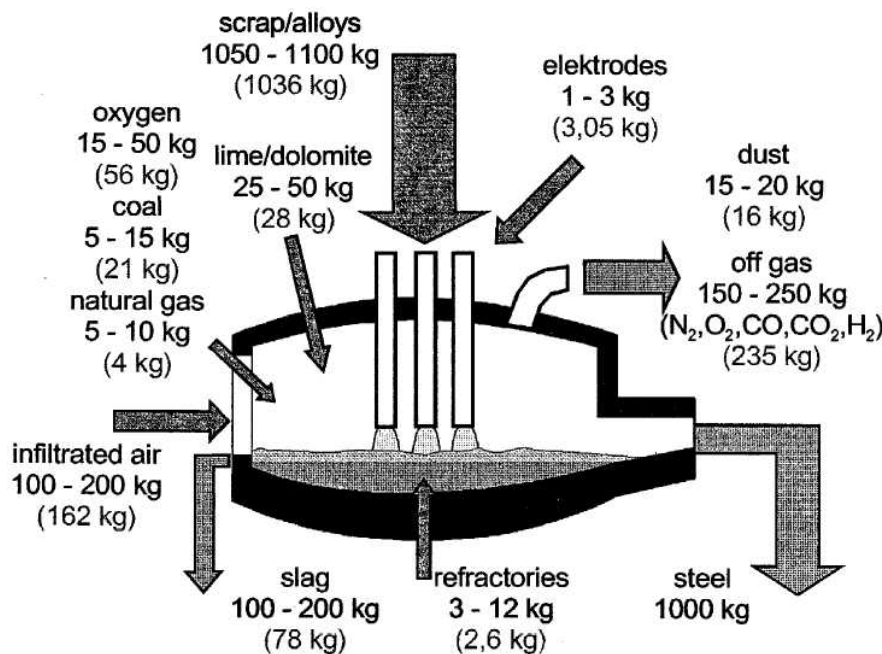


Fig. 8: Data for the mass input and output of the electric arc furnace

The table 1 lists the mass input into the electric arc furnace and the reactors of the secondary metallurgy, distinguished in metallic partitions and surcharges, for concrete reinforcing steel, structural steel as well as high alloy ferritic and austenitic stainless steels. Further materials, as the consumption of refractories for hearth and ladle and/or converter as well as electrodes, are not considered /8/. This list shows that for the melting of the different steel grades the specific mass distinguish clearly. These affects also the energy input.

		concrete steel	structural steel	ferritic stainless steel	austenitic stainless steel
		Kg/tliquid	Kg/tliquid	Kg/tliquid	Kg/tliquid
mass input electric arc furnace					
metallic input	unalloyed steel scrap	1000	1015	750	310
	alloyed steel scrap			90	490
	pig iron, cast iron	100	75		
	other alloys			260	240
	X metallic input	1100	1090	1100	1040
additions	lime	30	22	48	50
	dolomite	10	7		
	coal	14	11	6	12
	Z additions	54	40	54	62
mass input secondary metallurgy (ladle, AOD-converter)					
metallic input	alloys cooling			35	70
	scrap	17,5	31	30	60
additions	additions	4,5	6	70	70

Table 1: Data for the mass input in the electric arc furnace and the secondary metallurgy reactors /8/

Energy balance of the electric arc furnace

The high part of the energy costs from the processing costs of the electric steel production results in a high importance coming up to the energy balance of the electric arc furnaces. The aims of energy balances during the electric steel production are:

- energetic evaluation of the process
- reduction of the energy costs through decrease of the energy losses and utilisation of waste heat
- substitution of electrical energy and improvement of the energy efficiency

The basis for the energetic balancing of the electric arc furnace is the law for conservation of energy (1st law of thermodynamics). Generally this can be noted for an open system 191

$$\begin{array}{ll}
 \text{Sum of the energies, that are transported as} & \text{Change of the} \\
 \text{heat } Q, \text{ work } W, \text{ with the streaming medium} & \text{energy } U \text{ of the} \\
 \text{Has well as through metallurgical reactions} & = \\
 \text{R above the system boundaries} & \text{open system}
 \end{array}$$

and/or formally for the time dependent variation

$$\left(\frac{dU}{d\tau} \right)_{Open} = \sum_{i=1}^n (\dot{Q}_i + \dot{W}_i + \dot{H}_i + \dot{R}_i) \quad (2)$$

Under the assumption that the energy stored in the furnace is identical after every heat eq. (2) is

$$\sum_{i=1}^n \left[\int_{\tau_A}^{\tau_E} (\dot{Q}_i + \dot{W}_i + \dot{H}_i + \dot{R}_i) d\tau \right] = 0. \quad (3)$$

The fig. 9 schematically shows an electric arc furnace with the specification of the system boundary for the balancing of the system according to the 1st law of thermodynamics. The power supply of the system (transformer, possibly necessary compensation systems) and the high power supply with the occurring electric losses will be accounted in the balance. Thus the measurement of the electrical power input P_{el} and/or the electrical energy input of a heat occurs before the transformer.

$$W_{el} = \int_{\tau_A}^{\tau_E} P_{el}(\tau) d\tau \quad (4)$$

The further equations for the preparation of the energy balances of electric arc furnaces are noted in the table 2. Systems for the scrap preheating and the related post combustion units are usually/often included in the balance. On the other hand the energy used for the dedusting system (approx. 20 to 45 kWh/t /7/) and the ladle furnaces are not considered with a so choosed boundary.

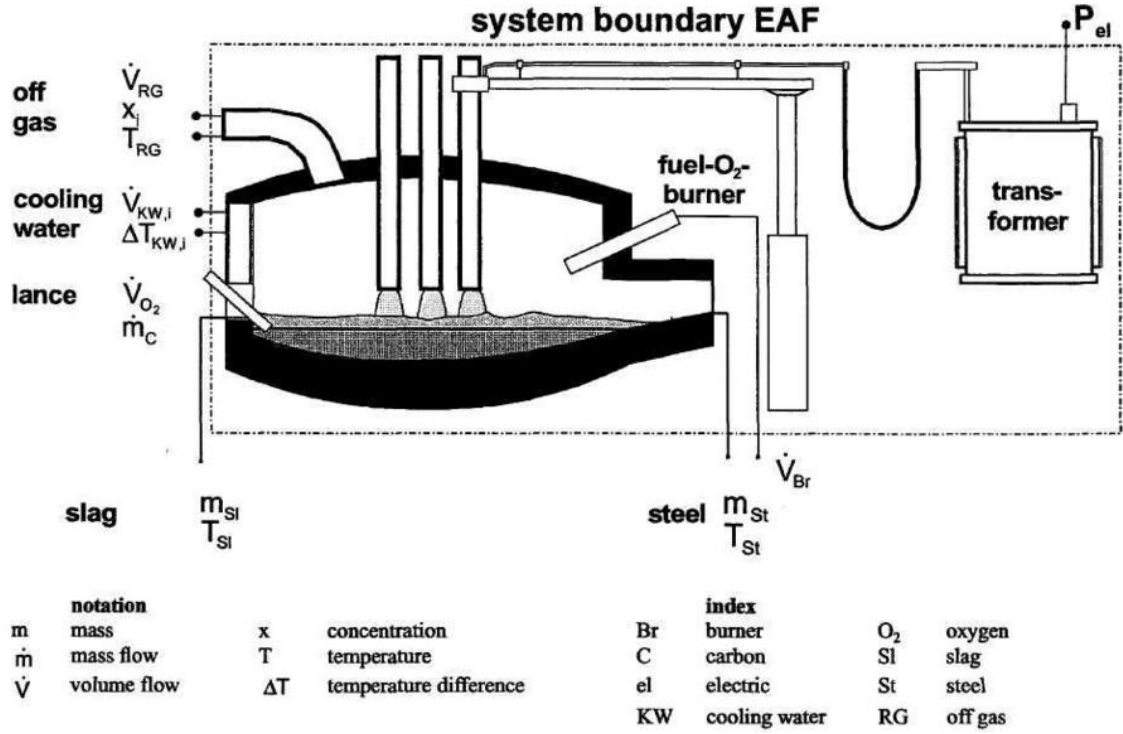


Fig. 9: System boundary for the electric arc furnace

		energy flow, power	energy	comment
In- put	electric energy	P_{el}	$W_{el} = \int_{\tau_A}^{\tau_F} P_{el} d\tau$	
	fuel-O ₂ -burners	$P_{Br} = \dot{V}_{Br} h_u$	$W_{Br} = \int_{\tau_A}^{\tau_F} \dot{V}_{Br} h_u d\tau$	
	chemical reactions		$W_i = \Delta m_i \Delta h_i$	mass balance necessary- s. table 4
Out- put	enthalpy steel		$W_{St} = m_{St} h_{St}(T)$	energy data s. table 3
	enthalpy slag		$W_{Sl} = m_{Sl} h_{Sl}(T)$	data s. table 3
	cooling water	$P_{KW,i} = c_{KW} \dot{V}_{KW,i} \Delta T_i$	$W_{KW,i} = c_W \int_{\tau_A}^{\tau_F} \dot{V}_{KW,i} \Delta T_i d\tau$	vessel, cover, elbow, high current cables, transformer
	off gas	$P_{RG} = c_p(x_i, T_{RG}) \dot{V}_{RG} \Delta T_{RG}$ $+ \sum_{i=1}^n x_i h_{u,i} \dot{V}_{RG}$	$W_{RG} = \int_{\tau_A}^{\tau_F} c_p(x_i, T_{RG}) \dot{V}_{RG} \Delta T_{RG} d\tau$ $+ \int_{\tau_A}^{\tau_F} \sum_{i=1}^n x_i h_{u,i} \dot{V}_{RG} d\tau$	

Table 2: Equations for the energy balance of the electric arc furnace

temperature t °C	spec, enthalpy steel h_{St} kWh/t	spec, enthalpy slag h_{Sl} kWh/t
1530	365	595
1600	385	627
1620	390	635
1640	395	643
1660	400	652
1680	405	660
1700	410	669

Table 3: Data for the energy balance of the electric arc furnace

reactions					energy of the reaction	
Si	+	O ₂	→	SiO ₂	- 8.70 kWh/kg _{Si}	-10,92 kWh/m ³ O ₂
Mn	+	0.5 O ₂	→	MnO	-1.95 kWh/kg _{Mn}	-9,56 kWh/m ³ O ₂
2 Cr	+	1.5 O ₂	→	Cr ₂ O ₃	-3.05 kWh/kg _{Cr}	-9,44 kWh/m ³ O ₂
S	+	O ₂	→	SO ₂	-2.75 kWh/kg _S	-3,94 kWh/m ³ O ₂
2 Fe	+	1.5 O ₂	→	Fe ₂ O ₃	- 2.03 kWh/kg _{Fe}	-6,74 kWh/m ³ O ₂
Fe	+	0.5 O ₂	→	FeO	- 1,32 kWh/kg _{Fe}	-6,58 kWh/m ³ O ₂
C	+	O ₂	→	CO ₂	- 9.10 kWh/kg _C	-4,88 kWh/m ³ O ₂
C	+	0.5 O ₂	→	CO	- 2.55 kWh/kg _C	-2,73 kWh/m ³ O ₂
CO	+	0.5 O ₂	→	CO ₂	- 2.81 kWh/kg _{CO}	-7,02 kWh/m ³ O ₂

Table 4: Chemical reactions for the energy balance of electric arc furnace

Evaluation of energy balances of the electric arc furnaces

For the evaluation of the energy balance of the electric arc furnace the efficiency is used.

$$\eta_N = \frac{\text{energy benefit}}{\text{energy input}} \quad (5)$$

By definition the efficiency is the ratio of the energy benefit and the energy input. The enthalpy of the steel melt is designated as energy benefit of the electric steel production. Going out of (5) the efficiency can be defined by

$$\eta_{N,el} = \frac{\text{enthalpy steel}}{\text{electric energy input}} \quad (6)$$

The development of the last years to an increased contribution of metallurgical - chemical reactions to the entire energy input is not considered by this formula. On the basis of a complete energy balance the following degree of efficiency can be calculated.

$$\eta_{N,ges} = \frac{\text{enthalpy steel}}{\text{total energy input}} \quad (7)$$

This definition of the efficiency considers also the other energy inputs (fuel - oxygen - burner, oxygen metallurgy, oxidation of metals, etc.).

Energy balances of different electric arc furnaces

The following energy flow diagrams of electric arc furnaces clearly show that the energy input consists of electric energy, fuels (gas, oil, coal) and exothermic (chemical - metallurgical) reactions. The output of energy is the enthalpy of the liquid steel which is taken as energy benefit of the electric arc furnace process, the enthalpy of the slag, the heat transported with the cooling water from the water-cooled panels, the off gases as well as radiation losses.

The shown energy balances distinguish considerably from each other. The energy flow diagram of a 110-t EAF shown in fig. 10 from 1980 is valid for the production of alloyed structural steel /5/.

This EAF is equipped with natural gas-oxygen-burners and no additional ladle furnace was installed at the time of the determination of this energy balance. The tapping temperatures were $>1700^{\circ}\text{C}$. In addition high amounts of charged oil yielding flakes lead to comparably high specific off gas losses.

The energy flow diagram of a 120-t EAF represented in fig. 11 is valid for the production of stainless steel /12/. The tapping temperature is 1550 to 1600°C with a following secondary metallurgy in an AOD converter. This EAF is equipped with a steam cooling system. In this case the enthalpy of the produced process steam is to be treated as energy benefit from the wall cooling and the off gas system.

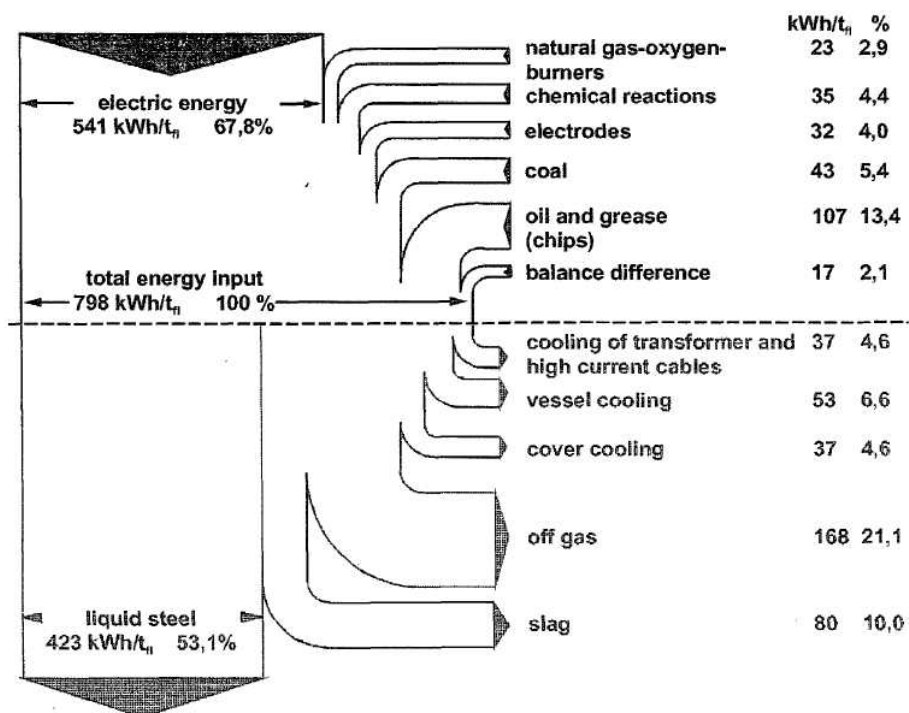


Fig. 10: Energy balance of a 100-t-EAF for the melting of alloyed structural steel (status: 1980)

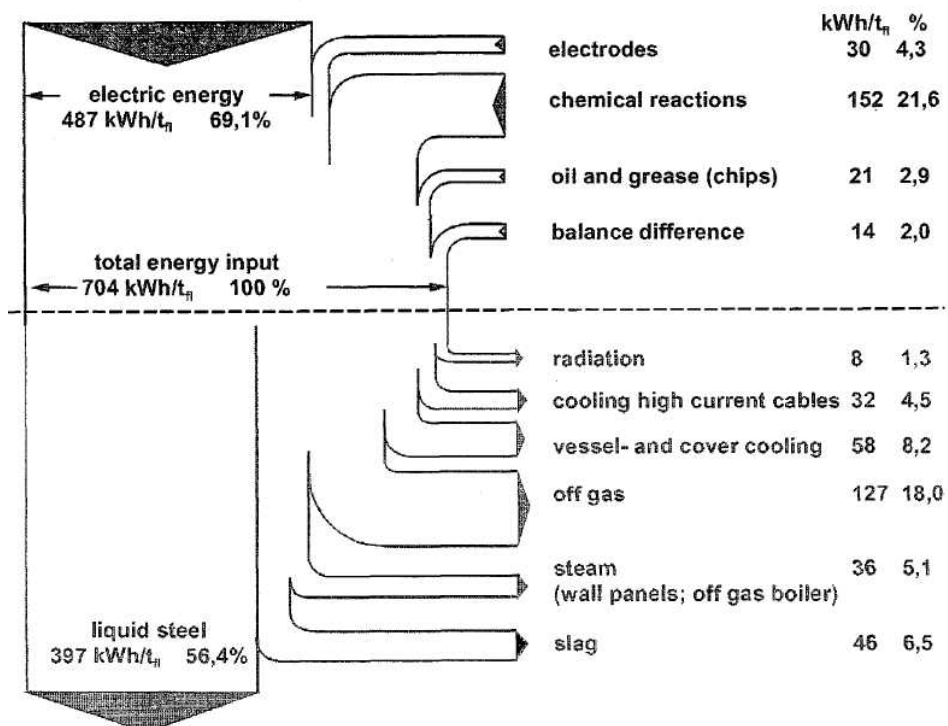


Fig. 11: Energy balance of a 120-t-EAF for the melting of stainless steel (status: 1989)

For the evaluation of the energy balance an extension of the efficiency defined in (7) its necessary to consider the decoupled energy used in other processes

$$\eta_{N,ges-WR} = \frac{\text{enthalpy steel} + \text{steam}}{\text{total energy input}} \quad (8)$$

In fig. 12 a further energy flow diagram of a 60-t EAF is represented /13/. This energy balance is characterised by that, that a high specific oxygen rate is injected and an additional scrap pre-heating system is installed. The total energy input is 729 kWh/t and is for instance in the order of magnitude of the before shown energy balances. The part of the heat through metallurgical reactions is 30 % and the energy recovered is 31 kWh/t.

Fig. 13 shows the comparison the energy balances of a conventional electric arc furnace with a finger shaft furnace. After that the reduction of the entire energy input of 680 kWh/t results around 95 kWh/t on 585 kWh/t. In this presentation the energies which are needed for the off gas post combustion remained probably without consideration. The reduction of the specific electric energy input leads however to clear increases in productivity of such systems.

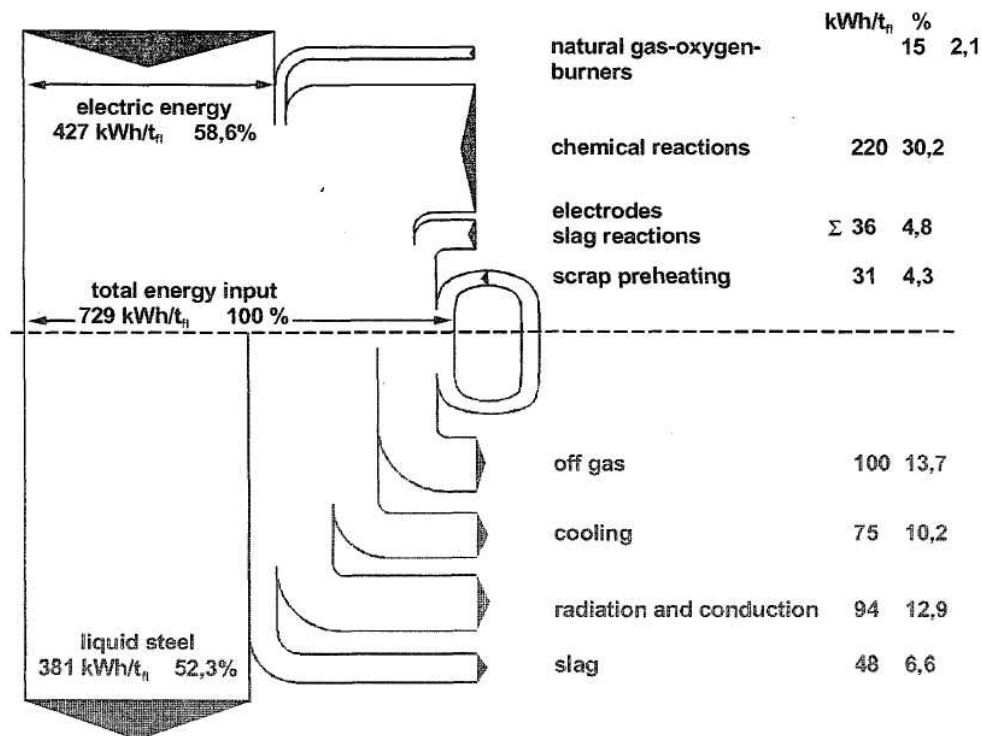


Fig. 12: Energy balance of a 60-t EAF with scrap pre-preheating (status: 1990)

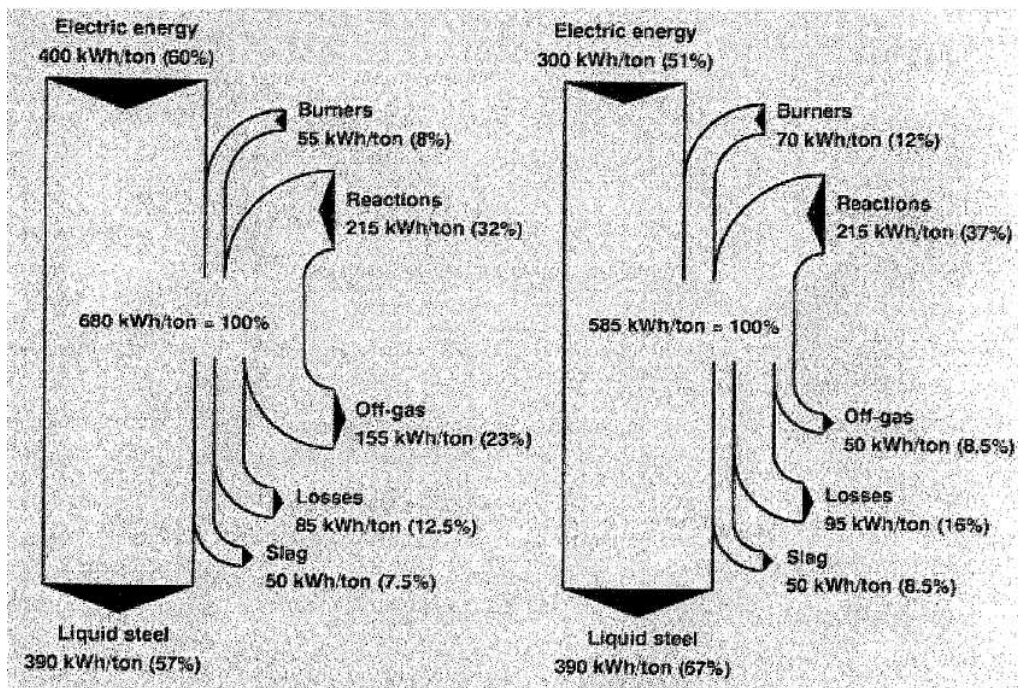


Fig. 13: Comparison of the energy balances of a conventional EAF with a finger shaft furnace /45/

The actual results for energy balances (mean value from 27 charges) of a 100-t-EAF are represented in fig. 14. The mean values of the mass balances are given in fig. 8 (values in brackets). The EAF is characterised by a high specific oxygen rate. The specific power consumption is less than 400 kWh/t, the total energy input however is 810 kWh/t; this value is still comparable with the data's of an EAF of 1980 (fig. 10).

The generation of complete energy balances requires still supplementary measurements at EAFs. So additional measurements for the composition (CO , CO_2 , O_2 , CH_4 , H_2), volume flow and temperature of the off gas at the elbow are necessary. The determination of the moisture (H_2O) of the off gas occurs from equilibrium calculations. The time dependent composition and cooling rate of the cover are given in fig. 15.

The values of the different efficiencies are listed in table 5.

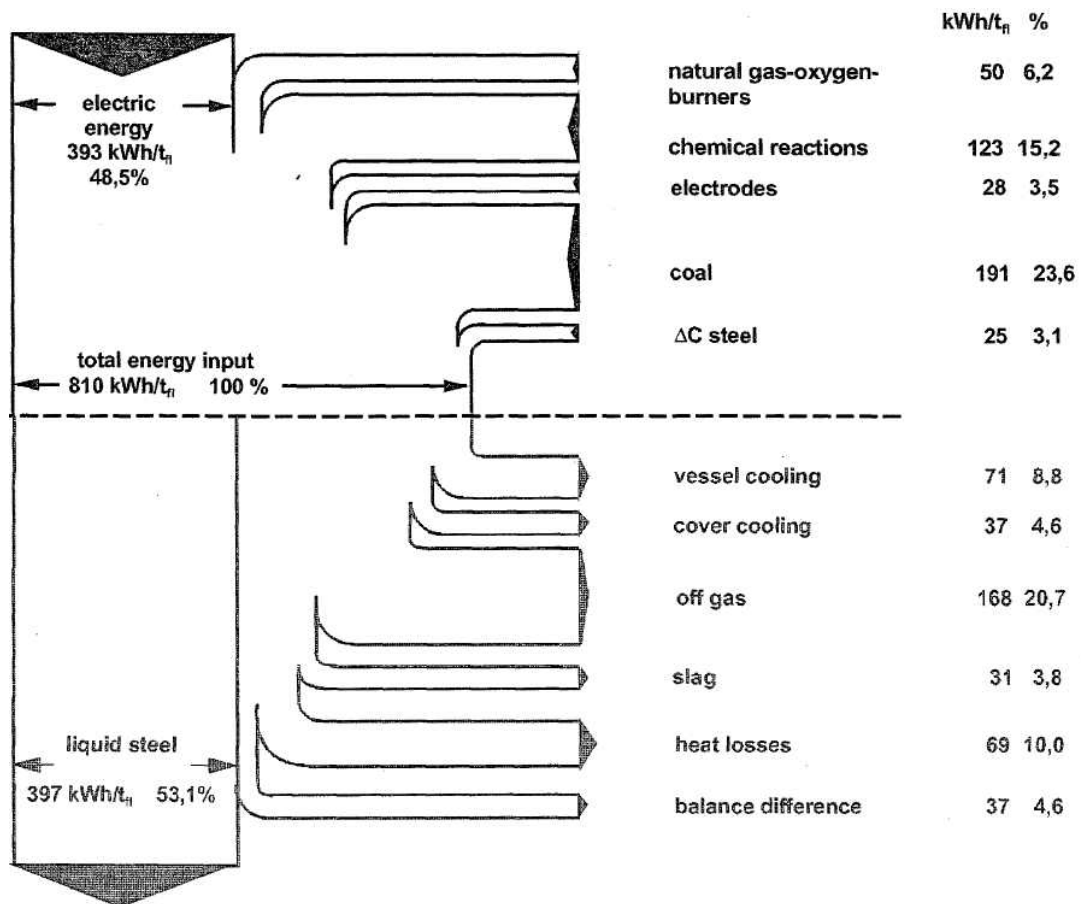


Fig. 14: Energy balance (mean value from 27 heats of a 100-t EAF) - (status: 1999)

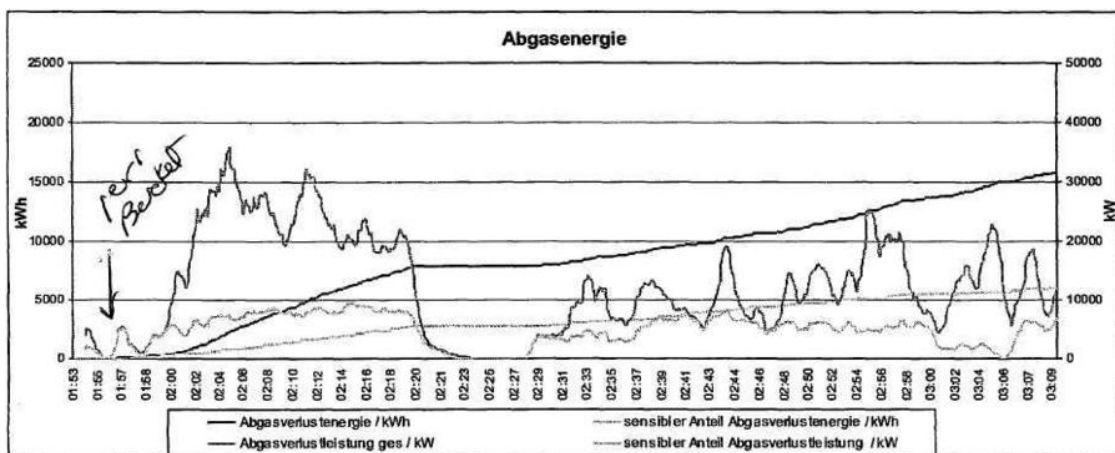


Fig. 15: Off gas and cover cooling data depending on the time

	status	$\eta_{N1} = \eta_{N,el}$	$\eta_{N2} = \eta_{N,gesl}$	$\eta_{N3} = \eta_{N,ges-WRI}$
100t-furnace structural steel	1980	72,8	53,0	
120t-furnace stainless steel	1989	81,5	56,4	61,5
60t-furnace scrap preheating	1990	89,2	54,6	
conventional furnace finger-shaft-furnace	1998	97,5 130	57,4 66,7	
100t-furnace	1999	101	49,0	

Table 5: Efficiencies of EAF's for the production of different steel grades or with different process engineering

Process and plant technologies influencing the energy balance

In the following the most important parameters on the energy balance and in particular the specific energy input of the electric arc furnaces are supposed to be considered. In fig. 16 the factors influencing the energy input of the electric arc furnace are shown schematically. Subsequently these factors are quantified.

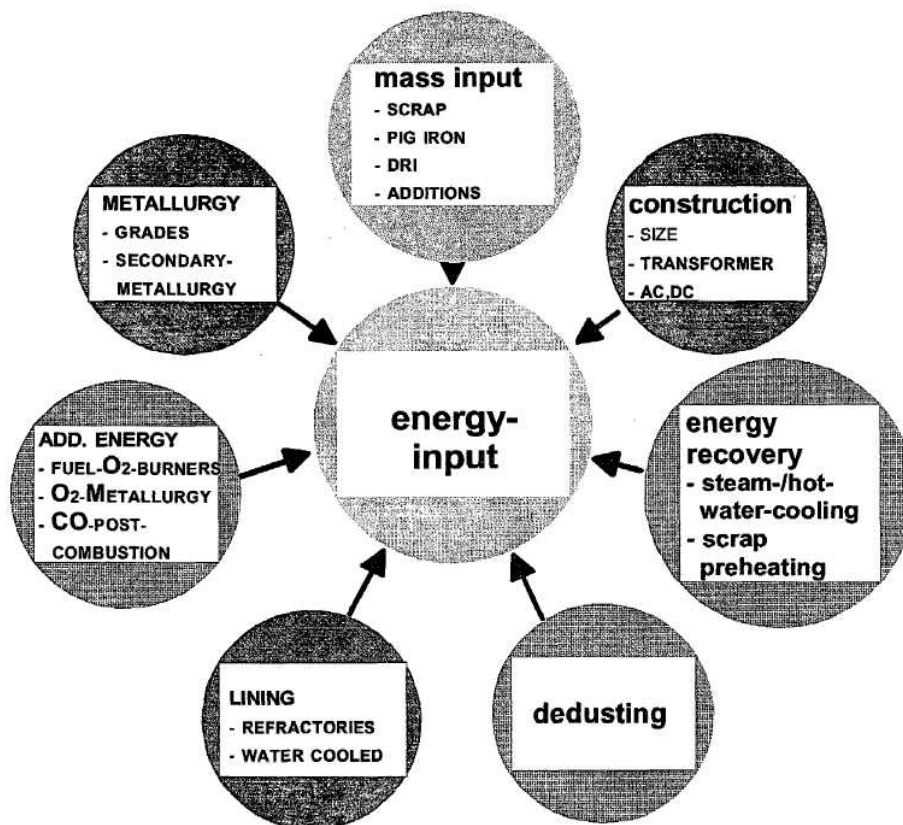


Fig. 16: Factors of the specific energy input of the electric arc furnace

In /18/ the variables of the specific electric energy input were determined with statistical methods and the data of 14 EAFs without scrap preheating and with 100% scrap charging. The specific electric energy input W_R necessary after that shows equation (9).

$$W_R = 300 \frac{kWh}{t} + 900 \frac{kWh}{t} \left(\frac{G_E}{G_A} - 1 \right) + 1600 \frac{kWh}{t} \frac{G_Z}{G_A} + 0.7 \frac{kWh}{t \cdot K} (T_A - 1600^\circ C) + 0.85 \frac{kWh}{t \cdot min} t_C - 8 \frac{kWh}{m^3} M_G - 4.3 \frac{kWh}{m^3} M_L - 2.8 \frac{kWh}{m^3} M_N \quad (9)$$

1) supplement 1996

GE charging weight in t

GA tapping weight in t

GZ weight of additions in t

TA tapping temperature in °C

tc tap to tap time in min

MG specific consumption of natural gas of the burners in m³/t

ML specific consumption of oxygen of the lance in mVt

MN specific consumption of oxygen for CO-post combustion in m³/t

An modified formula of this equation is published from Kohle in 2000 /47/ (9a)

$$W_R = 375 \frac{kWh}{t} + 400 \frac{kWh}{t} \left(\frac{G_E}{G_A} - 1 \right) + 80 \frac{kWh}{t} \frac{G_{DRI} + G_{HBI}}{G_A} - 350 \frac{kWh}{t} \frac{G_{HM}}{G_A} + 1000 \frac{kWh}{t} \frac{G_Z}{G_A} + 0.3 \frac{kWh}{t \cdot K} (T_A - 1600^\circ C) + 1 \frac{kWh}{t \cdot min} (t_S + t_N) - 8 \frac{kWh}{m^3} M_G - 4.3 \frac{kWh}{m^3} M_L - 2.8 \frac{kWh}{m^3} M_N + 0.3 \frac{kWh}{t} (W_V - W_{vm})$$

GDRI weight of DRI in t

GHB weight of HBI in t

GHM weight of hot metal in t

TA tapping temperature in °C

t_S power on time in min

t_N power of time in min

W_V energy losses (if measured) with mean value W_{vm}

Additions

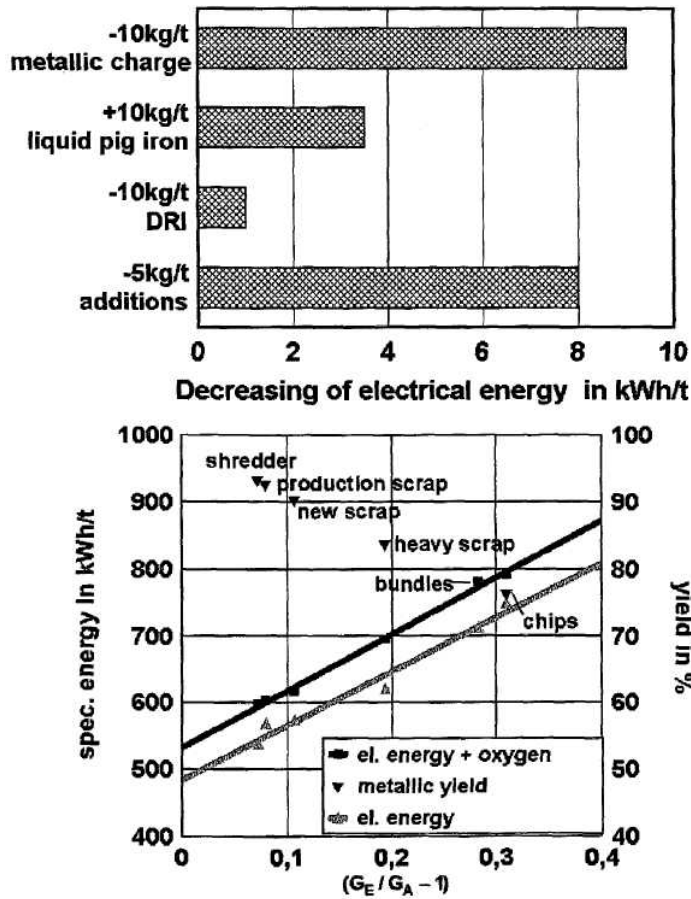
The influence of the variation of metal charge by scrap and alloys on the specific energy input is described in (9), (9a) due to a statistical analysis of data from different EAF's. In 719/ the

behaviour of different scrap grades with different densities is represented onto the yield as well as the energy input (fig. 17). By the smaller yield of scraps with lower specific weights an increased mass input is necessary, that takes effect in an additional input of energy. From these data a similar term can be determined from $850 \text{ kWh/t} \cdot (G_E/G_A - 1)$.

With the application of sponge iron the electric energy input will increase with a higher part of the sponge iron (approx. $1 \text{ kWh}/\%$ sponge iron) and decrease with a lower degree of metalisation (+5,5kWh per 1 % smaller degree of metalisation) /20/. The specific energy input can be lowered by the addition of solid and/or liquid pig iron. In /21/ a specific decrease of the energy input of 3 to 4 ($\text{kWh/t}_{\text{liquid}}/\%$ liquid pig iron) is indicated. This is equivalent to

$$300 - 400 \frac{\text{kWh}}{t} \frac{G_{HM}}{G_A}.$$

For the additional oxygen input no data are given.



$$\Delta W_{R, \text{Einsatz}} = 900 \frac{\text{kWh}}{t} \left(\frac{G_E}{G_A} - 1 \right) + 1600 \frac{\text{kWh}}{t} \frac{G_Z}{G_A} - 350 \frac{\text{kWh}}{t} \frac{G_{RE}}{G_A} + 100 \frac{\text{kWh}}{t} \frac{G_{DRI}}{G_A}$$

Fig, 17: Effects of the material input onto the specific electrical energy input of the electric arc furnace

Influence of the furnace size

For a number of investigated electric arc furnaces with capacities of 2 to 120 t both the specific energy input (total energy, electric energy) and the values of the already defined efficiencies are given in fig. 18 related to the mass input /11/. The small EAFs ($m < 40$ t) are furnaces in foundries. In these furnaces mostly a more extensive metallurgy is necessary because the melt is prepared completely in the furnace. The larger furnaces are marked with an intensive secondary metallurgy. The energy input decreases with increasing furnace size.

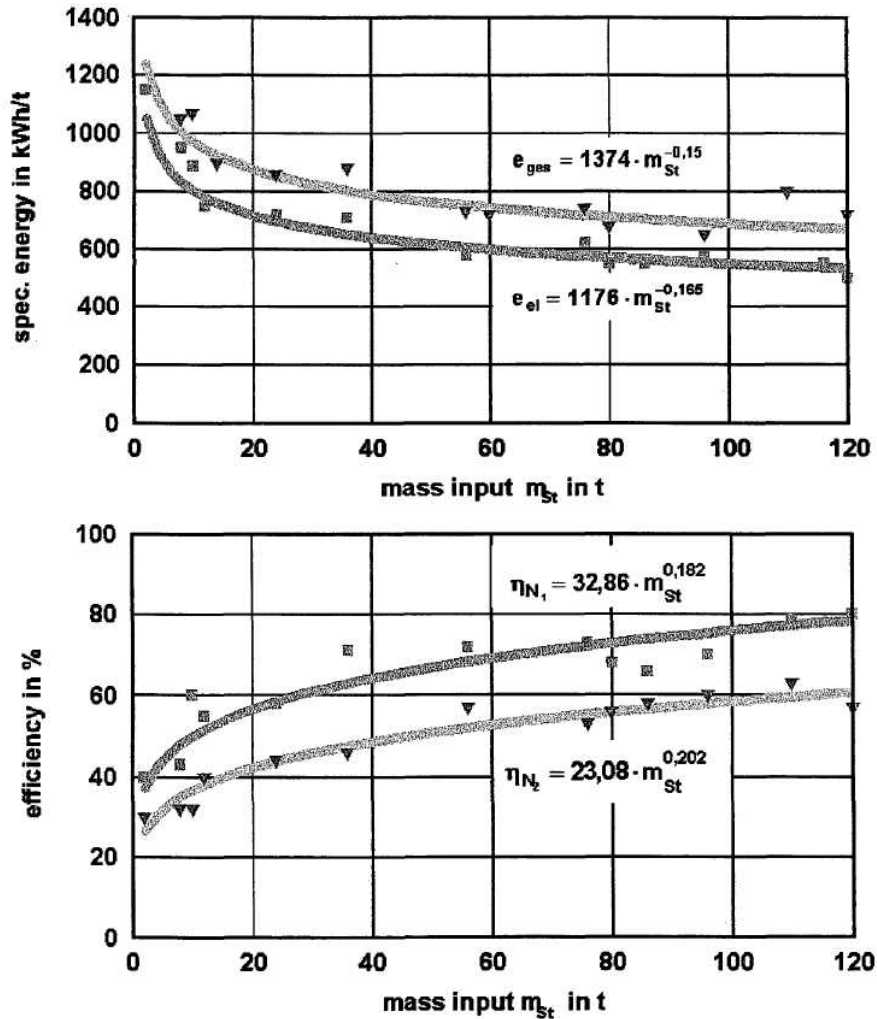


Fig. 18: Energy efficiencies of different size electric arc furnaces

Supplementary energy

An essential aim of modern electric arc furnaces is the increasing of the productivity through increased power supply. Additive energies are fed to the EAF by fuel-oxygen-burners as well as oxygen lances in addition with coal injection.

Fuel - oxygen - burners

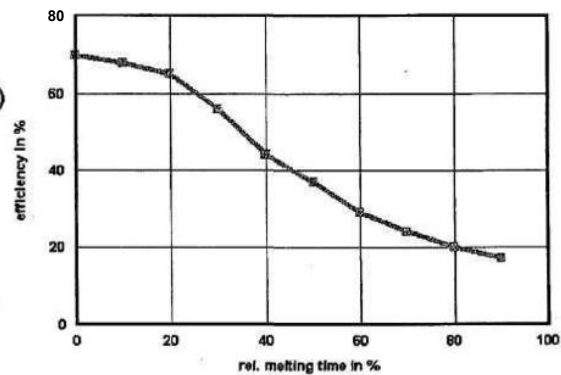
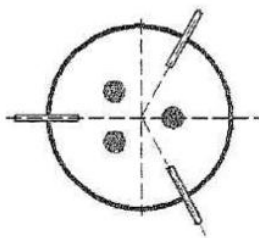
The application of fuel - oxygen burners, that are mainly operated with the oil or natural gas, is to be seen under the following aspects:

- Increased productivity of the furnace system in the melting period (additional energy input by fuels)
- increasing the thermal symmetry of the AC-EAF during the melt down period
- energetic improvement of the melting process.

With the application of these technologies it is to be noted that an increase of the specific off gas volume occurs. Through the decrease of the combustion efficiency of the fuel - oxygen - burners with advanced melting time (fig. 19), the operating period of fuel - oxygen - burners is limited on the start period of the melting process. The added specific natural gas is 3,5 to 6 m³/t. This corresponds to a specific energy input of approx. 30 to 50 kWh/t /18,22/ at a net calorific value for natural gas of $h_u = 32,6 \text{ MJ/m}^3$ ($h_u = 9,05 \text{ kWh/m}^3$). Studies for the determination of the substitution potential of the electrical energy by fuel oxygen burners at a 100-t UHP EAF showed, that the sum of the specific energy input from electrical energy and fuel energy increases only slight (fig. 20) /23/. Thus the necessary electrical energy input reduces at 7.3 and/or 8.4 kWh/m³ EG (cf. (9)).

targets: increased power

thermal symmetry of the furnace in the melt down period ($e < 35 \text{ kWh/t}$)



Fuels: Natural gas, light oil, coal

Fig. 19: Fuel-oxygen-burner

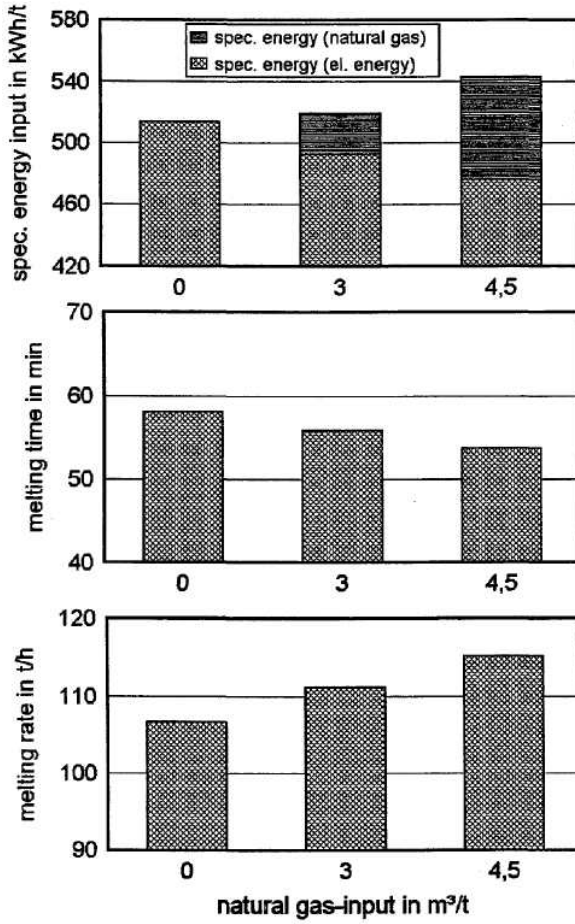


Fig. 20: Effects of different specific natural gas inputs of jet-burners

A further possibility for the substitution of electrical energy through fossil fuels consists in the combustion of coal with oxygen. In /24-26/ is reported on experiments at an experimental furnace as well as at a 150-t EAF. For a 150-t EAF with a specific coal input of 6.5 kg/t ($h_u = 9.4$ kWh/kg) a reduction of the electrical Energy input of 46 kWh/t is indicated. This corresponds to an equivalence value of 7 kWh_{el}/kg_{coal}. Own studies for the melting of stainless steels confirm these values. The effect of the energy input with coal ($A_{e_{coal}}$) onto the reduction of the electric energy consumption (Δe_{el}) conducts according to /25,26/

$$\frac{\Delta e_{el}}{\Delta e_{coal}} = \frac{\eta_f}{\eta_{el}} = 0.75 \quad (10)$$

The combustion efficiency for anthracite coal with the parameters air number and/or the ratio CO/CO₂ is plotted as a function of the temperature of the off gas in fig. 21. For an estimated efficiency of the electrical energy input $\eta_{el} \leq 0.93$ from eq. (10) results an average combustion efficiency of 0.7.

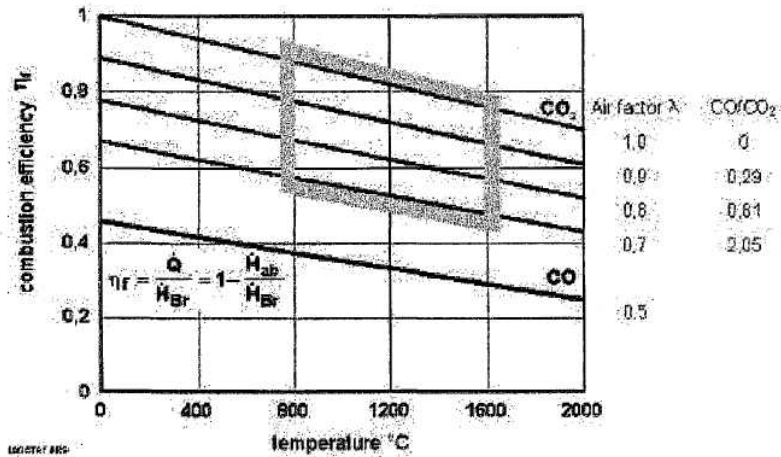


Fig. 21: Combustion efficiency for anthracite coal

Oxygen - Metallurgy

The application of oxygen (fig. 22) performs an essential contribution to an increased productivity of electric arc furnaces. The fuels are carbon, iron, silicon, manganese as well as oils and greases and organic constituents of the scrap. The aims of the oxygen metallurgy are:

- increase of the productivity,
- decrease of the specific electric energy input.

As the energy flow diagram (fig. 12) shows, up to 30 % of the energy input can be provided through exothermic reactions. The most important chemical reactions are listed in table 4. For the reduction of the electric energy input a value of approx. 2.5 kWh/m³O₂ is indicated in /7,22/. This value results from the non-complete combustion of carbon to carbon monoxide.

Fig. 23 gives higher values from of 3 to 5 kWh/m³O₂. This values can be explained with the reactions of oxygen with iron (table 4). In (9) a value of 4.3 kWh/m³O₂ is considered. Additionally to the costs for the oxygen also the primary energy use for the production of the oxygen of 1,9 kWh/m³O₂ is to be considered.

CO-post combustion

In the off gases of the EAF are according to the state of the melting process concentrations of CO to 25 %, of CO₂ between 15 and 25 % as well as H₂ to 10 % occur in the case without CO-post combustion /27/. For increasing the oxygen input of 4 to 10 m³/t a reduction of the specific electric energy input by 15 to 18 kWh/t can be realised (table 6).

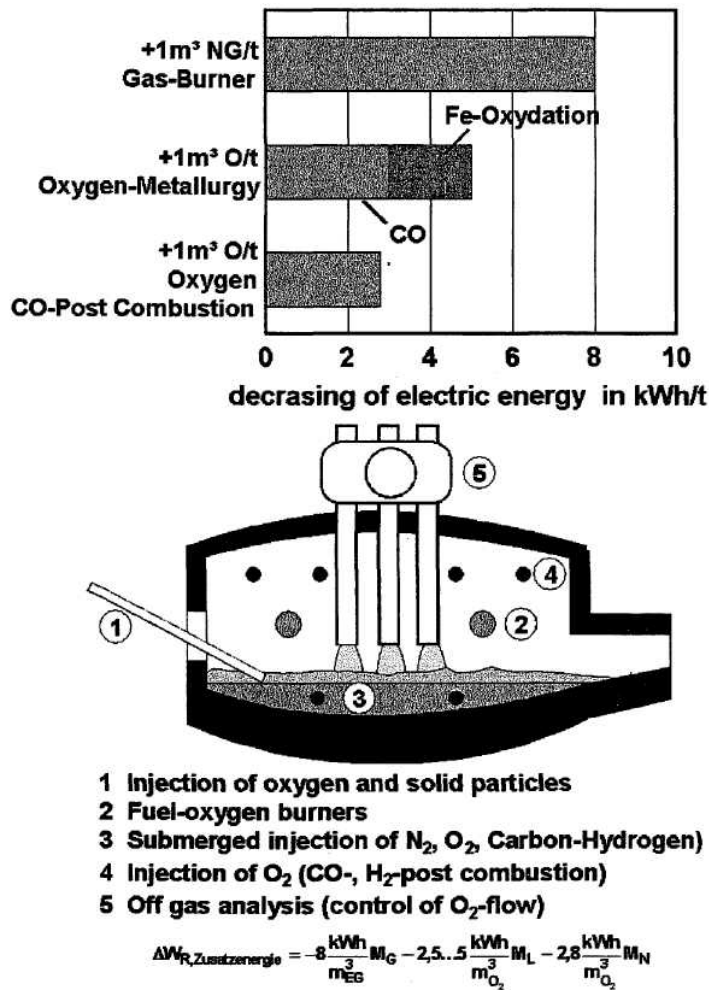


Fig. 22: Effects of additional energies on the electrical energy input for the EAF

Data	before	after	before	after	before	after	before	after
Spec, apparent power (kVA/t)	730	730	860	860	715 HP	715 HP	580 LP	580 LP
Natural gas (Nm ³ /tKn.)	5,3	3,6	-	-	4,5	5,1	5,6	5,8
Oxygen (Nm ³ /tKn.)	35,6	45,6	14,0	32,0	27,2	32,7	33,6	37,1
Carbon (kg/tKn.)	12,6	11,8	2,0	7,0	10,3	10,0	10,1	10,0
N of injectors	-	4	-	6	-	6	-	6
Stirring gas	-	-	N ₂	N ₂	N ₂	N ₂	N ₂	N ₂
Tap-to-tap (min)	51,5	47,8	64	58	61,3	57,7	70,8	67,3
Power on time (min)	40,5	36,8	46,0	40,0	48,2	44,9	57,5	52,4
El. Energy (kWh/t Kn.)	372	347	447	403	408	384	377	359

HP = high power

LP = low power

Table 6: Results with ALARC-PC™ CO-post combustion /28/

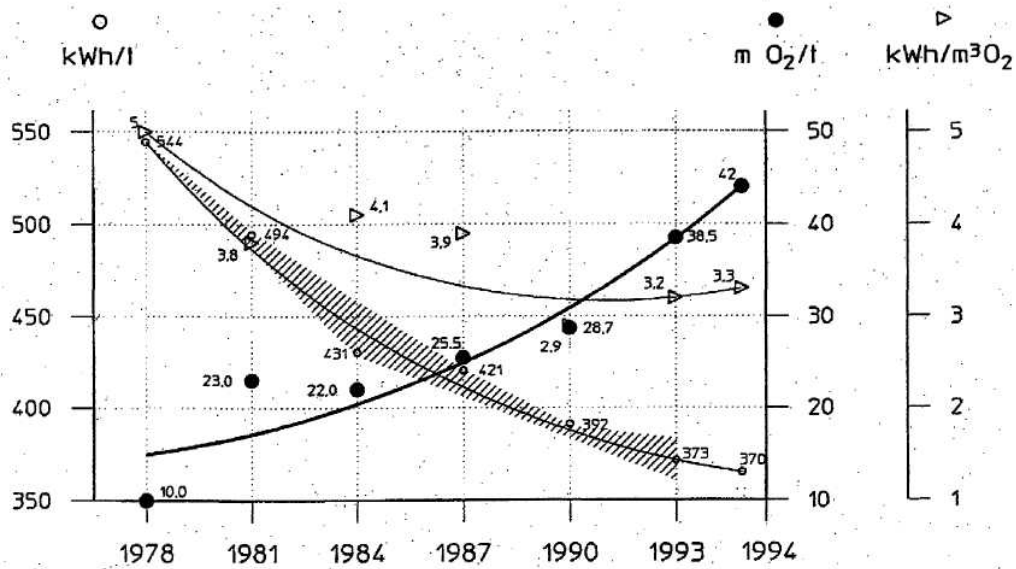


Fig. 23: Development of oxygen-technology at BSW /28/

Ladle furnace

In secondary-metallurgical treatment lines in EAF steel mills ladle furnaces are state of the art (fig. 24). The decrease of the tap temperature of the EAF (fig. 25) at simultaneous reduction of the alloy addition into the EAF feeds to a clear increase of productivity of the EAF.

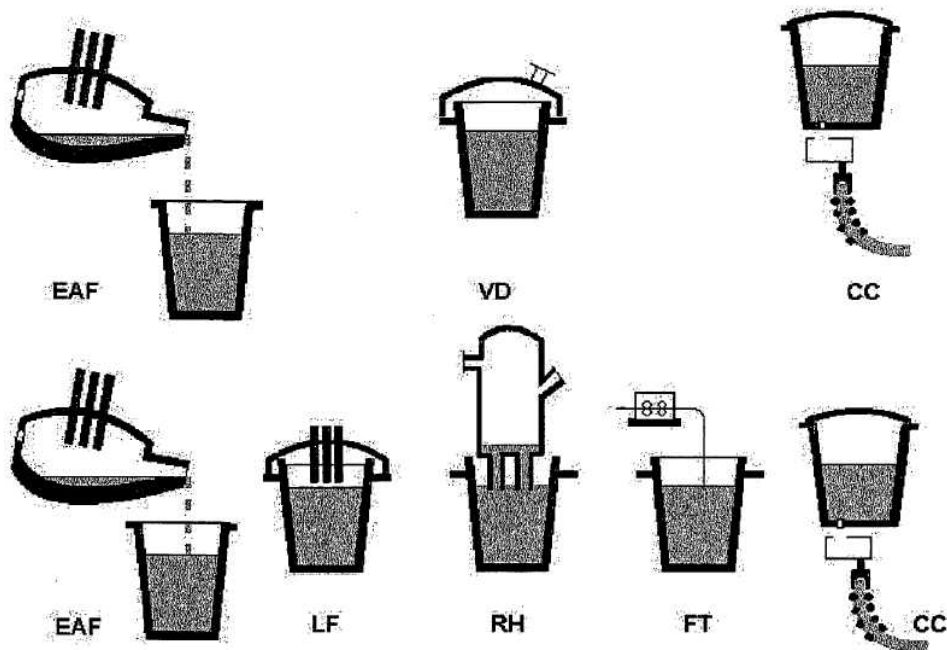


Fig. 24: Process technology of secondary metallurgy

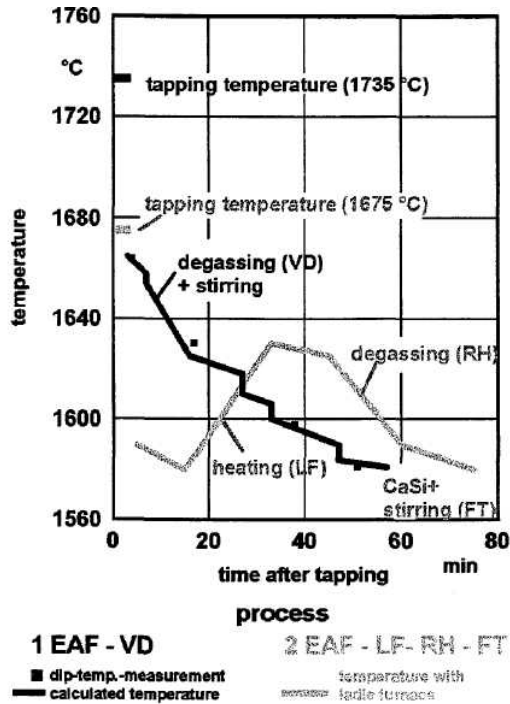


Fig. 25: Variation of the temperature of the melt during the ladle furnace treatment

From the energetic viewpoint a reduction of approximately 10 kWh/t of electrical energy results for a combination of EAF and LF. On one hand side there is an energy consumption of 30 kWh/t of the ladle furnace and on the other hand side a reduction of 40 kWh/t of electric energy for the case of a 100-t-EAF resulting from the decrease of the tapping temperature by 60 K (table 7).

From that an efficiency of $\eta=30\%$ of the EAF calculates for this temperature range with a specific heat capacity of the liquid steel of $c = 700 \text{ J/kgK}$. The energy consumption for the increase of the temperature of the melt of around $\Delta T=10\text{K}$ is 6.6 kWh/t. The reduced electrode consumption for the EAF is compensated by the corresponding electrode consumption of the ladle furnace/39-41/.

Decreasing of tapping temperature	60 °C
Reduction of the electric energy into the EAF	-40kWh/t
Electric energy input of the ladle furnace (LF)	+ 30 kWh/t
Shortening of the „tap-to-tap“-time	8 min
Increasing of the productivity	7t/h
Decreasing of refractory-consumption	1 kg/t
? electrode consumption EAF + LF	$\pm 0 \text{ kg/t}$

Table 7: Advantages with the application of a ladle furnace in EAF steel plants - typical values for 100t-heats -

Bottom stirrer

The bath flow can be improved by bottom gas stirring elements in the EAF. Through that a reduction of the energetic and metallurgical non-equilibrium's in the melt results. The advantages of the bottom gas stirring are (fig. 23):

- lowering of the specific energy input
- decrease of the melting time
- more homogeneous melts concerning temperature and composition
- metal - slag reactions are nearer at the equilibrium

As an order decreases of the tap temperatures are indicated in the literature by 7 °C for structural steels /29/ and 32 °C for stainless steels /30/. Through that a decreased specific energy input of 10 to 20 kWh/t /29/ results. Different types of bottom gas stirrers are shown in fig. 26.

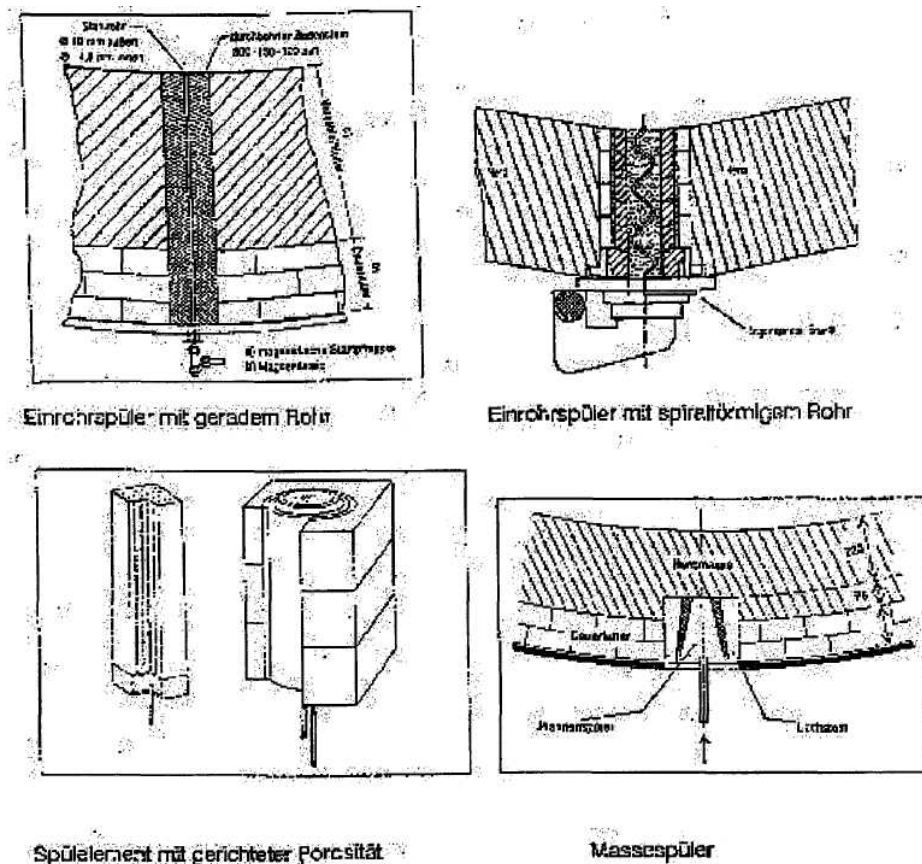


Fig. 26: Types of bottom gas stirrers for EAFs

Optimisation and further use of the off gases

The off gas losses of electric arc furnaces to the environment are 80 to 170 kWh/t_{liquid}. For the use of this energy recuperation measures are practised using the enthalpy of the off gases directly (scrap preheating) or non-direct (steam cooling). Through that the off gas losses become smaller onto the environment than the ones directly emitted from the EAF.

For the order of priority of industrial energy saving measures the following possibilities result especially for the electric arc furnace (table 8):

1. energetic process optimisation due to the reduction of the off gas losses through the improvement of the off gas suction and/or CO post combustion
2. energy recuperation (process intrinsic use) through scrap preheating
3. energy recuperation (factory intrinsic use) through process steam generation
4. energy recuperation (external use) through hot water cooling for house heating

	energy recuperation	cost effectiveness	investment	examples for the EAF
1	energetic process optimisation	high	low	Process organisation Substitution of electric energy by fuels / O ₂ Plant optimisation
2	energy recuperation (process intrinsic use)	high	medium	Scrap preheating New furnace concepts with integrated scrap preheating
3	energy recuperation (factory intrinsic use)	medium	medium	Steam generation for internal use
4	energy recuperation (external use)	low	high	Steam generation for external use (district heating)

Table 8: Order of priority for the realisation of industrial energy saving measures

Optimisation of the off gas suction

As already was shown, the off gas energy is between 15 and 20 % of the total energy input. The off gas volume flows are to be adjust on values, that the specific dust being exhausted is in the range from 12 to 15 kg/t for structural steel grades and 15 to 18 kg/t for stainless steels. Since the part of the off gas volume flow is time-dependent, an energy saving potential of approx. 15 kWh/t can be opened through an optimised off gas control system based on a fume detector (fig. 27) /31/.

Scrap preheating

The scrap preheating (fig. 28) is an energy recuperation measure which influences the energy balance and the productivity of the electric arc furnaces directly positively. Next to the ad-

advantages as decrease of the specific energy consumption, shortening of the melting time, lowering of the electrode consumption as well as drying of the scrap the pollutant formation through non-metallic constituents containing in the scrap can be a disadvantage. Often supplementary measures are necessarily for the fulfilment of legal rules.

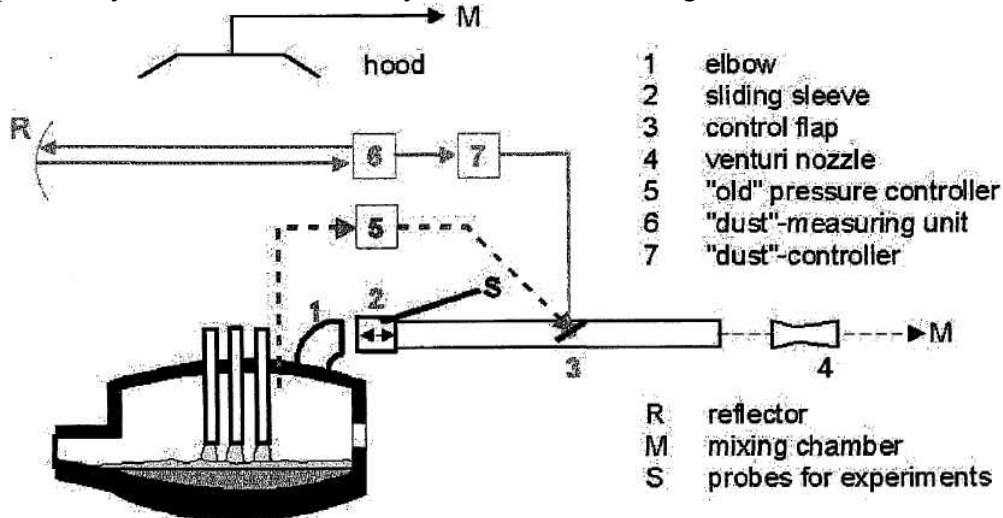


Fig. 27: Off gas suction

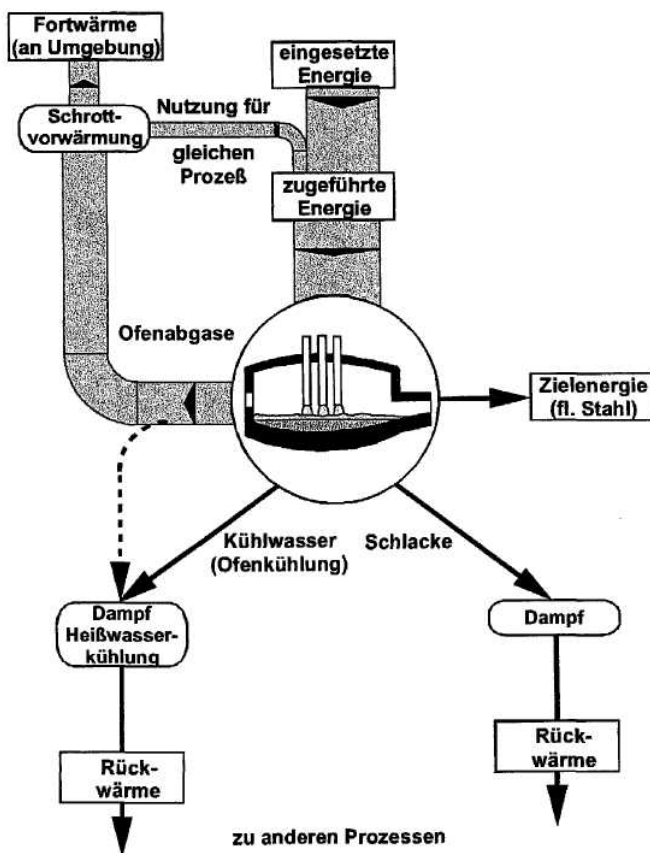


Fig. 28: Basic principles for the energy recuperation from the electric arc furnace

At the beginning of the seventies fossil fuels as oil or natural gas with the price advantage compared with electrical energy were used for scrap preheating. Today mainly the enthalpy of the directly exhausted off gases are used (fig. 29). During the consideration of the available off gas potential for scrap preheating (fig. 10 to 12) it must be considered that the off gases are not completely exhausted directly by the fourth cover hole (elbow). The part of the indirectly exhausted off gas is about 20 to 30 % of the total off gas. An overview of the achieved reduction of the electrical energy input shows fig. 30. The energy saving potential is 40 to 50 kWh_{el}/t for conventional scrap preheating systems.

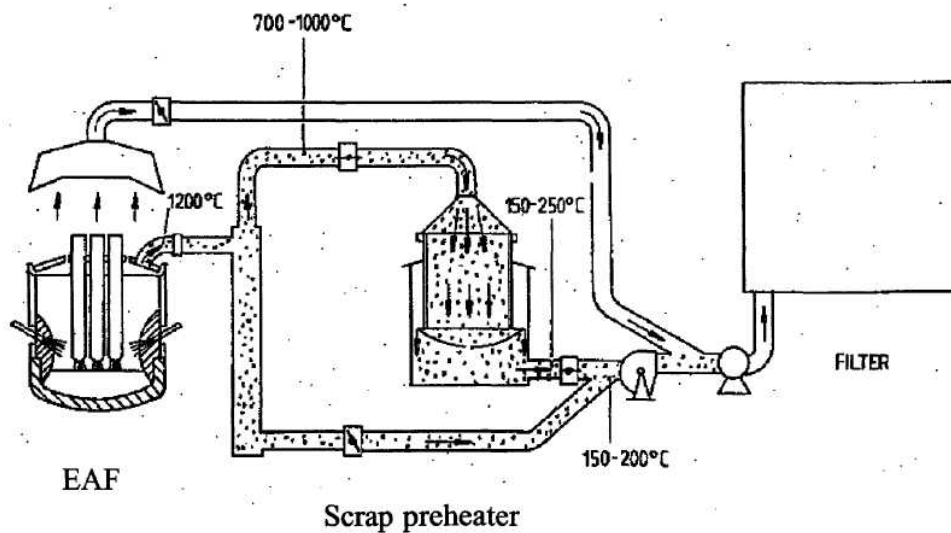


Fig. 29: Principle scheme of scrap preheating with off gases from EAF

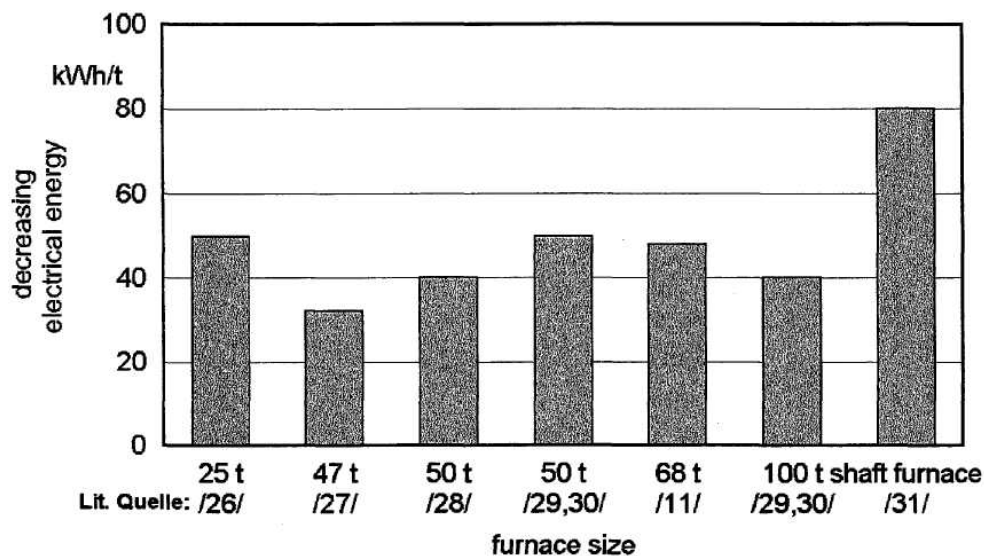


Fig. 30: Decrease of specific electrical energy input from scrap preheating

With integrated systems (e.g. Shaft Furnace) up to 80 kWh_{el}/t can be saved. These values are valid for the condition, that no supplementary measures are necessary from environmental control reasons. For the compliance of the legal rules the off gases must be burned after. This is necessary because the low temperature off gases contain pollutants, as hydrocarbons (VOC) and carbon monoxide. About the energy necessary for the post combustion there are only small information.

Others

Other technologies for the energy optimised EAF process like

- tapping technology
- energy recovery from the EAF-cooling systems for
 - ◆ process steam (**Fig. 31**)
 - ◆ heating energy (**Fig. 32**)
- use of slag enthalpy

are described in /17/.

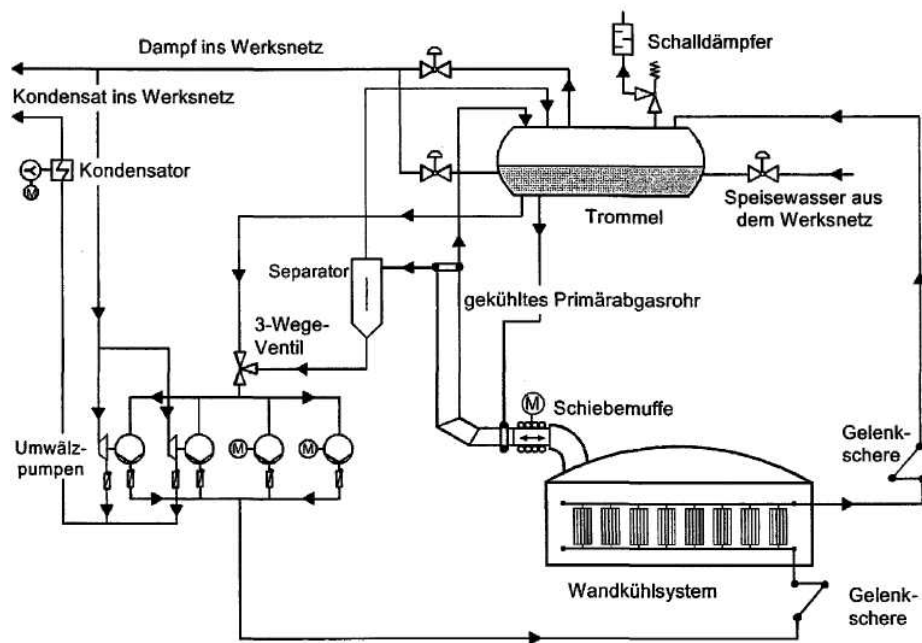


Fig. 31: Steam cooling of the UHP furnace of KruppThyssen Nirosta GmbH

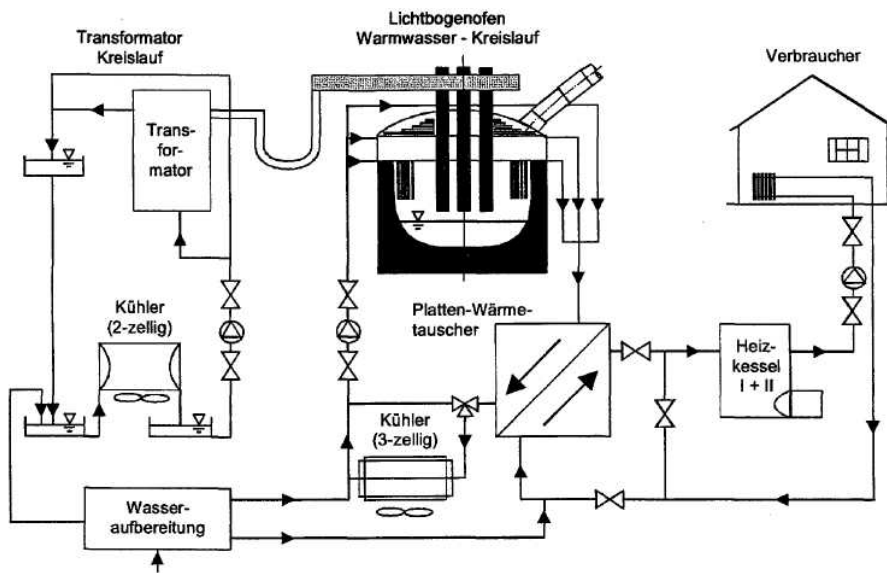


Fig. 32: Energy recuperation with hot water cooling at the electric arc furnace

Summary and outlook

Actually the development of EAF's with integrated scrap preheating system are state of the art. Different designs as the ConSteel Furnace (energy saving of approx. 80 kWh/t /7/), the shaft furnace (saving electric energy of approx. 80 kWh/t /37/) and/or the twin shell shaft furnace, (fig. 33) (electric energy consumption of approx. 330 kWh/t /42/) as well as the IHI furnace from Tokyo Steel are already implemented.

Further techniques in the stage of development are for example the Comelt-electric arc furnace /43/ and the Contiarc scrap melting technique (fig. 34 /44/). With the Comelt technique the scrap is melted with 4 direct current electrodes. Above the furnace hearth a scrap filled shaft is located. Through that the off gases leave the furnace. The energy saving potential with regard to the total energy consumption is indicated with approx. 100 kWh/t. This technique development was stopped in the meantime.

The Contiarc process is a continuously operating ring shaft furnace heated with a central direct current arc. Through the good hooding only small false air entry is expected and the off gas results mainly from the metallurgical reactions. An electric energy input is expected by 250 kWh/t if additionally about 70 kWh/t are fed by primary energy. This corresponds to a lowering of the energy input of approx. 200 kWh/t in comparison with a modern Electric arc furnace without scrap preheating.

It is to be expected that supplementary energy for the post combustion of the furnace off gases is necessary.

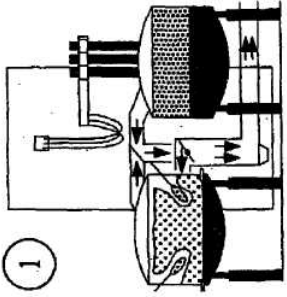
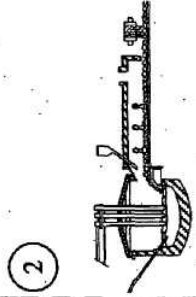
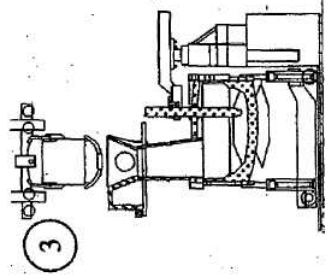
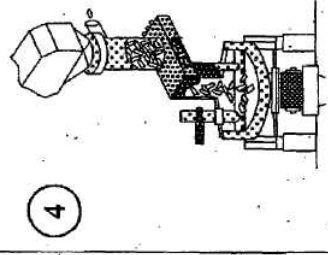
Bild 6.7.1. Ausgeführte und projektierte Ofenkonzepte		1	2	3	4
					
Name		Twin-Shell-EAF	Consteel	Fuchs-Schacht-Ofen	IHFI
Lieferant		verschiedene	Intersteel Technology	Fuchs	
Stand der Entwicklung		Mehrere Öfen	Mehrere Öfen	Mehrere Öfen	1. Ofen in Betrieb
Anteil vorge-wärmter Schrott		50 %	100 %	40-70 %	100 %
Schrott-chargierung		chargenweise	kontinuierlich	chargenweise	kontinuierlich
Emission beim Chargieren		ja	nein	ja	nein
Hallenentstaubung notwendig		ja	nein	ja	nein
Power-on-Zeit		91 %	> 75 %	66 %	> 75 %
Nutzung von Primärenergie		zeitweise, η sinkt mit Schmelzzeit	kontinuierlich, η niedrig	zeitweise, η sinkt mit Schmelzzeit	kontinuierlich, η hoch

Fig. 33: Realised EAF concepts /46/

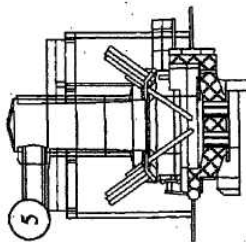
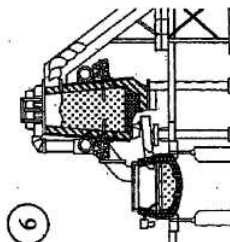
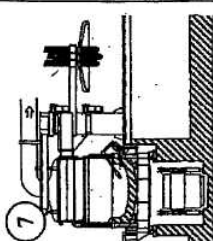
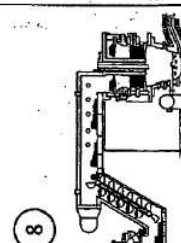
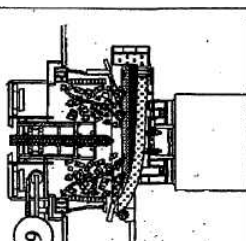
					
Name	COMELT	LS-DOF	MEF	MECOF	Contiarc
Lieferant	VOEST-ALPINE	EMPCO	MDH	NSC	MDH
Stand der Entwicklung	Versuchsöfen	Konzept	Kombination von EAF/EOF	Konzept	Versuchsöfen
Anteil vorge-wärmter Schrott	100 %	100 %	50 %	100 %	100 %
Schrott-chargierung	chargenweise	chargenweise	chargenweise	chargenweise	kontinuierlich
Emission beim Chargieren	nein	nein	ja	nein	nein
Hallenentstaubung notwendig	nein	nein	ja	nein	nein
Power-on-Zeit	> 75 %	~ 100 %	50 %	> 75 %	~ 100 %
Nutzung von Primärenergie	zeitweise, η sinkt mit Schmelzzeit	kontinuierlich, η hoch	zeitweise, η sinkt mit Schmelzzeit	kontinuierlich, η hoch	kontinuierlich, η hoch

Fig. 34: Future EAF concepts /46/

Literature

- /1/ **Statistisches Jahrbuch der Stahlindustrie 1996**
Hrsg.: Wirtschaftsvereinigung Stahl, Verlag Stahleisen, Düsseldorf, 1996
- /2/ **Zörcher, H.:** Stand der Elektrostahlerzeugung in Deutschland
Stahl und Eisen 114 (1994) 4, S. 75/9
- /3/ **Field, L.I.:** The Impact of Energy Conservation
Iron & Steelmaker (1979) 1, S. 8-16
- /4/ **Szekely, J.; Trapaga, G.:** Zukunftsperspektiven für neue Technologien in der Stahlindustrie
Stahl und Eisen 114 (1994) 9, S. 43/55
- /5/ **Fett, F.; Pfeifer, H.; Siegert, H.:** Energetische Untersuchung eines Hochleistungselectric arc furnaces
Steelund Eisen 102 (1982) 9, S. 461/5
- /6/ **Baillet, G.; Lemiere, F.; Moriamez, G.; Le Coq, X.; Roth, J.L.; Russo, P.:** Scrap Quality Control and Optimum Use in Usinor-Sacilor's EAF's
5th European Electric Steel Congress, Paris, June 19-23, 1995
- /7/ **The Electric Arc Furnace**
International Iron and Steel Institute, Brussels, 1990
- /8/ **Persönliche Angaben einzelner Werke**
- /9/ **Baehr, H.D.:** Technische Thermodynamik
Springer Verlag, Berlin, 1973
- /10/ **Sommer, F.; Plockinger, E.:** Elektrostahlerzeugung, 2. Auflage
Verlag Stahleisen, Düsseldorf, 1964
- /11/ **Pfeifer, EL:** Energietechnische Untersuchung der Plasmatechnik bei der Stahlerzeugung
Verlag Stahleisen, Düsseldorf, 1992
- /12/ **Brod, EL; Kempkens, F.; Strohschein, H.:** Energiereichgewinnung aus einem UHP-Electroelectric arc furnace
Steelund Eisen 109 (1989) 5, S. 229/38
- /13/ **Gripenberg, H.; Bninner, M.; Petersson, M.:** Optimal Distribution of Oxygen in High-Efficiency Electric Arc Furnaces
Iron and Steel Engineer (1990) 7, S. 33/7
- /14/ **Altfeld, K.; Schneider, A.:** Energiebilanzen von Elektrolichtbogenofen - Auswirkungen wassergekühlter Ofenelemente
Steelund Eisen 103 (1982) 20, S. 979/84
- /15/ **Klein, K.-EL; Paul, G.; Koster, V.:** The application of progressive energy-saving measures at Badische StaMwerke AG (BSW) MPT-Metallurgical Plant and Technology (1986) 1, S. 44/52
- /16/ **Bredchoft, R.; Hammer, E.E.; Unger, K.-D.:** Umbau eines 80-t-Electric arc furnaces der Thyssen-Edelstahlwerke AG - Kühlkreisläufe unter besonderer Berücksichtigung der Verdampfungskühlung für Wand- und Deckelelemente
Steelund Eisen 106(1986) 19, S. 1011/15
- /17/ **Pfeifer, H.; Fett, F.N.; Hcinen, K.-EL:** Möglichkeiten zur Verbesserung der Energy balancedes Electric arc furnaces
Elektrowarme international 46 (1988) B2, S. 71/77
- /18/ **Kohle, S.:** Einflußgrößen des elektrischen Energieverbrauchs und des Elektrodenverbrauchs von Lichtbogenofen
Steelund Eisen 112 (1992) 11, S. 59/67
- /19/ **Ameling, D.; Strunck, F.-J.; Wolf, J.:** Ausbringungsuntersuchungen bei verschiedenen Schrottsorten
Steelund Eisen 105 (1985) 20, S. 1055/8
- /20/ **Schliephake, H.; Ropke, G.; Piotrowski, W.:** Einsatz von Eisenschwamm in den Electroelectric arc furnace der Ispat-Hamburger Stahlwerke
Steelund Eisen 115 (1995) 5, S. 69/72
- /21/ **Scheidig, K.:** Roheisen aus dem Sauerstoff-Kupolofen als alternativer Einsatzstoff für den Electroelectric arc furnace
Steelund Eisen 115 (1995) 5, S. 59 / 65

- /22/ **Adolph, H.; Paul, G.; Klein, K.-H.; Lepoutre, E.; Vuillermoz, J.C.; Devaux, M.:** A New Concept for Using Qxy-Fuel Burners and Oxygen Lances to Optimize Electric Arc Furnace Operation
Iron and Steelmaker (1989) 2, S. 29/33
- /23/ **Heinen, K.-EL; Siegert, H.; Polthier, K.; Timm, K.:** Einsatz von Erdgas-Sauerstoffbrennern an Hochleistungslichtbogenofen Steelund Eisen 103 (1983) 18, S. 855/61
- /24/ **Welbourn, B.C.; Broome, K.A.:** The Development and Operation of Oxy-Coal Burners for Assisted Melting in Electric Arc Furnaces
Europaischer ElektrosteelKongreß, Florenz, 29. Sept. -1. Okt. 1986, R3.7
- /25/ **Gorringer, J.; Illingworth, D.H.; Welbourn, B.C.:** Improvements in Energy Efficiency and Improved Operating by Using Oxy-Coal Burners for Assisted Melting at Stocksbridge Engineering Steels
3. Europaischer Elektrostaahl-Kongress, Bournemouth, 1989, S. 194 / 9
- /26/ **Welbourne, B.; Gorringer, J.; Illingworth, D.; Kennedy, B.:** Oxy-Coal Burners to replace Electricity intheEAF
- /27/ **Pfeifer, EL:** Erstellung einer Massen-, Energie- und Exergiebilanz für den
100-t-UHP-Elektroofen der Krupp Stahlwerke Südwestfalen
Diplomarbeit, Fachbereich Maschinentechnik, Universität GH Siegen, 1980
- /28/ **Klein, K.-H.; Schindler, J.E.:** Einsatztechnik für unlegierte Kohlenstoffstähle
In: Elektrostahlerzeugung
Hrsg.: Heinen, K.-H.
Verlag Stahleisen, Düsseldorf, 1997
- /29/ **Bachmayer, J.; Hoffken, E.; Strunck, F J.; Wolf, J.:** Bottom Stirring With the Thyssen Long-Time Stirrer at the Oberhausen EAF Shop of Thyssen SteelAG
Iron and Steelnaker (1991) 2, S. 22/26
- /30/ **Cipolla, J.; Chan, A.H.; Pawliska, V.:** Experience of Inert gas Stirring in the EAF at Armco Butler
Iron and Steelnaker (1991) 2, S. 27/30
- /31/ **Stockmeyer, R.; Heinen, K.-EL; Veuhoff, H.; Siegert, EL:** Einsparung von elektrischer Energyam Electric arc furnace durch eine neue Ausqualmregelung
Steelund Eisen 110 (1990) 12, S. 113/6
- /32/ **Kishida, T. u.a.:** Scrap Preheating by Exhaust Gas from Electric Arc Furnace
Iron and Steel Engineer (1983) 11, S. 54/61
- /33/ **Schermer, K.:** Verminderung des Einschmelzstromverbrauchs des Electric arc furnaces durch Ausnutzung der im Abgas enthaltenen Wärme zum Schrottwarmer
Elektrowärme international 39 (1981) B3, S. 138/42
- /34/ **Tomizawa, F.; Howard, E.C.:** Scrap Preheating with a Clean House Enclosure and Associated Operation Benefits
Iron and Steelnaker (1985) 11, S. 30/42
- /35/ **Kimura, S. u.a.:** Effect of Scrap Preheater on the Operation of Electric Furnaces
SEASI Quarterly (1983) 1, S. 43/52
- /36/ **Watanabe, H u.a.:** Scrap Preheater for Electric Arc Furnace
Iron and Steel Engineer (1983) 4, S. 45/50
- /37/ **Ehle, J.:** Neuere Entwicklungen des Elektroelectric arc furnaces
. VDEh-Seminar "Elektrotechnik des Electric arc furnaces", Hamburg, 1996
- /38/ **Weichert, C; Scholz, R.:** Persönliche Mitteilung;
Inst. für Energieverfahrenstechnik und Brennstofftechnik, TU Clausthal
- /39/ **Glitscher, W.; Heinen, K.-H.; Zorcher, H.:** Betriebliche Erfahrungen mit dem Einsatz eines 40-t-Electric arc furnaces als Pfannenofen bei der Krupp Südwestfalen AG
Steelund Eisen 105 (1985) 6, S. 331/4
- /40/ **Rheinhardt, M.; Sittard, J.:** Einsatz eines Pfannenofens zur Elektrostahlerzeugung für kleinformigen Knuppelstrangguß
Steelund Eisen 103 (1983) 24, S. 1267/70
- /41/ **Hornich, H.; Landl, H.P.; Henders, S.:** Erfahrungen beim Betrieb eines Pfannenofens bei der Marien-Mitte Graz
Steelund Eisen 104 (1984) 12/13, S. 587/9

- /42/ **Ehle J.; Knapp, H.; Kuhn, R.:** Neue Entwicklungen bei Drehstrom-Lichtbogenofen
Steelund Eisen 114 (1994) 6, S.I 11/3
- /43/ **Berger, H.; Mittag, P.:** Der Comelt-Elektroelectric arc furnace mit schrag angeordneten Seitenelektroden
Steelund Eisen 115 (1995) 9, S. 53/58
- /44/ **Reichelt, W.; Hofinann, W.:** Contiarc - Ein neuartiges Schrottschmelzverfahren
Tagungsbericht ETG-Tage '95
ETG-Fachbericht 57 (1995), VDE-Verlag
- /45/ **Ehle, J.; Knapp, H.; Moser, H.:** Finger shaft technology: latest improvements and results
Steel World, Voll. 3, No. 2, p. 24/32
- /46/ **Hofinann, W.; Becker, L.:** Trends im Electric arc mmacebau
Hrsg.: Heinen, K--H.
Verlag Stahleisen, Dusseldorf, 1997, S. 387/94
- /47/ **Kohle, S.; Hoffmann, J.; Baumert, J. C; Nyssen, P.; Filippini, E.:** Improving the Productivity of Electric Arc Furnaces
ECSC, Techn. Report 3, Jan. - Dec. 2000, BFI

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Electrode Control of Arc Furnaces

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Electrode Control for AC Arc Furnaces

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1 Introduction

The electrode controller is an essential component for the operation of any arc furnace. Its purpose is to maintain the furnace working point demanded by the operator. This task can not be done by the controller on its own. The proper function and coordination of several components is rather necessary for an optimized arc furnace process. The most important preconditions are:

- Sufficient power supply from the mains,
- Proper design of mechanical, hydraulic and electrical components,
- Correct selection of the controller setpoint under consideration of the requirements of the mains, the furnace shell, the furnace transformer as well as the type of scrap to be melted.

Various different requirements are competing with each other and with the physical possibilities. Some of them even rule out each other.

Fig. 1 demonstrates the position of the electrode controller in the focus of various interests surrounded by requirements in different fields. Thorough consideration and coordination is necessary to achieve an optimum of furnace operation result. These aspects shall be highlighted during the paper.

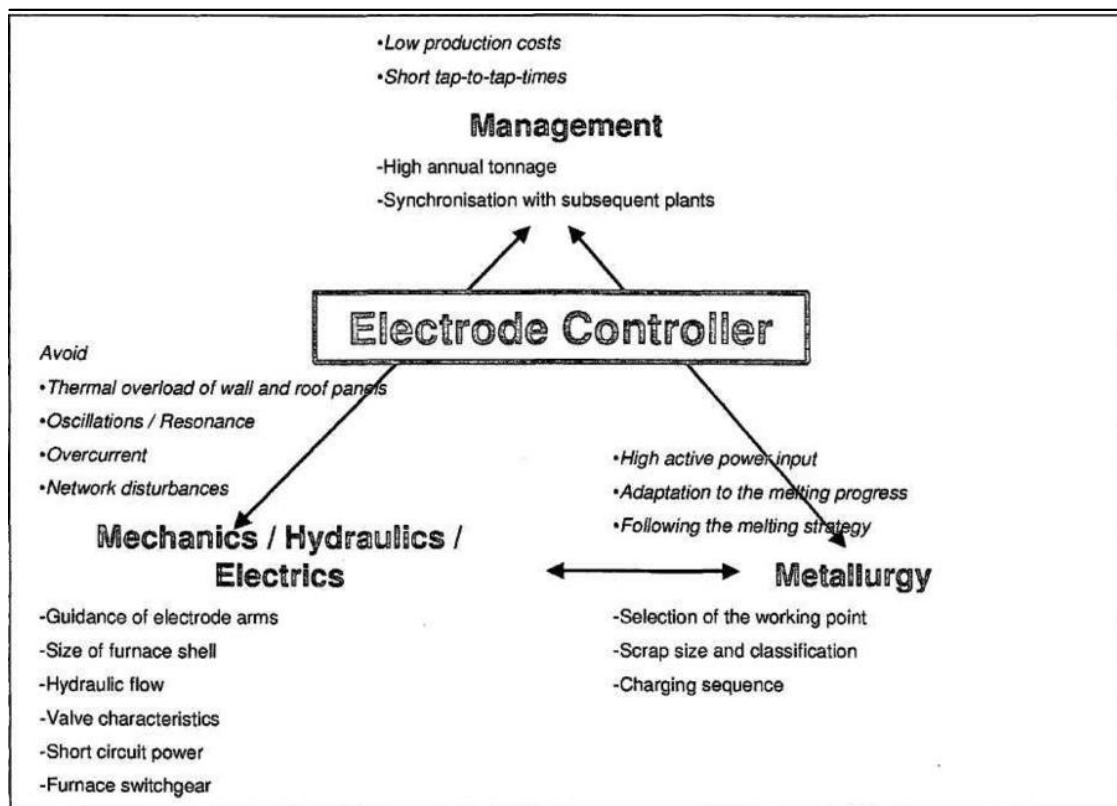


Fig. 1 The electrode controller in the focus of various interests

Basic features of a digital controller will be explained. Its general tasks as well as their limits, but also the possibilities for an extension of these tasks by means of automation equipment will be shown.

2 What can the electrode controller do? 2.1

The Arc Furnace System

The intention using an electric arc furnace is to melt down scrap in the shortest possible time consuming the least possible energy. This is done with the heat of an arc with appropriate power and length. The position and integration of the electrode controller within the arc furnace system is shown in Fig. 2.

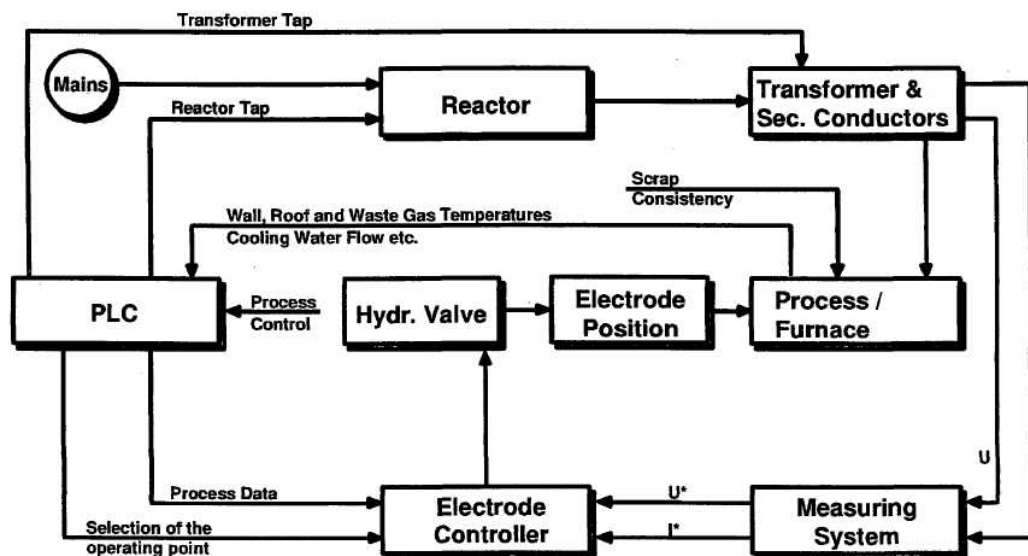


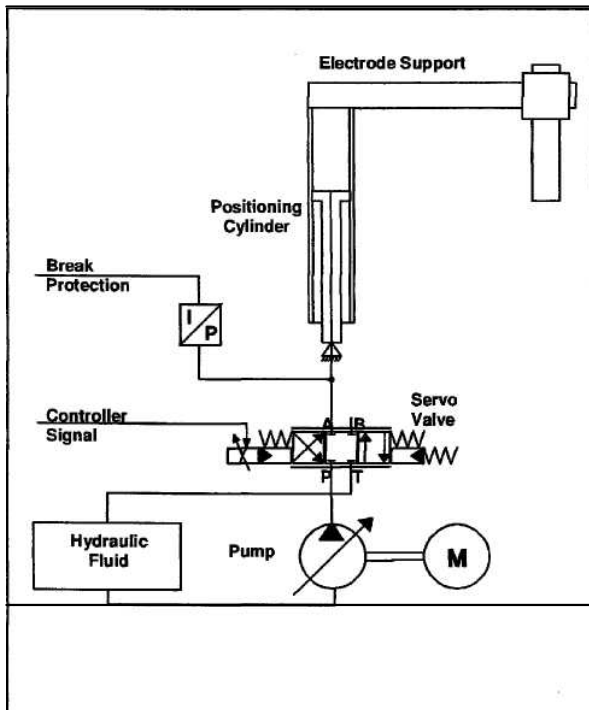
Fig. 2 Block diagram of the arc furnace system

Please note that there are only a few components / signals which have a direct interface with the controller. The mech./hydr. actuators and the working setpoints have the highest priority and require a detailed consideration and coordination. The reliable measurement of voltage and current is an inevitable precondition for the proper function of the controller. Other process data can be taken into consideration as far as they are available as characteristic electrical signals.

2.2 Hydraulic electrode positioning

The adjustment of the arc length is done by positioning of the electrodes. Considerable masses have to be moved by means of hydraulic equipment which influences the furnace operation as well as the controller design. See Fig. 3 for a typical hydraulic diagram for the movement of one electrode.

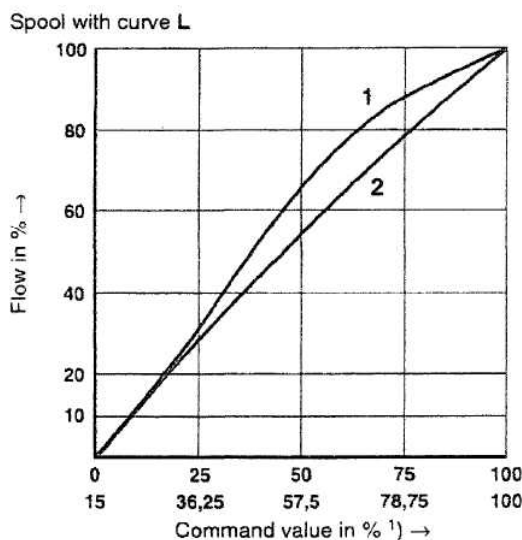
2.2.1 Selection of the control valve



The control valve is the only component which is directly influenced by the electrode controller. It has to fit to both the controller and the masses to be moved.

There should be a proper correlation between both the range of the controller's output signal and the desired electrode speed during regulation mode. The maximum speed should be achieved at approx. 80% of the output range. Over-sizing causes an operation around the zero point where special conditions are ruling (see above). Higher electrode speeds for manual operation can better be achieved using a by-pass.

Fig. 3 Typical hydraulic diagram for the positioning of one electrode



Furthermore, the valve characteristic should be linear over the entire range (see Fig. 4). A sharp bend in the curve in order to speed the electrode up in critical situations is rather a disturbance and is critical itself. If a significant non-linearity can not be avoided the output signal according to Fig. 6, line (2), should be further processed to compensate this.

The valve response time is also a very important feature. A typical figure is 20-80 ms (equals 1-4 AC cycles!) from closed to open position (see Fig. 5) while an electrode including support structure can be accelerated from zero to 80 mm/s within 100-500 ms, at the best.

Fig. 4 Servo valve characteristic
[Reference: Rexroth]

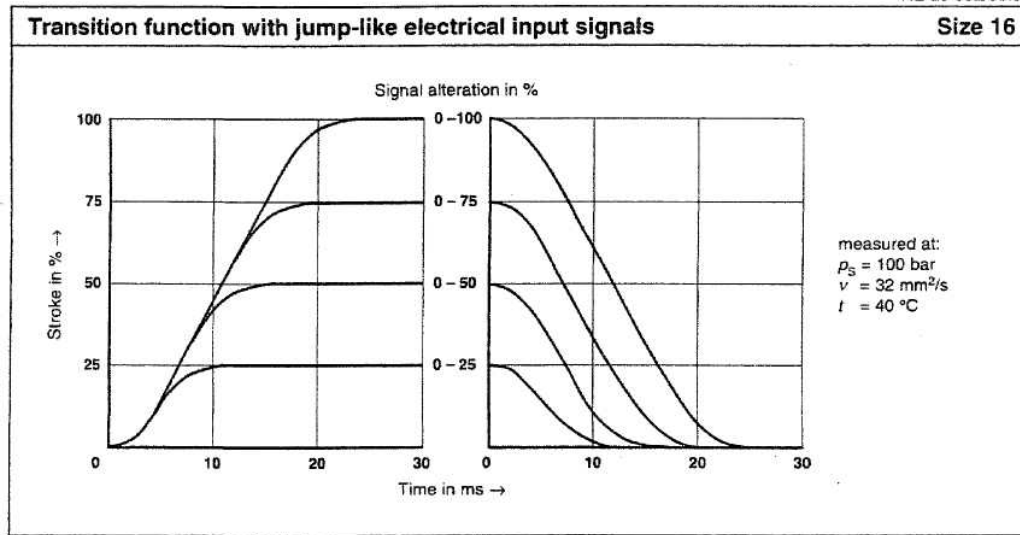


Fig. 5 Step-response of a servo valve
 [Ref.: Rexroth]

In addition, the system comprising mechanical masses and compressible hydraulic fluid is an oscillator. Its resonance frequency is depending on the size of the masses, the dimensions of the electrode support and the length of the hydraulic pipes. A typical figure is 2-7 Hz. In order not to initiate oscillations during acceleration the control signal has to be damped. The signal slope should not be shorter than 300 ms.

2.2.2 Adaptation of the control signal to the valve

Principally, a P-controller can be used with good results of the furnace operation. The controller output is proportional to the deviation from the setpoint. With a constant gain K_p the graph is a straight line (graph 1 in Fig. 6).

Close to the zero point the signal has to be adapted to the characteristics of the valve (graph 2 in Fig. 6). These are:

Proportional and servo valves do not close completely in neutral position. Due to its weight the electrode moves down even though there is no control signal for the valve. This movement is compensated by an offset (a) which, however, can be adjusted for the present electrode weight, only. Movements as a consequence of different electrode weights after burn-off or nipping are of minor importance and can be disregarded. The same applies to the dead-band of the valve (b) where significant flow is not achieved with very low deviation of the valve piston from the neutral position.

On the other hand electrode movement with very low deviations from the setpoint shall be suppressed. Therefore, a dead-band of the controller can be adjusted (c).

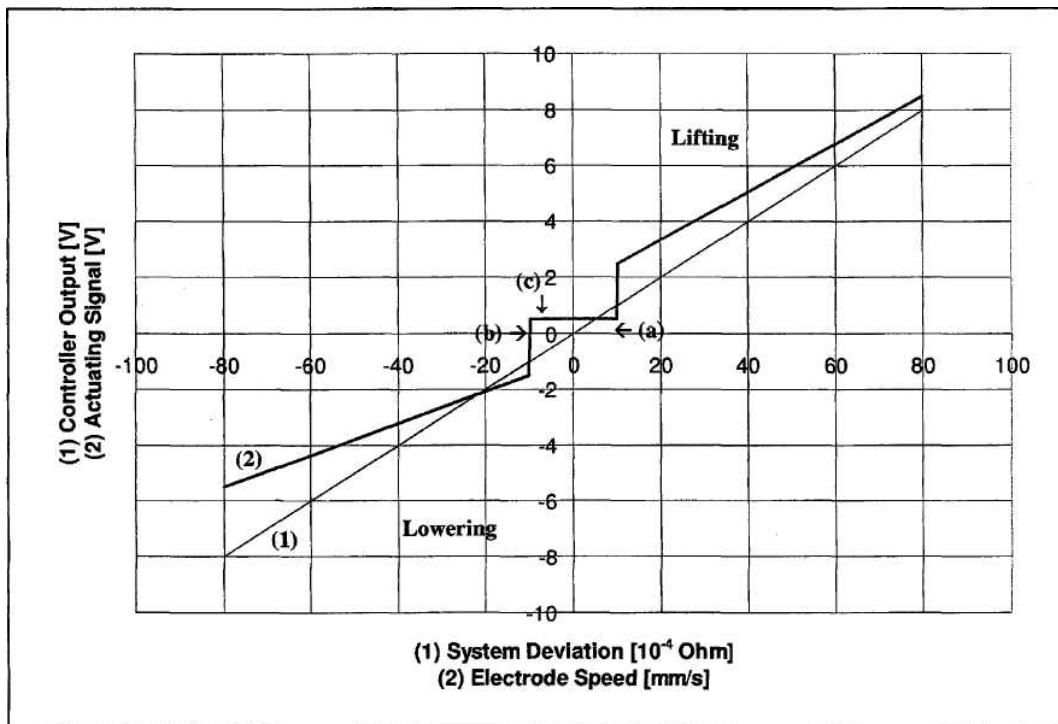


Fig. 6 Controller Output (1) and Actuating Signal (2) of the Electrode Controller

The correct signal for maximum electrode speed during regulation mode can be set by automatic adjustment moving the electrodes repeatedly up and down between the upper and lower limit switches. Linear interpolation defines the graph between the maximum and the respective offset. Different slopes for raising and lowering may turn out. The weight of the electrode arm and friction of the system is compensated automatically.

2.3 Controller tasks

Some basic features of an electrode controller are essential in order to allow a proper furnace operation and to avoid damage to its electrical and mechanical components.

Under the consideration that the electrode controller can only act by means of the measured voltage and current it can only perform such tasks which are directly related to these variables. Principally these are limited to

- start arc ignition avoiding electrode breaking,
- avoid short circuit,
- move the electrode in order to meet the controller setpoint.

2.3.1 Arc ignition

During the furnace start a safe arc ignition must be done. First all electrodes are lowered at the same time. While the first one hits the scrap it is stopped when its voltage is close to zero. Further lowering would either break or dip the electrode. As soon as the circuit is closed when the second electrode touches the scrap both are

raised again until the current meets the controller setpoint. So does also the third electrode.

The same procedure takes place during the furnace operation when the arc is lengthened or even extinguished due to collapsing scrap. The concerned electrode is lowered until the arc is ignited and/or the setpoint has been recovered again.

If an electrode should meet non-conducting material (e.g. a pile of lime) in the scrap while it is lowered for ignition the necessary voltage and current signals are not available. Further lowering would lead to an electrode breaking and must be stopped. This situation is recognized by a pressure switch detecting a low pressure in the electrode lifting cylinder. The controller then raises the electrode again and starts another attempt for ignition. In case of repeated failures the furnace control has to interrupt this procedure.

2.3.2 Avoid short-circuit

If collapsing scrap causes over-current or short-circuit the corresponding electrode is raised with maximum speed. Because of the coupling between the currents also both other phases are involved in the over current. Therefore it is useful to raise all electrodes for a quick elimination of the over current.

Very often over-current or short-circuit occurs when the arc burns a narrow shaft into the scrap which suddenly collapses and hits the electrode in an upper area. Usually the electrode speed is not sufficient to reduce the current before the furnace breaker trips. This is not an insufficiency of the regulator neither an inevitable event. Not the effect but the cause must be fought, namely by an earlier change of the working point from short to longer arc thus melting the scrap in a greater area.

The furnace breaker trip current is depending on the characteristic of transformer, switch gear and trip relay. A proper design and adjustment should be done before the electrode controller is used for optimization.

2.3.3 Avoid resonance

The natural frequency of the vertical oscillator "electrode arms / electrodes / hydraulic fluid" is approx. 2-7 Hz. The electrode current is modulated with the same frequency. Filters for the controller output signal shall suppress this modulation in order to avoid damage to the electrodes and arms by resonance.

2.3.4 Avoid dipping of electrodes

In order to avoid dipping of the electrodes into the bath the arc impedance must never become lower than the short-circuit impedance. Therefore the electrodes are raised when the impedance falls below a preset limit giving an alarm to the operator. This case is of relevance at smaller furnaces like ladle furnaces where the operating voltage is low and dipping is unacceptable because of contamination of the steel.

2.3.5 A void hot spots

The electrode controller can not avoid hot spots by its own, but the operator can avoid them by means of the controller. Excessive heat radiation upon the furnace wall is a consequence of a non-adequate working point. As soon as a protective layer of scrap has been molten down and gives way for the radiation to the wall a new working point with lower power and/or a shorter arc must be selected. This can be done manually by the operator according to his discretion or by an automation system. In that case the temperature monitoring of the cooling water and/or the calculation of the refractory wear index gives a feed-back for the preset of a new working point (see also chapter 4.3.2 below).

Especially during the liquid phase of the heat, depending on the type of steel to be produced, foaming slag is built up. This covers the arc at least partially in order to maintain the high power without damaging the furnace.

3 What does the electrode controller control?

3.1 Working point of the furnace

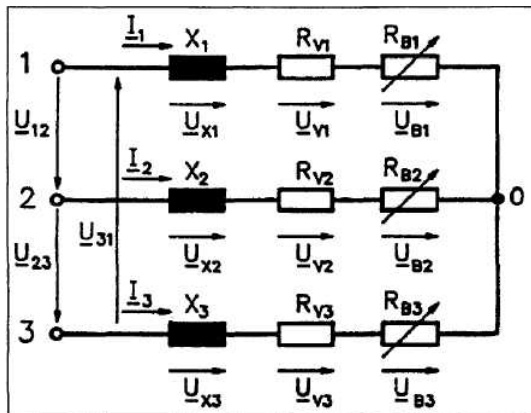


Fig. 7 Simplified equivalent circuit diagram of the electric arc furnace

For the performance of its original task the controller needs a working point. This is represented by the electrical data of the desired arc. In order to define these data knowledge of the equivalent circuit diagram is inevitable. During lots of scientific investigations it was tried to establish an equivalent circuit diagram which describes the furnace process reliably. For the results and the difficulties concerning non-linearity, asymmetry, time-variance and electromagnetic coupling please refer to other papers of this seminar.

For consideration of the electrode controller we may use the simplified equivalent circuit diagram (Fig. 7) where

- all reactances are represented by the reactance of the high current conductors X_i
- all resistances are represented by the resistance of the high current conductors R_{vi}
- the electric arc is similar to a resistance R_{Bi} and is proportional to its length,
- all components are linear and time-constant,
- the three phases are independent from each other.

Thus, the furnace process is characterized by the circle diagram in Fig. 8. A working point can only be on a line of constant voltage within the limits of the working area. These limits are:

- (1) max. electrode current according to the design of transformer and conductors,
- (2) max. apparent power supplied by the transformer,

- (3) max. secondary voltage,
- (4) limit of stable arc (max. $\cos(\varphi)$),
- (5) min. secondary voltage,
- (6) short-circuit line (min. $\cos \varphi$).

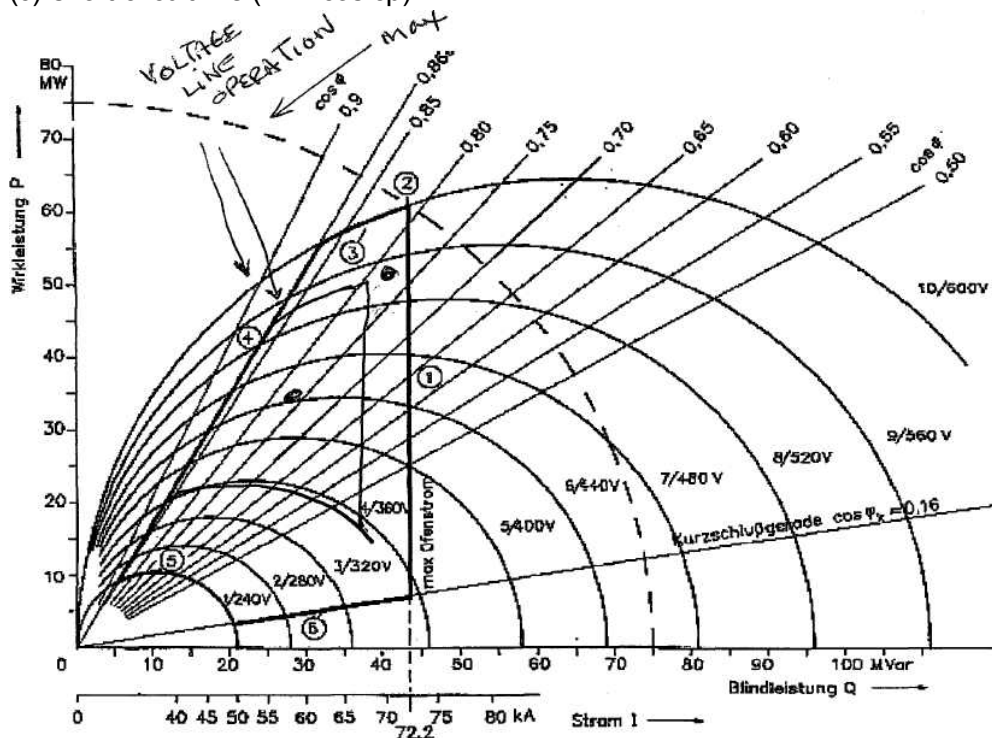


Fig. 8 Simplified circle diagram of an AC arc furnace

For the furnace operation **the user** has to select at least one working point per voltage tap which is in accordance with the production requirements. This working point of the furnace defines voltage and current and consequently the dependent values active power, reactive power and $\cos \varphi$ / arc length.

3.2 The controlled variable

In order to achieve the desired process parameters one of them has to be defined as the variable to be controlled. Since electrode voltage and electrode current are the only values available by measurement the basic controller setpoint is a current reference and the deviation $\mathbf{D} = \mathbf{I} - \mathbf{I}_{\text{ref}}$ is compensated by the controller. In practice there are two options for $\mathbf{I}_{\text{ref}}$:

3.2.1 Current control

$\mathbf{I}_{\text{ref}}$ may be the requested electrode current which is entered as the setpoint $\mathbf{I}_{\text{set}}$ for each transformer tap. That means that the controller operates in current control mode compensating the deviation $\mathbf{D} = \mathbf{I} - \mathbf{I}_{\text{set}}$ for each phase. Because of the coupling

between the phases due to $\sum_{j=1}^3 \mathbf{i}_j = 0$ current control is of limited use, only. It is an alternative solution in order to meet special side conditions like scrap quality or

stability of the power supply which should be checked during commissioning. However, it may be advantageous during overheating of liquid steel after melt-down or in ladles. Especially with single arm ladle furnaces current control is the preferred mode.

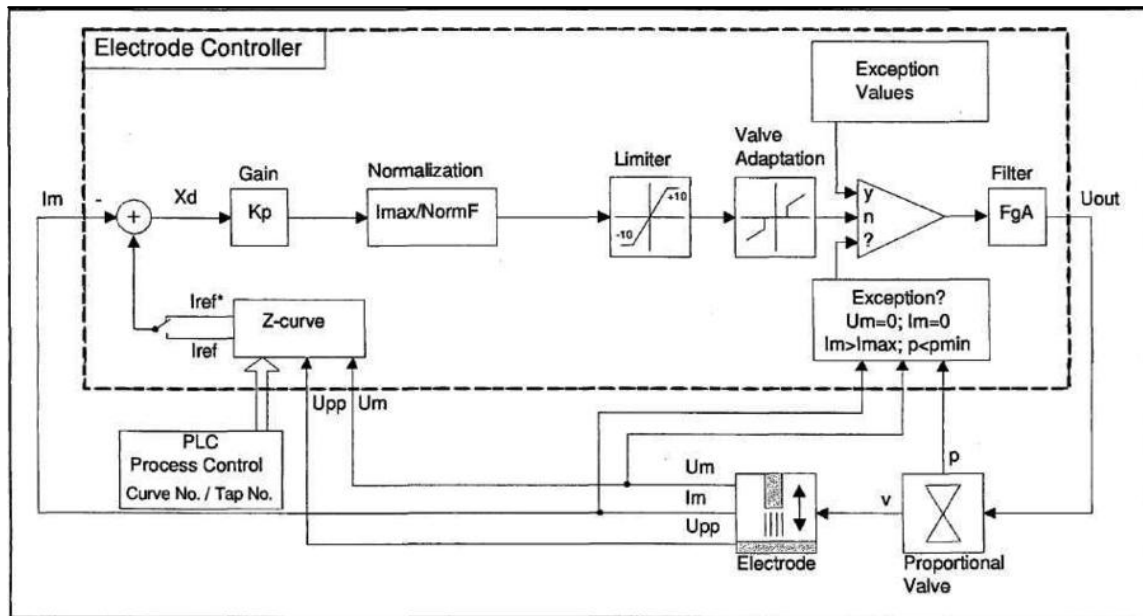


Fig. 9 Block diagram of a PC electrode controller [Ref.: ET Electrotechnology GmbH]

3.2.2 Impedance control

For a better independence of the phases and a more constant arc length I_{ref} is calculated from the desired phase impedance whereby the controller setpoint becomes the impedance weighted with the phase current forming the deviation

$$D = I_m - I_{ref}^* = I_m - \frac{U_m}{Z_{ref}} = \frac{I_m}{Z_{ref}} \cdot \left(Z_{ref} - \frac{U_m}{I_m} \right); \text{ with } Z_{ref} = \frac{U_{ppref}}{\sqrt{3} \cdot I_{mref}} \text{ and } U_{pp} = \frac{U_{12} + U_{23} + U_{31}}{3}.$$

The impedance is used as a controller setpoint with broad success. The setpoint Z_{ref} is based on the phase-to-phase voltage U_{pp} and does not suffer from wide fluctuations of the phase voltage especially during the melt-down period. Fig. 9 shows the block diagram of a PC based electrode controller.

3.3 The controller setpoint

The controller setpoint is defined by the secondary current of each voltage tap and implies the desired process data like arc length, coscp, active and reactive power. These U-I-couples are taken from the furnace circle diagram and stored in the controller. The more realistic the circle diagram is the smaller is the deviation of the furnace working point from the controller setpoint.

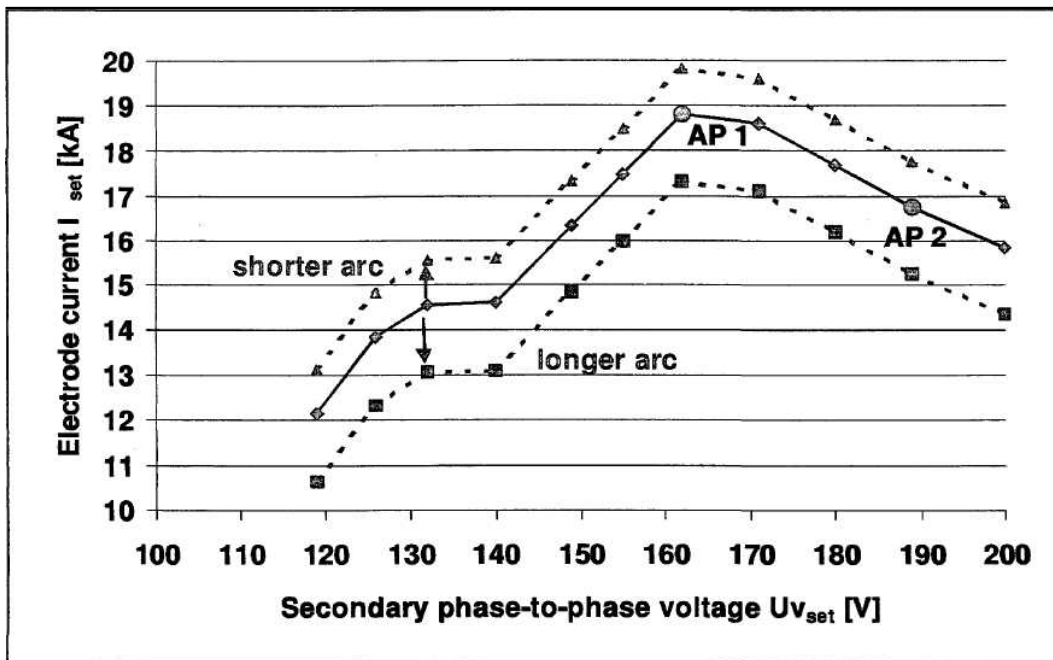


Fig. 10 Controller setpoint characteristic

A typical controller characteristic for a ladle furnace is shown in Fig. 10. Each point of these curves is a controller setpoint according to the relevant phase voltage. The desired process data belonging to the selected points are listed in Table 1 in the annex.

During impedance control a new controller setpoint is calculated by interpolation if the actual phase voltage differs from the scheduled one. The actual voltage and the current according to the curve are used. Thus, the setpoint is moving along the curve according to the voltage fluctuation. During current control the setpoint for each voltage tap remains constant independent from voltage fluctuations.

In order to approach the operating voltage as much as possible the setpoints should be entered under consideration of the transformer and mains instead of the rated values. Several curves may be defined representing a different arc length. Comparing with the furnace circle diagram: Vertical movement of the curve means shifting the furnace working point along the voltage circle.

The working point of the furnace is subject to a permanent variation by moving scrap within the total range between no-load and short-circuit operation. Additionally, fluctuation of both power supply and furnace reactance make the circle diagram extremely dynamic. The reasons can also be the operation of a neighboring furnace or network perturbations caused by others. Furthermore, incorrect design of the circle diagram by use of an insufficient calculation model causes the same effects. A verification by a short-circuit measurement and an update of the circle diagram is recommended during commissioning. Thus, the actual working point may accidentally be identical with the setpoint. Usually, however, the actual process parameters (U , I , P , Q , $\cos\phi$, arc length) do never meet the desired ones exactly.

For his reactions the operator has to follow his priorities e.g. for P, Q or $\cos\phi$. Knowledge about the furnace behavior as a consequence from the control mode in use is of high importance. Table 1 in the annex demonstrates how process parameters change with voltage or system reactance. The following results can be seen (AP1, tap 7):

- A) With lower voltage and
 - a) Impedance control (see also annex 1)
 - a working point turns out which has
 - * a lower current,
 - * a lower arc power,
 - * but an almost unchanged $\cos\phi$.
 - b) Current control (see also annex 2)
 - a working point turns out which has
 - * the same current,
 - * a lower arc power,
 - * and a lower $\cos\phi$.
- B) With lower system reactance and
 - a) impedance or current control (see also annex 3/5)
 - a working point turns out which has
 - * the same current,
 - * a higher arc power,
 - * and a higher $\cos\phi$.
- C) With higher system reactance and
 - a) Impedance and current control (see also annex 4/5)
 - a working point turns out which has
 - * the same current,
 - * a lower arc power,
 - * and a lower $\cos\phi$.

Surprising effects may come up using higher voltage taps if the setpoint characteristic has a negative slope because of the limited capacity of the furnace transformer:

- D) With lower voltage and
 - a) Impedance control (see also annex 6)
 - a working point turns out which has
 - * a significantly higher current,
 - * a lower arc power,
 - * but a lower $\cos\phi$.
 - b) Current control (see also annex 7)
 - a working point turns out which has
 - * the same current,
 - * a lower arc power,
 - * and a lower $\cos\phi$.

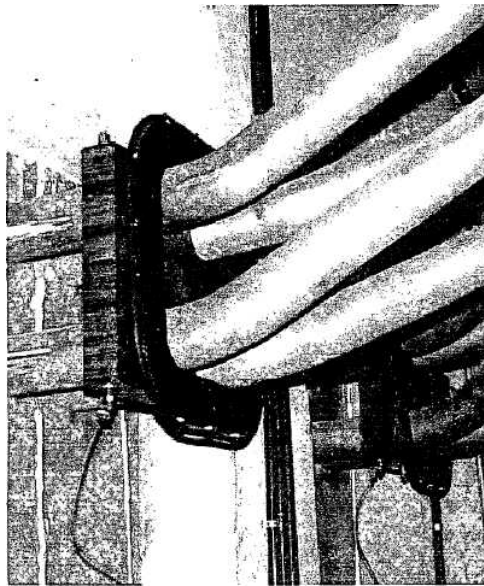
It is important to know that the electrode controller can not compensate these deviations in such a manner that all parameters can be recovered again. Therefore

priorities must be set defining optimization criteria. For the possibilities of an enhanced controller refer to chapter 4.3.

3.4 Measuring actual voltage and current

The values of voltage and current necessary for the calculation of the setpoints are easily available. It is sufficient and economical to measure on the low voltage side of the transformer and to take the r.m.s. values.

The **electrode voltage** is taken directly from the secondary bus bars in the transformer room. It is then being transformed to the signal level needed for the regulator.



The **electrode current** can be measured with current transformers on either side of the transformer. As an alternative Rogowski Coils have proven to be reliable sensors for the current. They provide an induced voltage proportional to the current through the surrounded conductors. The measuring signal does not suffer from saturation effects because there is no iron core. It also comprises harmonic currents due to its wide band characteristic. Easy installation, even after the furnace erection, is one more advantage versus current transformers. An example is shown in Fig. 11.

F

ig. 11 Rogowski Coils at the high current tubes of an AC EAF

4 Optimization criteria

Looking for optimization criteria from the controller's point of view we check the function blocks in Fig. 2 :

4.1 Mechanical and hydraulical design

We may assume that the mechanical design reasonably meets the process requirements. A further reduction of the masses to be moved, as far as possible, would be advantageous.

As shown in chapter 2.2 the total response time for a jump-like control signal is determined by the mechanical parameters and is much longer than 100 ms. That means

- The valves used are fast enough. Further speed-up would not bring a benefit.
- Cycle times of the controllers used are short enough as well (approx. 20 ms). No demand for faster processors is justified for pure control purposes.

Furthermore assuming that the valve characteristic meets the requirements there is no major potential for an optimization of the electrode control by the hydraulical equipment.

4.2 Power supply

The power supply by the furnace transformer may be expected to be as stable and free of losses as possible. Other design criteria are not relevant for the control aspects.

The availability of a reactor with on-load tap changer is one measure to optimize the furnace control. It is used for improved arc ignition and stabilization of the working point. On the other hand it causes a reduction of the power factor $\cos\phi$ resulting in lower active power. Therefore, the furnace process is started with high reactance which is lowered step by step during the heat.

The criteria for a change of transformer and reactor are based on the operator's experience. Further support can be given by automation equipment (see below).

4.3 Enhanced controller

Digital controllers based on PC's or PLC's have proven to be reliable components. The variables and algorithms used as described above are sufficient for the application and do not need major improvements.

The quality of the electrode control is rather essentially depending on a reliable input to the controller, mainly concerning

- acquisition and evaluation of voltage and current signals,
- acquisition and consideration of peripheral process signals,
- selection of adequate furnace working points by the process management.

Some of these requirements can be supported and improved by automation systems either connected to or integrated in the electrode controller.

4.3.1 Measuring and processing of voltage and current

Since voltage and current are the only process signals available for the electrode controller an adequate measuring system for reliable values is of highest importance. While the acquisition of these signals is relatively easy their processing causes major efforts but also provides more process information useful for an improved electrode control. Data acquisition by means of a Digital Signal Processor and storage of a wide history in a data base are preconditions for an adequate evaluation. Here some options which are being preferred differently by various suppliers:

- (1) Calculation of the actual **furnace reactance**,
- (2) **Mathematical modeling** of the furnace process,
- (3) **Neural modeling** of the furnace process,
- (4) Performing a **harmonic analysis** of the electrode current,
- (5) **Statistical evaluation** of suitable process data.

Comparing the planning and actions for a melt discloses the possibilities of optimization by an automated mode. Traditionally the operator defines a power diagram as the schedule for the course of the heat based on a static circle diagram. It provides the schedule for the selection of the transformer tap (Fig. 12 a) and the reactor tap (Fig. 12 b), if a reactor is available, during the heat.

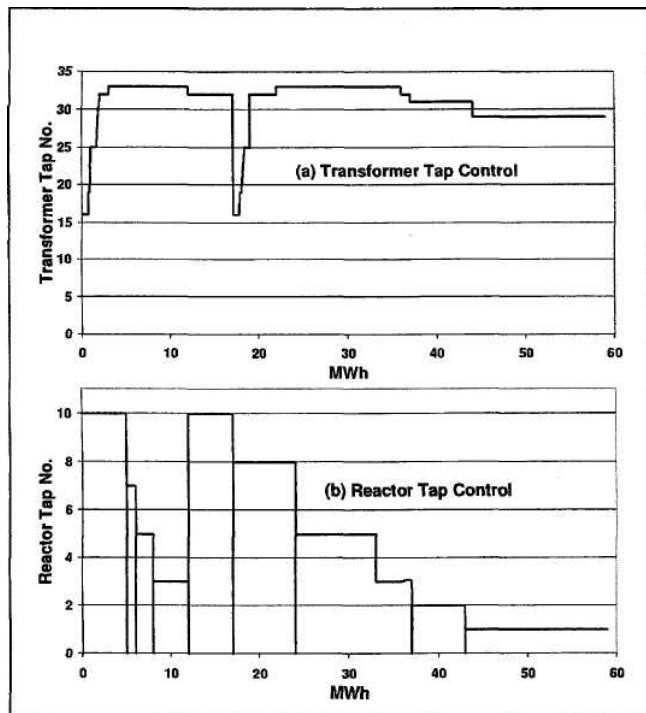


Fig. 12 Typical heat schedule

As mentioned above already even an experienced operator can only try to make the best selections and keep them for specific periods during the heat. Permanent judgment of the furnace performance is necessary. But he is not able to follow the dynamic change of the process data. This can rather be done with a suitable automation system, only. Therefore, also permanent information about the actual conditions of the heat must be made available.

4.3.2 Transformer Tap Control

The transformer tap is the basic means of defining the active power to be brought into the furnace. Its selection has to be made not only in accordance with the metallurgical requirements but also under the consideration that the furnace wall and roof do not get damaged by overheating. In order to avoid such "hot spots" the wall temperatures must be monitored and evaluated. The better the expected temperature can be estimated the more precise the moment of switching the transformer tap can be defined. Thus high power can be maintained longer without causing damage to the furnace.

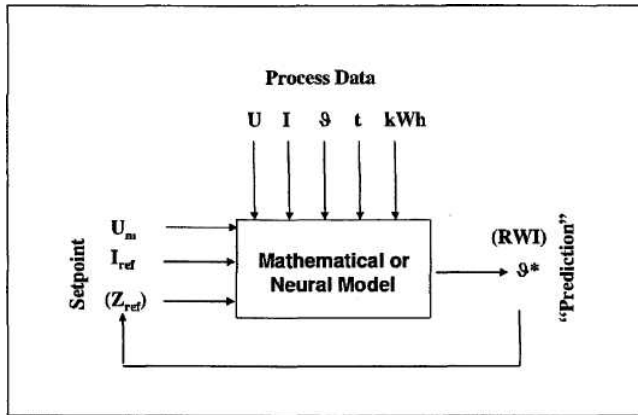


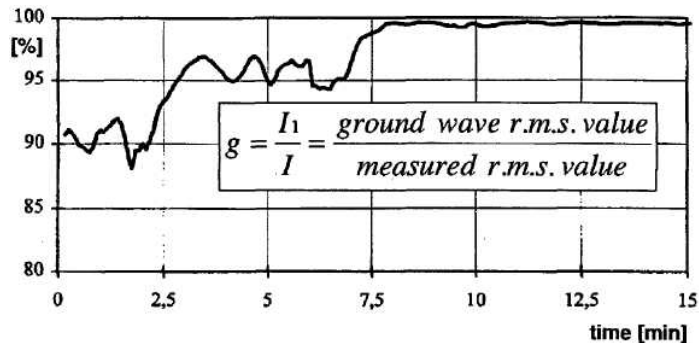
Fig. 13 Simplified block diagram for the "prediction" of the wall temperature

A mathematical or neural model can be used to "predict" the temperature characteristic (Fig. 13 shows the principle in a simplified manner). The feedback is used for an update and improvement of the controller setpoint. As an addition to or an alternative for the temperature the **R**efractory **W**ear **I**ndex (RWI) can be calculated representing the heat load upon the furnace wall.

Additional heat sources other than the electric arc, like burners and injection lances, have to be considered separately to let the electrode controller act properly.

4.3.3 Reactor tap control

Fig. 14 shows the ground wave content during melt down of scrap / DRI for structural steel in the ISPAT-HSW furnace. Characteristic levels can be seen during specific intervals.



These have been taken as an indication for a need of reactance for stabilization of the arc. With increasing ground wave content (= increasing arc stability) the reactance is reduced stepwise.

Fig. 14 Current ground wave content during melt down [Reference: ISPAT-HSW]

Fig. 15 shows the corresponding relation between g and each available reactor tap. The Hysteresis cares for a minimum of switch operations. Thus the use of the reactor could be minimized increasing the power input to the furnace while the arc was stabilized by the reactor.

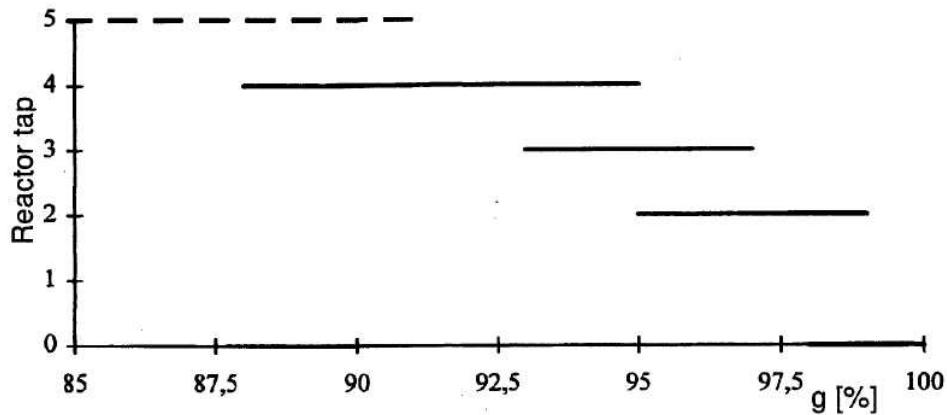


Fig. 15 Reactor control depending on the current ground wave content
[Reference: ISPAT-HSW]

The correlation between the ground wave content and the furnace reactance may not always be so strong as indicated in Fig. 14. It might vary from furnace to furnace depending on the type of scrap, the steel produced, the possibility of creating foaming slag or other reasons. Additional information about the heat status may be obtained by statistical evaluation e.g. the standard deviation of the controller setpoint as shown in Fig. 16. This helps to switch the reactor in an optimum point of time.

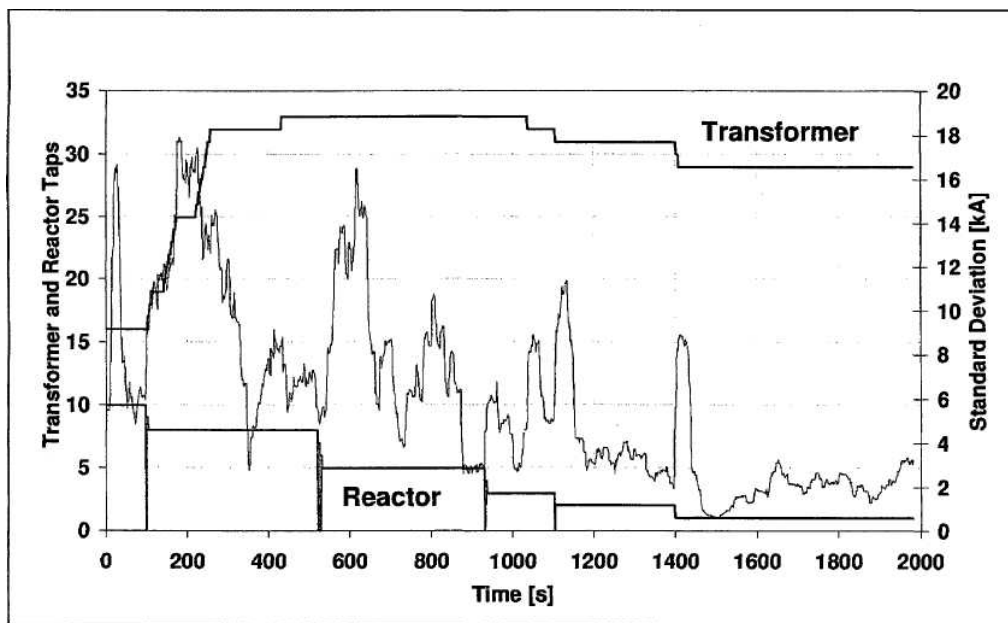


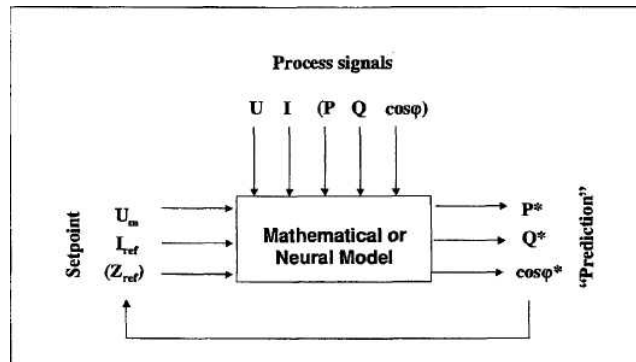
Fig. 16 Standard deviation of the electrode current from the controller setpoint

4.3.4 Dynamic controller setpoint

As shown above on each transformer tap a number of working points of the furnace can be selected within the allowed range. All furnace parameters (U, I, P₅ Q, arc

length/ $\cos\varphi$) are defined by the working point. It was also shown that the actual values differ from the desired ones more or less. For the definition of the correct working point both knowledge of the **actual one** and the consequences of the **desired one** is necessary.

By means of the actual voltages and currents the actual working point can be calculated and evaluated. Permanent re-calculation of the circle diagram allows to display the same in a graphic which eases the overview about the heat status for the operator. If there is an unacceptable deviation an updated working point should be preset.



For an automation system also here two options are available. Either a mathematical model or a neural network can be used (see Fig. 17 for the simplified schematic). Both methods shall give a feed-back for an update of the controller setpoint. Thus a permanent adaptation of the furnace working point is done which is aiming for an optimum power input.

Fig. 17 Simplified block diagram for the "prediction" of the furnace parameters

Please remember that no parameter can be changed without changing the other ones as well. Therefore the working point has to be selected under consideration of priorities and definition of an optimization strategy. In order to make the complexity clear again Fig. 18 shows the complex correlations between the working point setting and the consequences upon the furnace process.

In the general case maximum active arc power has the highest priority. It defines a single point on each voltage circle if the the voltage is set manually. With automatic tap changing there is only one point in the entire circle. All other parameters are depending on this point. These might include some with unwanted side effects like high electrode consumption or heat load on the walls (RWI). Thus, a high power input would be paid with electrodes or refractory material.

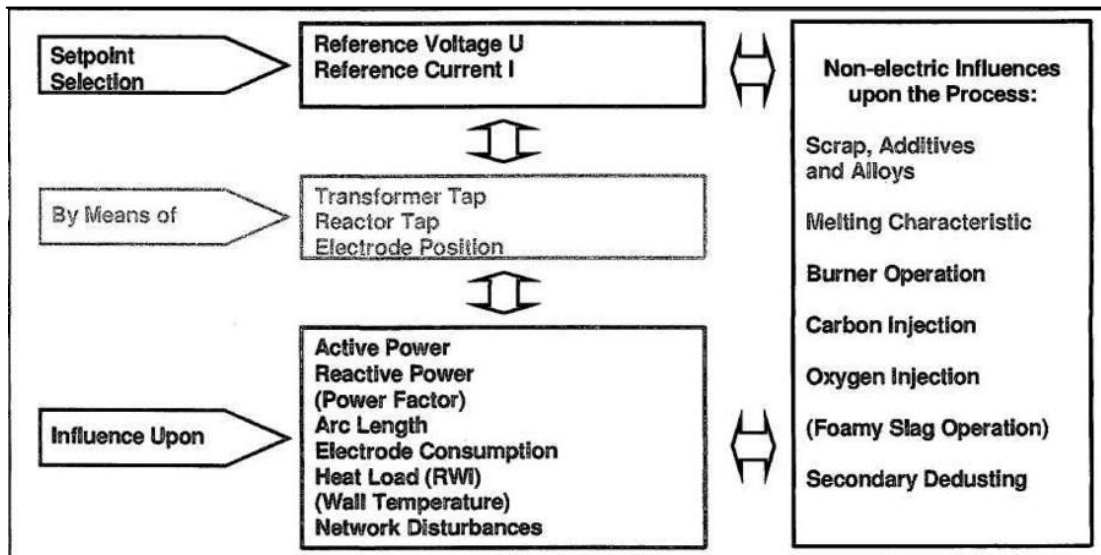


Fig. 18 Complexity of correlations between working point and furnace process parameters

In order to find not only the maximum but the optimum a tolerance for the active arc power must be defined. This allows the working point to move on the voltage circle within the defined tolerance. The direction of this movement depends on one or more subordinated criteria for which a ranking by weight factors must be done. This can be for example the current, the arc length or the reactive power. Latter one is an interesting feature under the aspect of flicker reduction caused by the fluctuation of the reactive power. The diagram in Annex 8 might demonstrate the wide interval for current or arc length opened by a relatively small fluctuation of the active arc power.

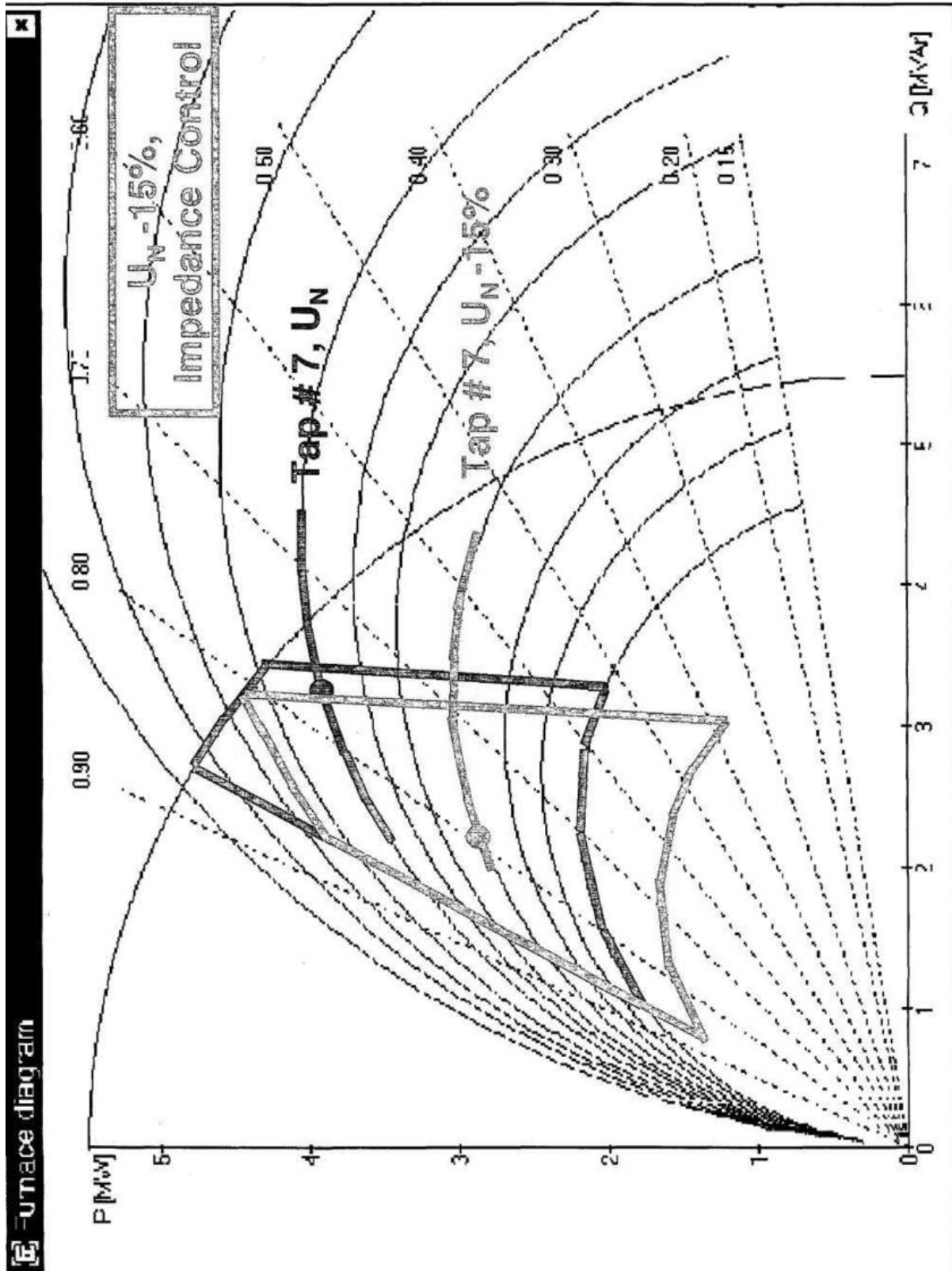
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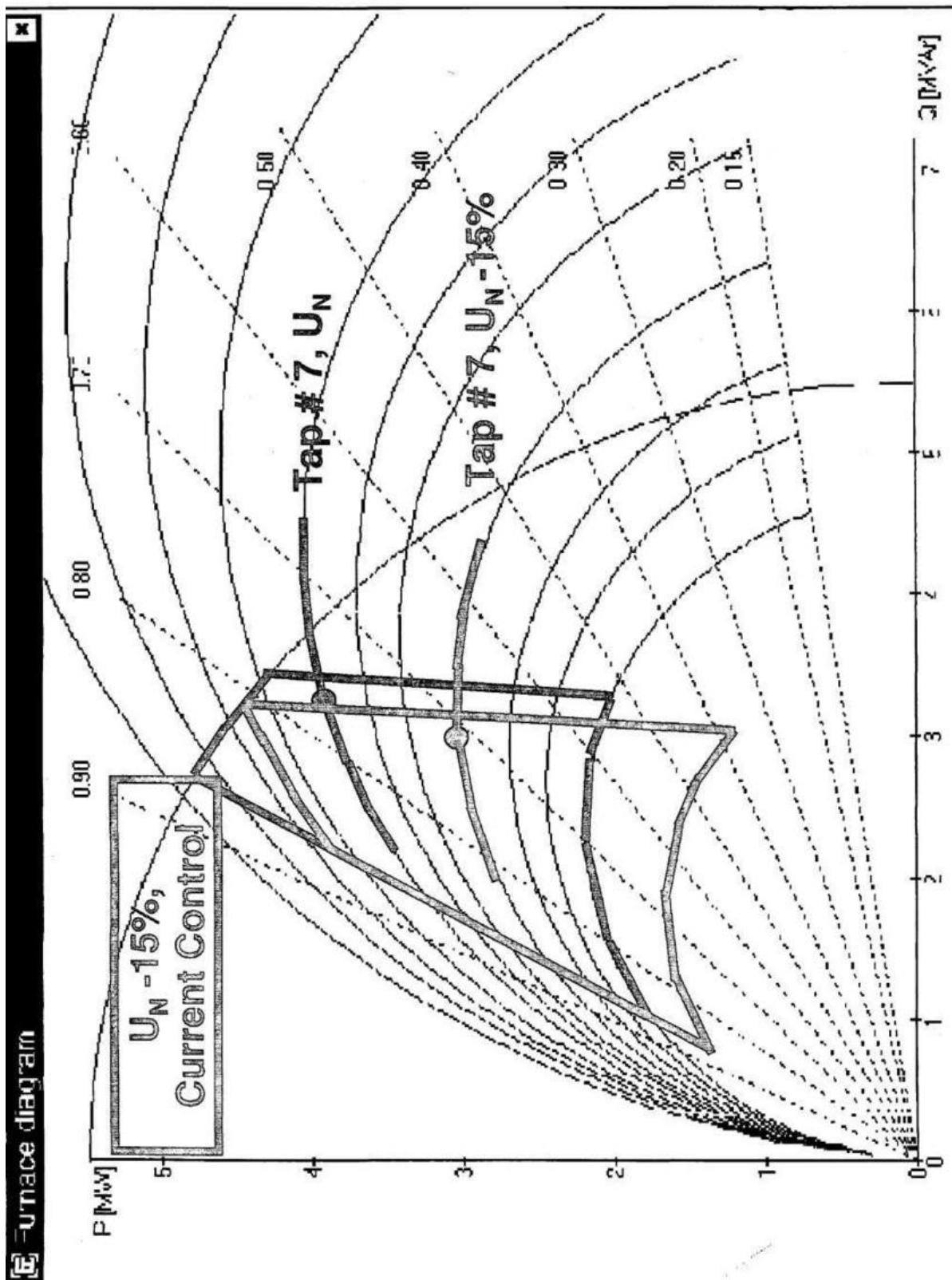
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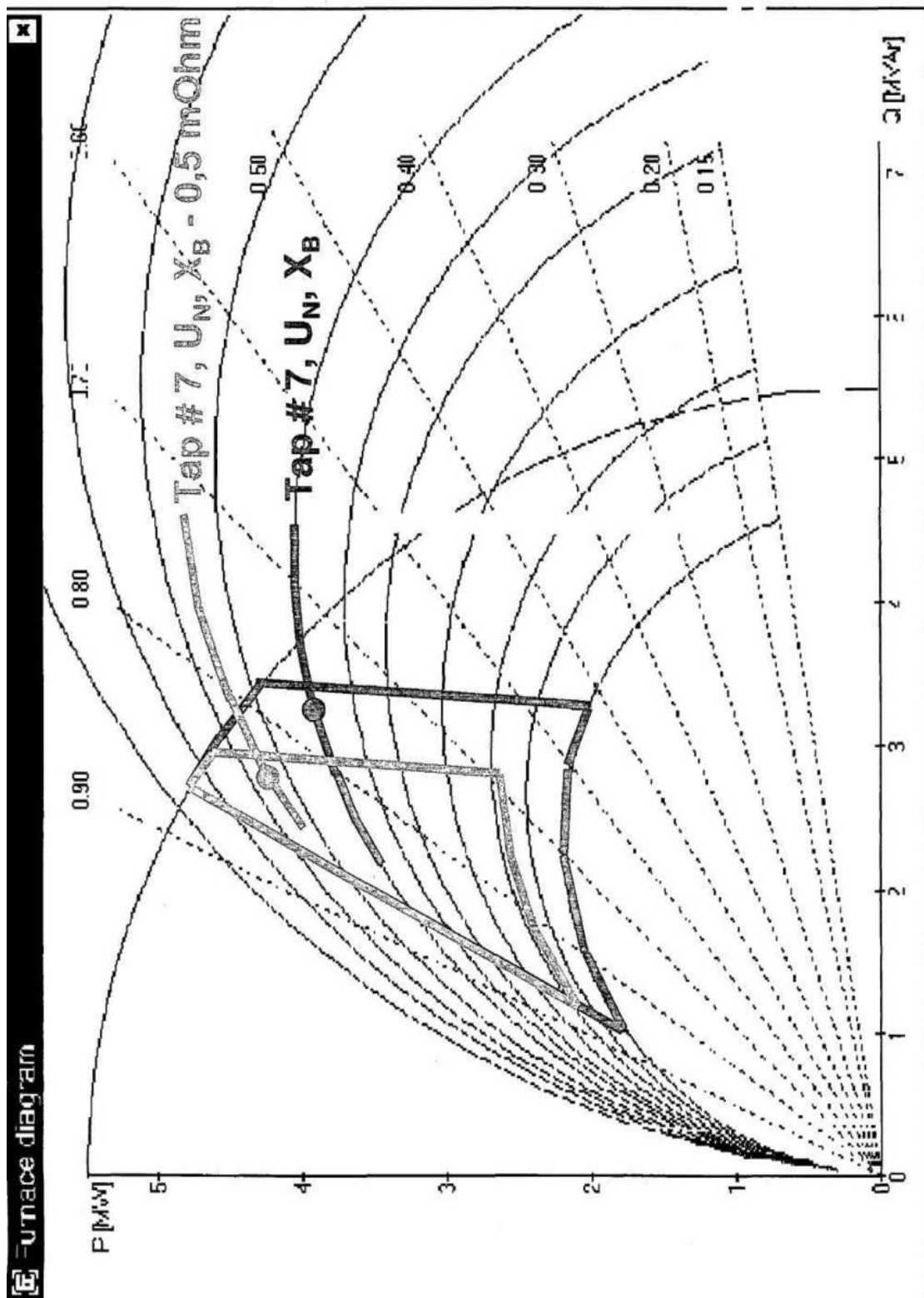
	U_N/V	U_{2Of}/V	I/kA	P_B/MW	$R_g/m\Omega$	$X_g/m\Omega$	$Z_g/m\Omega$	P/MW	Q/MVA_r	S/MVA	$\cos\phi$
Design data: Working point on tap 7	162	142,68	18,15	3,48	3,95	3,30	5,15	3,91	3,26	5,09	0,77
Assumption: U_N lowered by 15% Impedance control	137,7	125,29	15,4	2,58	4,06	3,14	5,13	2,89	2,23	3,65	0,79
Assumption: U_N lowered by 15% Current control	137,7	123,2	18,15	2,63	3,1	3,06	4,36	3,06	3,03	4,31	0,71
Assumption: X_B lowered by 0,5m Ω Impedance and current control	162	142,68	18,15	3,83	4,30	2,84	5,15	4,25	2,80	5,09	0,83
Assumption: X_B raised by 0,5m Ω Impedance and current control	162	142,68	18,15	3,05	3,52	3,76	5,15	3,48	3,72	5,09	0,68
Design data: Working point on tap 10	189	184,73	16,77	4,04	5,83	3,35	6,72	4,40	2,53	5,07	0,87
Assumption: U_N lowered by 15% Impedance control	160,7	147,87	17,88	3,42	4,16	3,10	5,19	3,95	2,95	4,93	0,80
Assumption: U_N lowered by 15% Current control	160,7	148,58	16,77	3,46	4,53	3,13	5,51	3,82	2,64	4,64	0,82

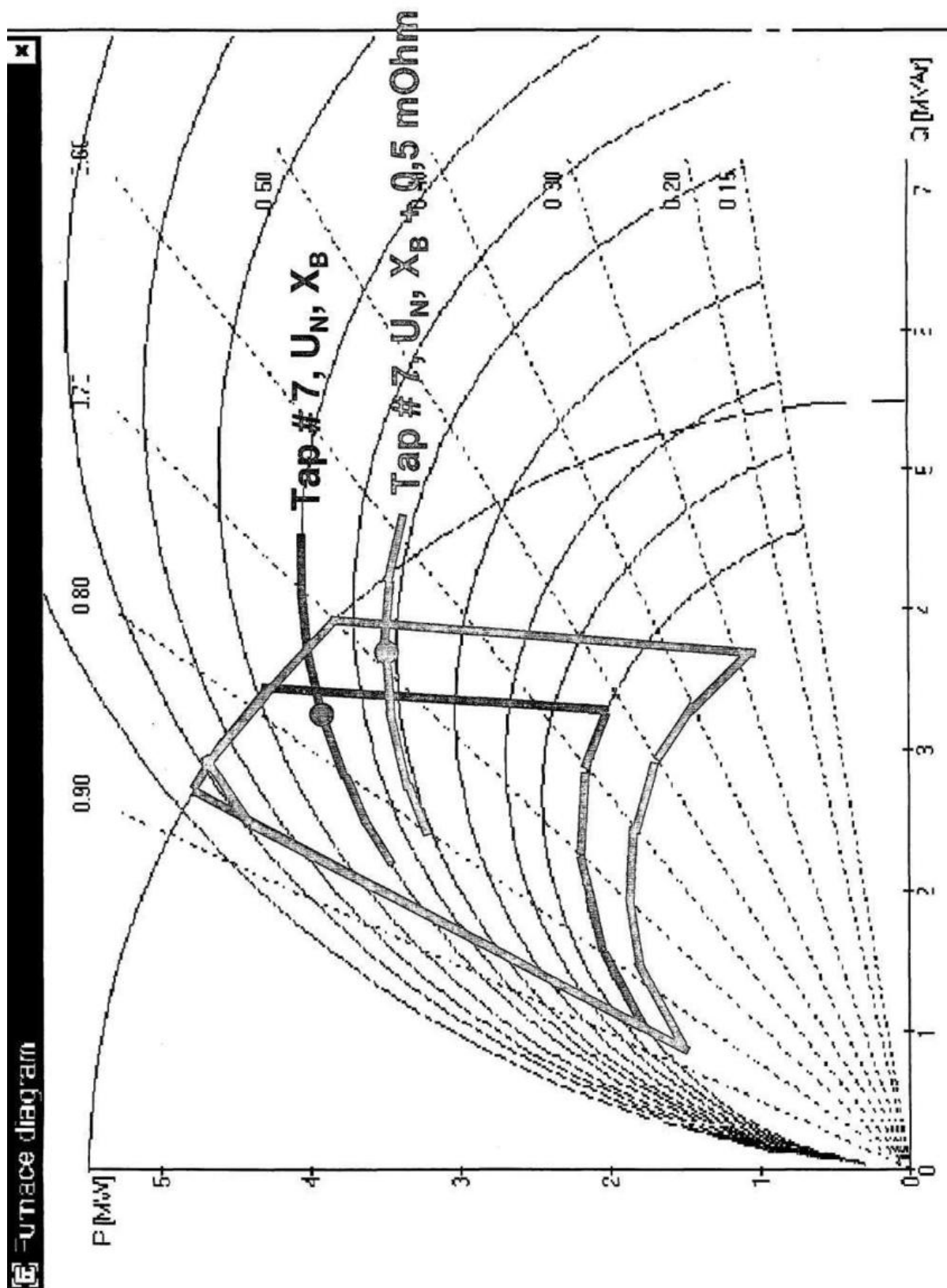
Table 1 Process parameters corresponding to diagrams in annex 1-8

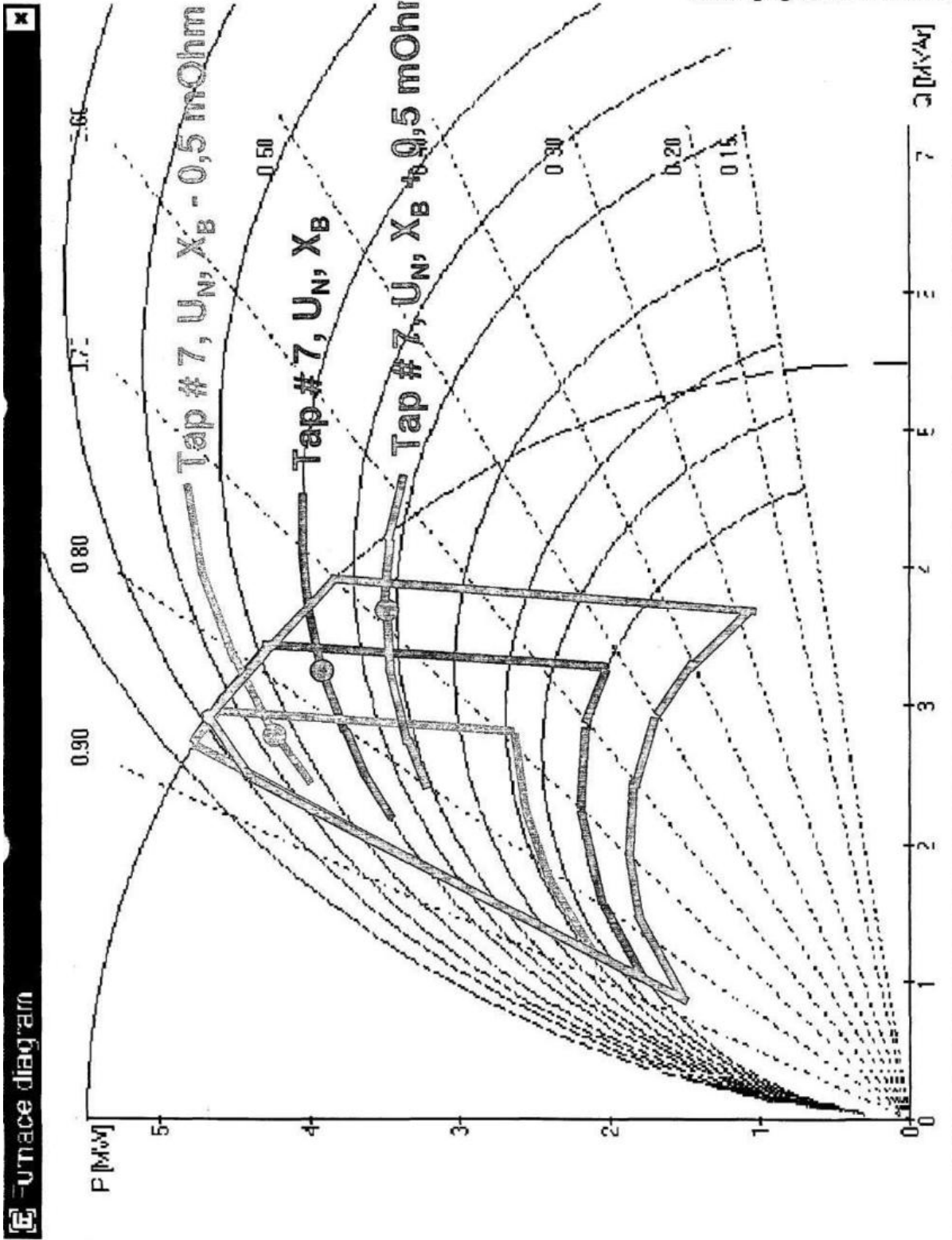
U_N	Rated tap voltage	R_g	Total resistance
U_{2Of}	Tap voltage during operation	X_g	Total reactance
P_B	Arc power	Z_g	Total impedance

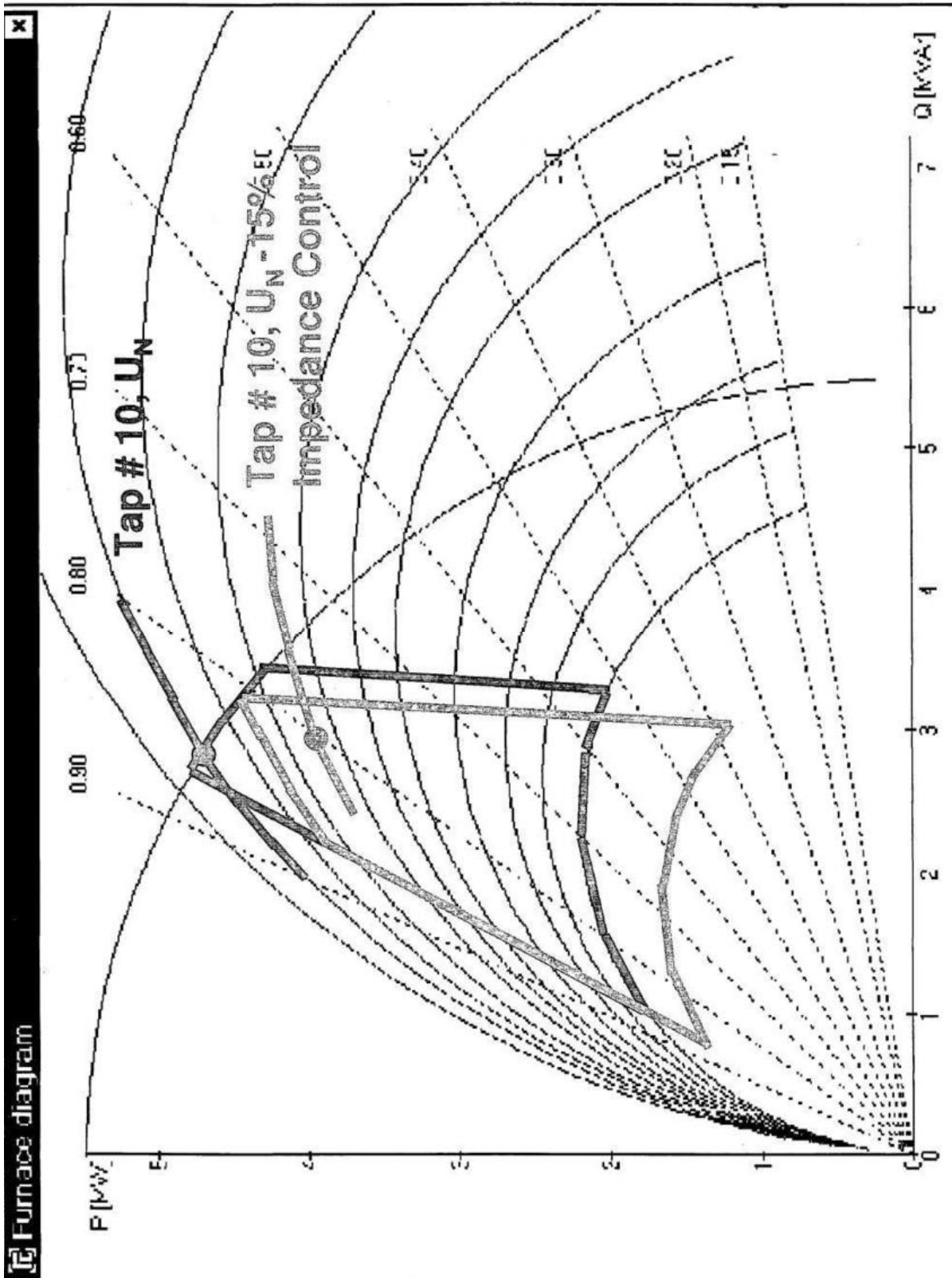


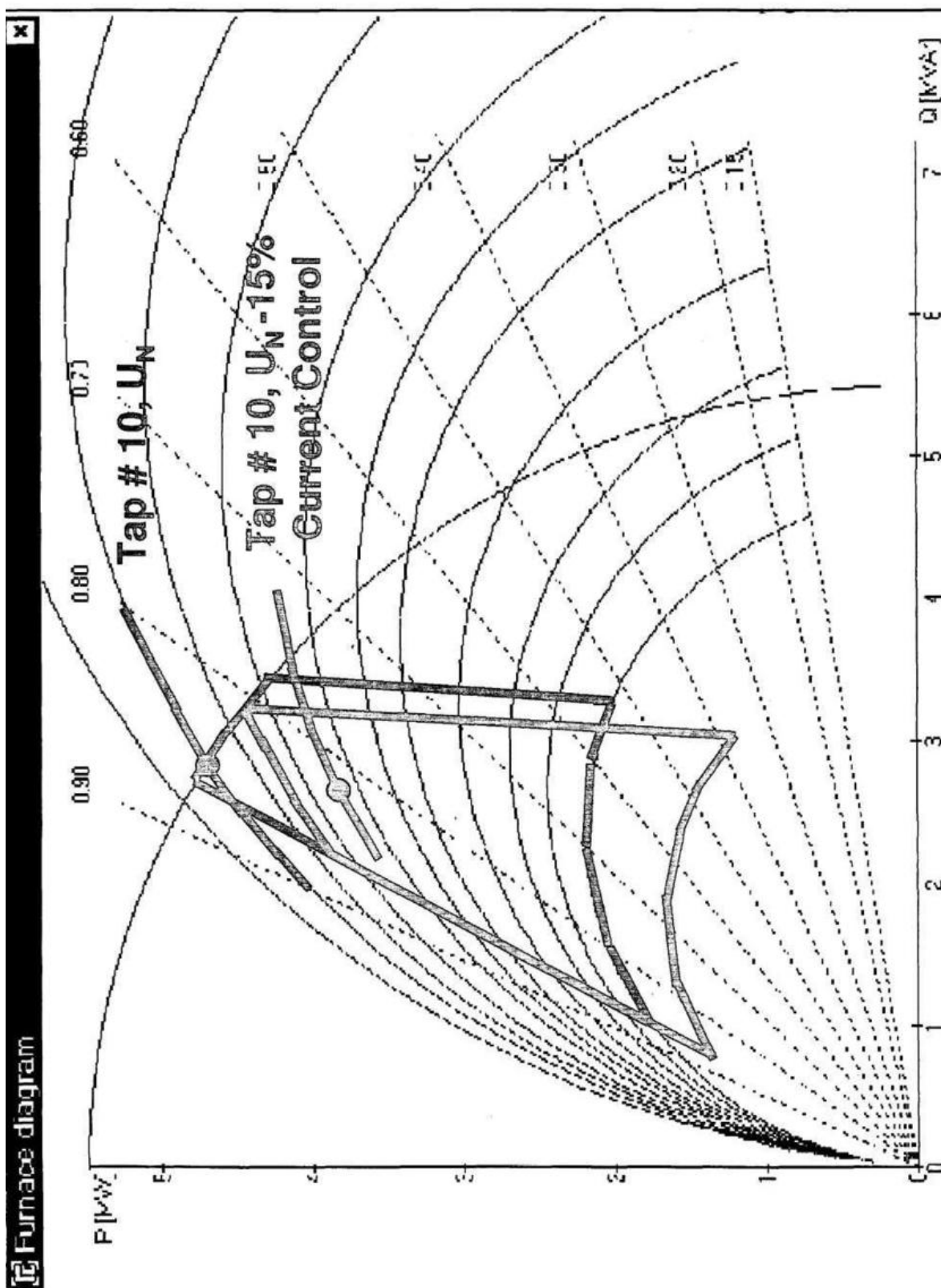


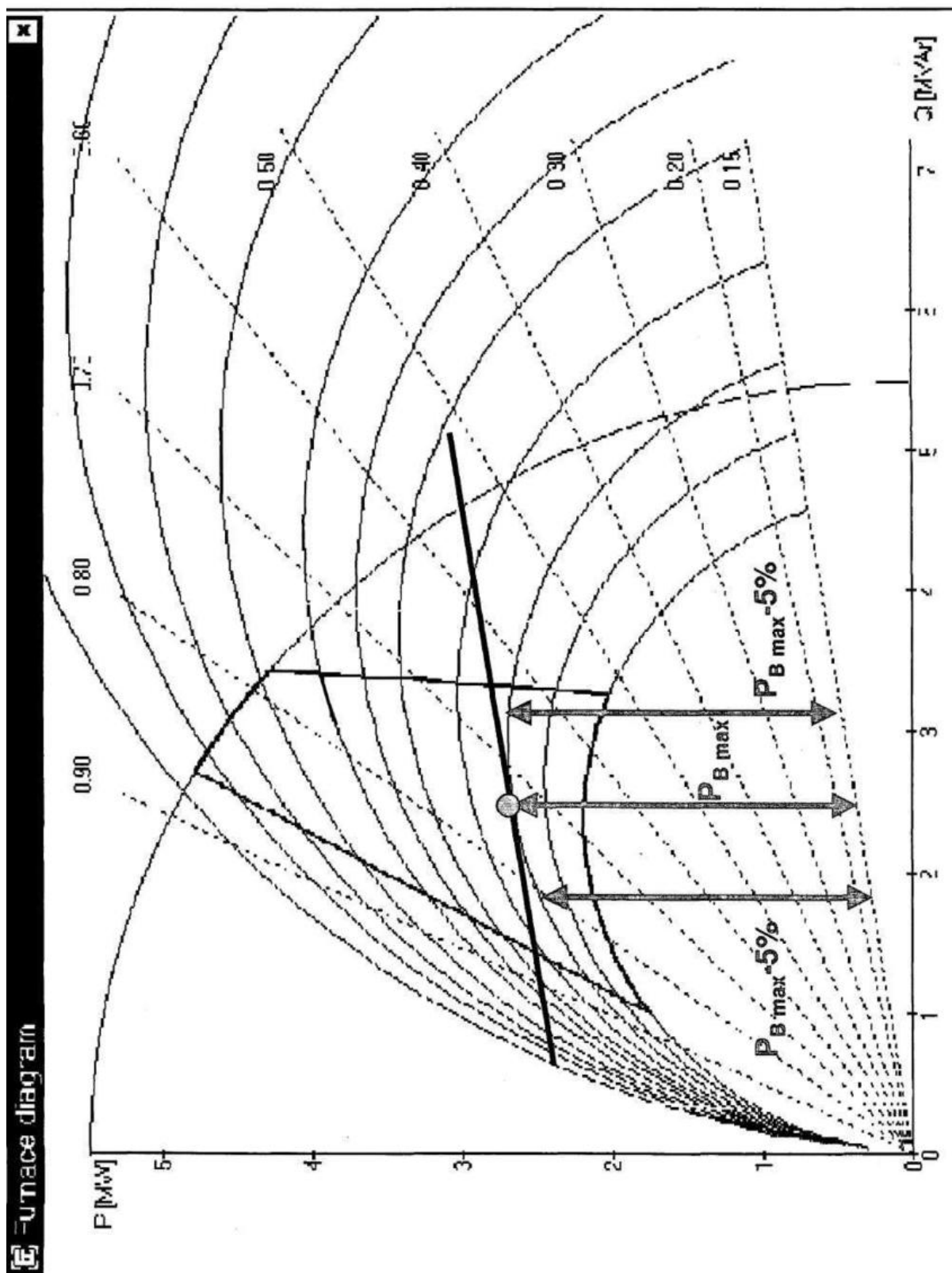


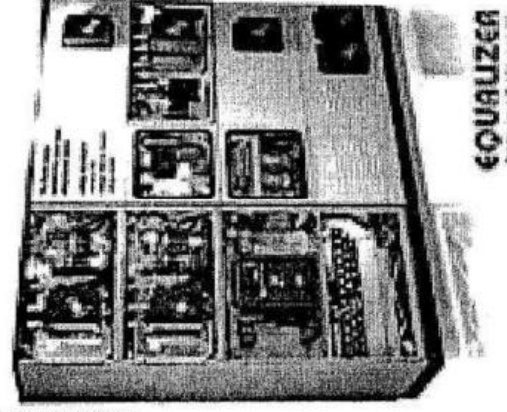












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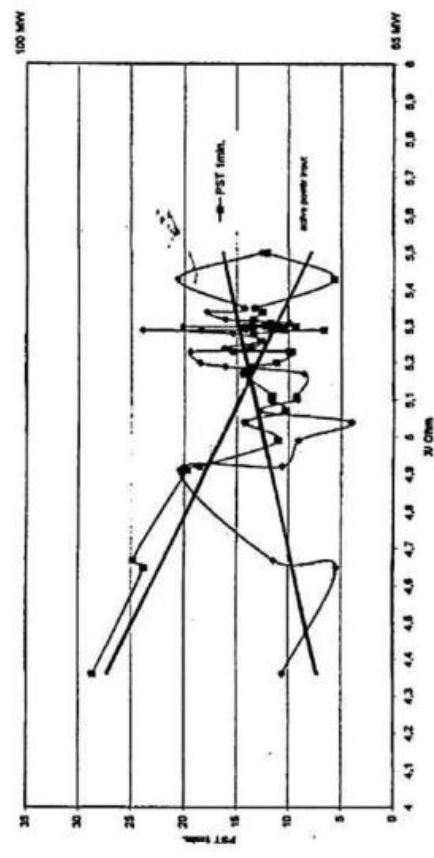
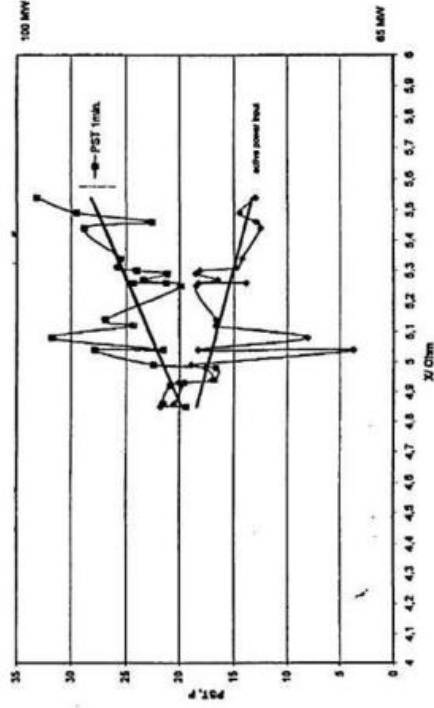
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Additional to fig. 11 high impedance furnace

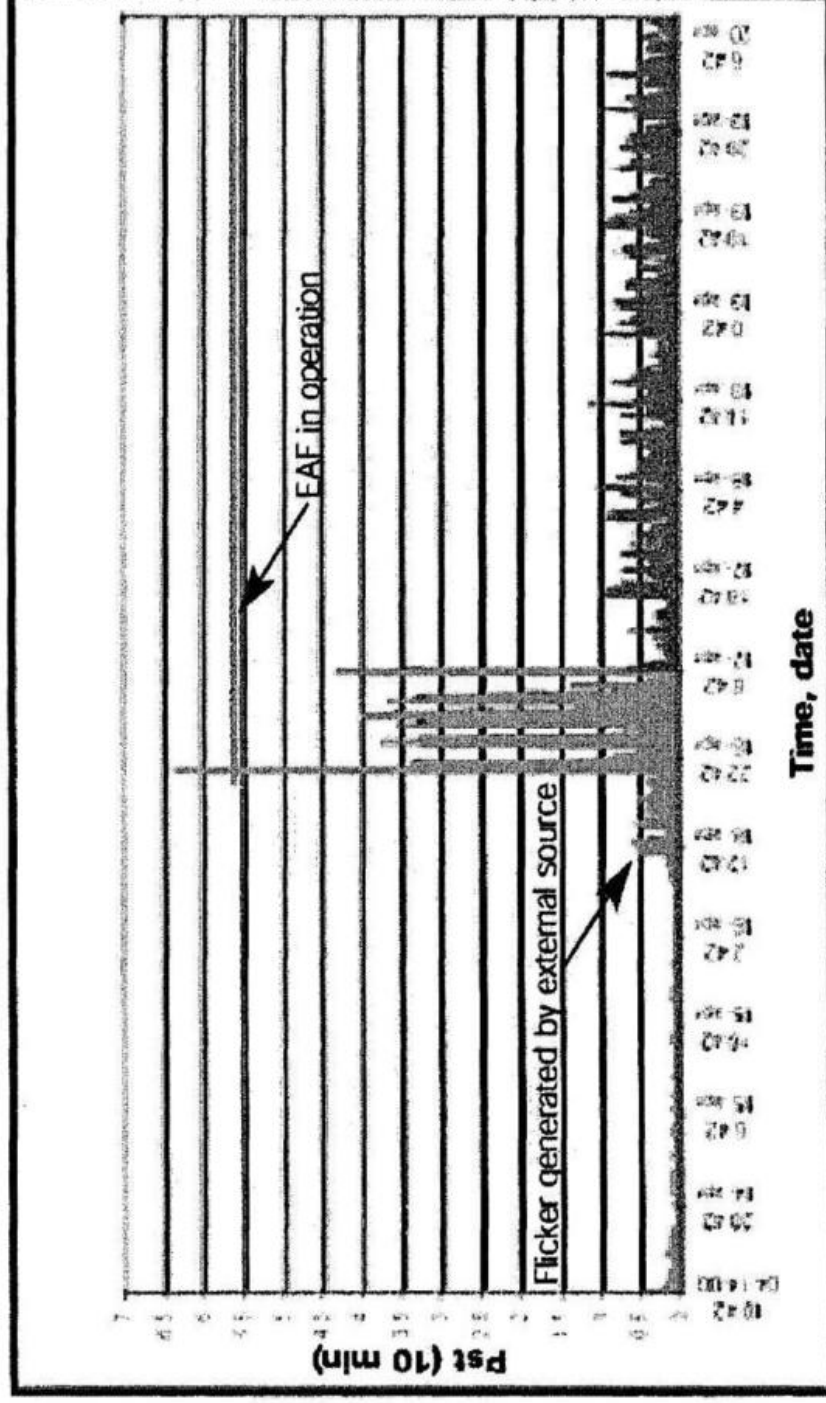
left: 1 min Pst-values and active power input in a **low-impedance** furnace as function of the operational reactance

right: 1 min Pst-values and active power input in a **high-impedance** furnace as function of the operational reactance



Additional figure regarding harmonics

Harmonic spectrum of the primary currents of an AC furnace



Flicker generation without and with SVC Light.

➡ Improvement SVC

Steel Academy

International Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Model-Based Control of AC Electric Arc Furnaces

Priv.-Doz. Dr.-Ing. Siegfried Kohle, formerly
BFI Betriebsforschungsinstitut, Düsseldorf

Model-based control of AC electric arc furnaces

1. AC arc furnace as an electrical system
2. Non-linear equivalent circuit diagram
3. **Linear equivalent circuit diagram**
 - 3.1 Origin of arc reactance
 - 3.2 Arc hysteresis and reactive power
 - 3.3 Reactance increase from fluctuation
 - 3.4 Single-phase equivalent circuit diagram
 - 3.5 Dependence of arc reactance
4. **Arc control for thermal wall load protection**
 - 4.1 Linearised model for electrical variables
 - 4.2 Control by asymmetrical impedance setpoints
 - 4.3 Control by asymmetrical transformer voltages
 - 4.4 Operator display of wall protection control system
 - 4.5 Statistical results of thermal wall load
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 - 5.1 Transfer of arc fluctuation to current fluctuation
 - 5.2 Selection of furnace operating points
 - 5.3 Voltage-reactance chart
 - 5.4 Current-power diagram
 - 5.5 Furnace operating diagram
6. Summary
7. References

1. AC arc furnace as an electrical system

SINGLE-PHASE SYSTEM

Resistance R

Voltage $U = R \cdot I$ power $P = R \cdot I^2 = U \cdot I$

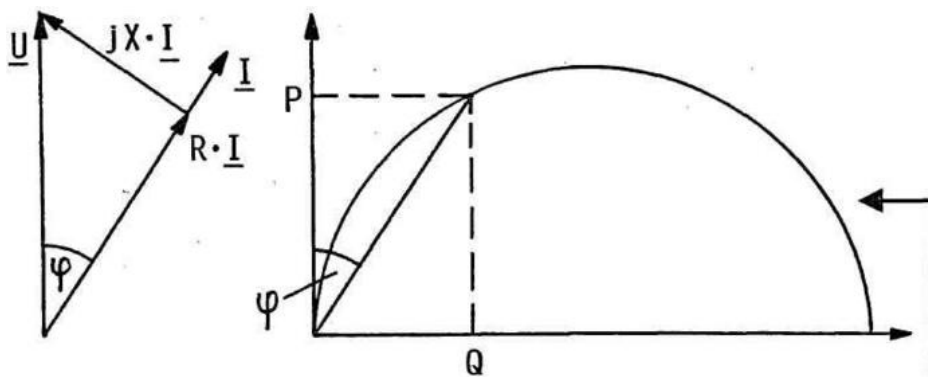
Impedance $\underline{Z} = R + jX$ with reactance X

$$\underline{U} = (R + jX) \cdot \underline{I} \quad P = R \cdot I^2 = U \cdot I \cdot \cos\varphi$$

reactive power $Q = \sqrt{(U \cdot I)^2 - P^2} = X \cdot I^2 = U \cdot I \cdot \sin\varphi$

phasor diagram

circle diagram



THREE-PHASE SYSTEM

single-phase ECD

Impedances $\underline{Z}_n = R_n + jX_n$

AC calculation, phasor diagram

Electric Arc Furnace

fluctuating arc voltages

non-linear arc characteristic

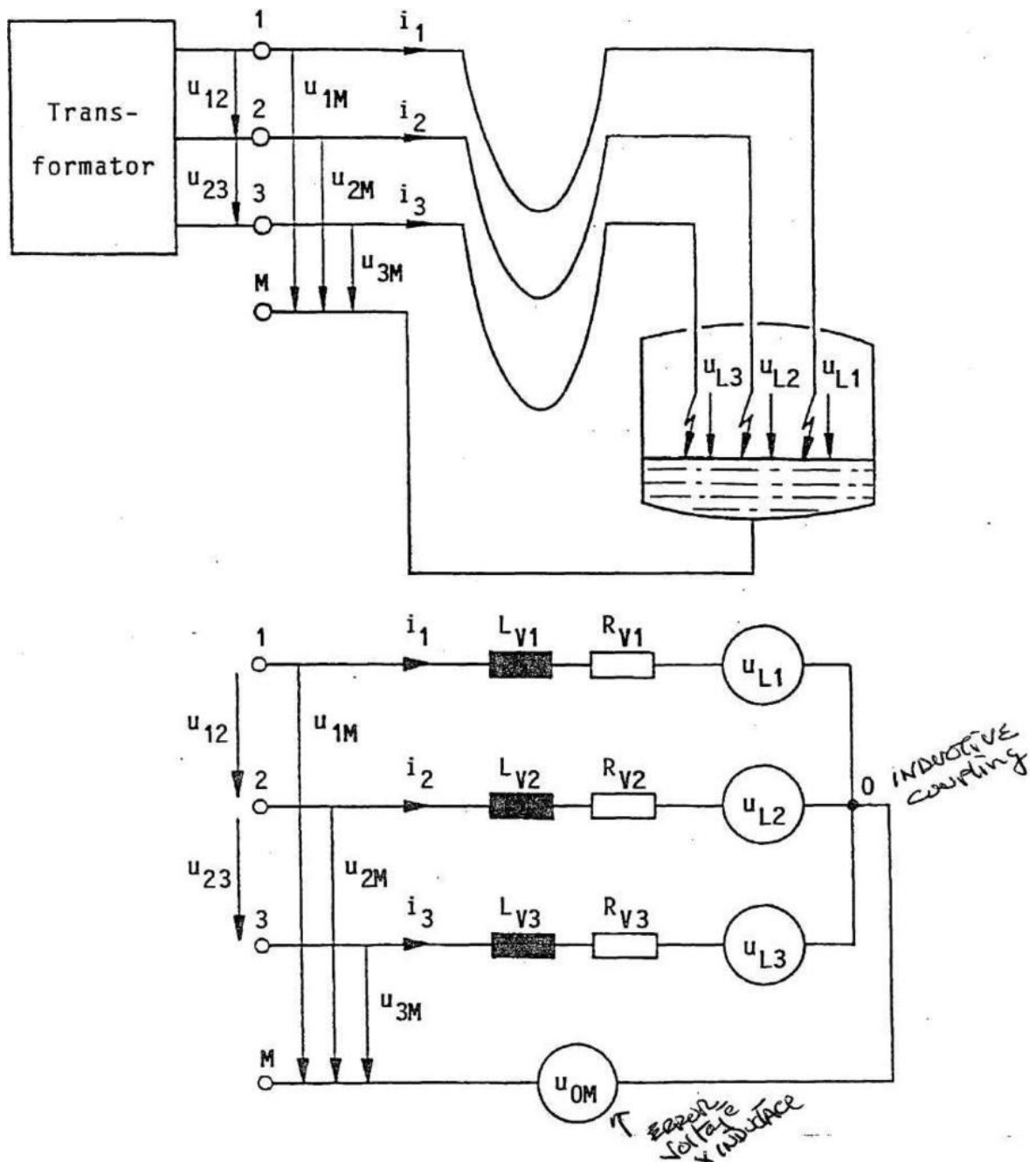
mutual inductive coupling

arc reactance model

linear ECD (3-phase)

non-linear equivalent circuit diagram (ECD)

2. Non-linear equivalent circuit diagram [1]

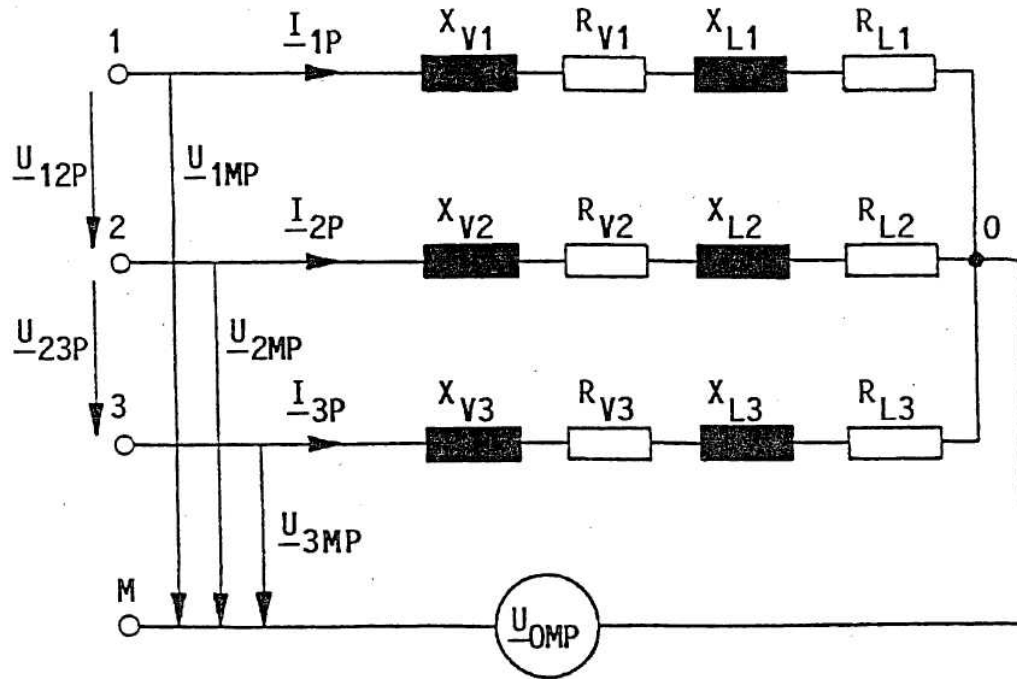


The furnace is an electrical system in star-connection with arc voltages u_{Ln} line resistances R_{Vn} and inductances L_{Vn}

Mutual inductive coupling gives the "error voltage" u_{0M}

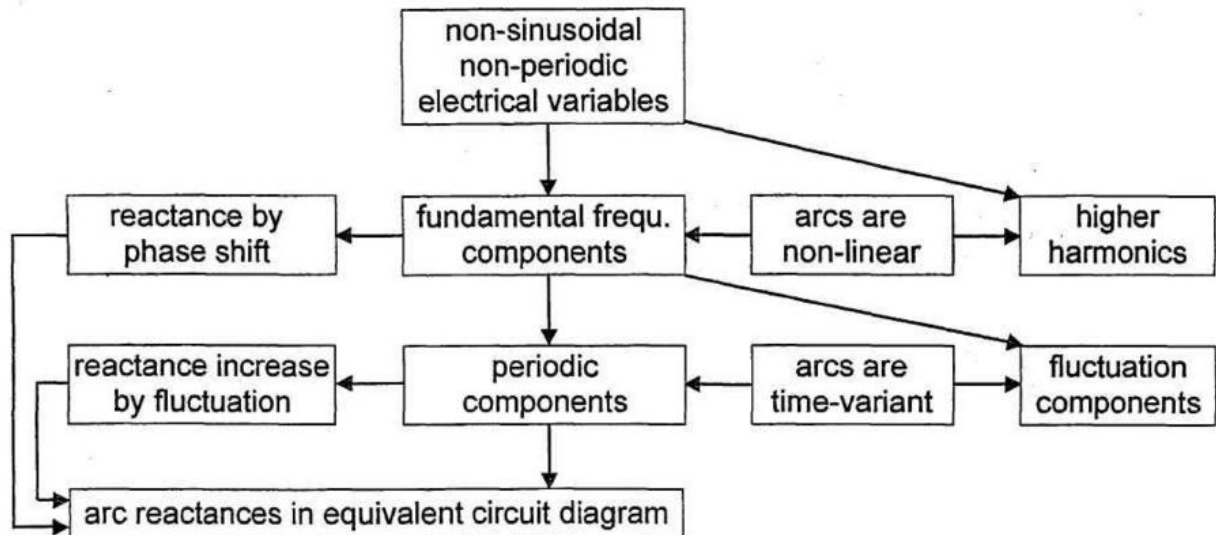
Line resistances and inductances can be measured in 3 short-circuit tests (2 electrodes dipped into the bath)

3. Linear equivalent circuit diagram [2]



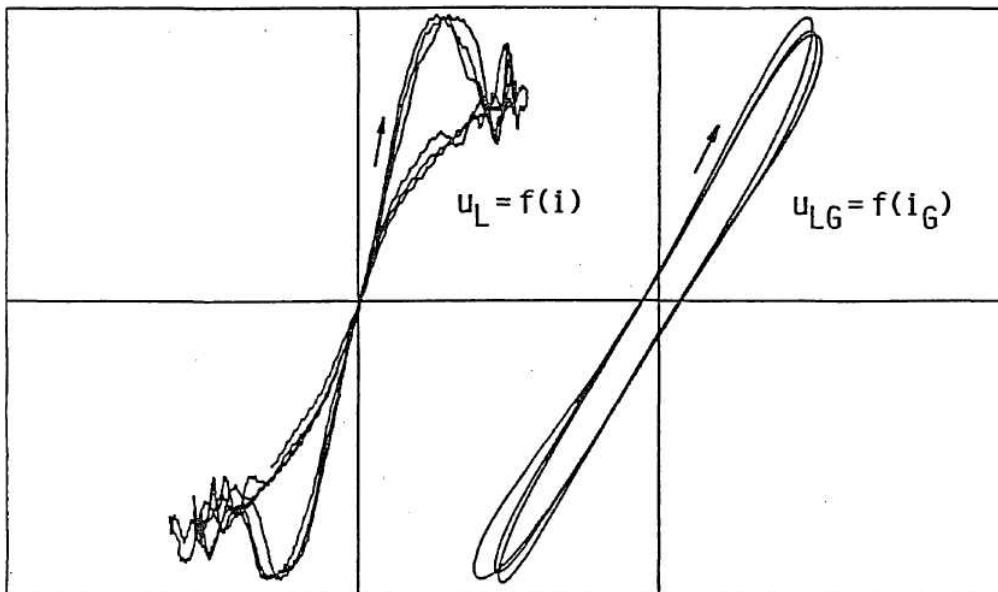
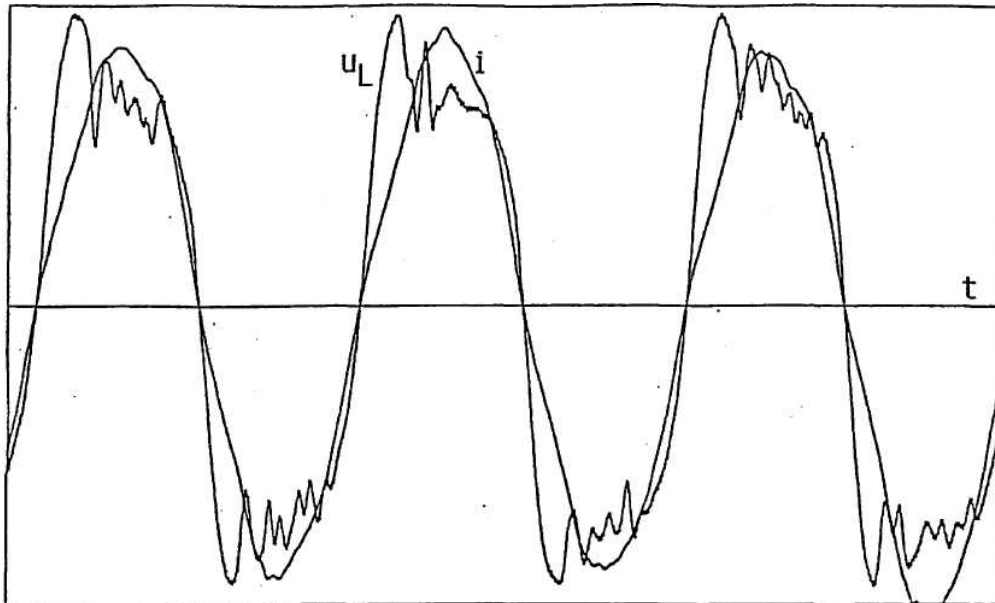
- Linear equivalent circuit diagram (ECD) should model rooted mean squares of electrical variables per phase
- Time-invariant, linear elements at sinusoidal voltages:
→ only periodic, fundamental frequency components of original variables can be represented by the ECD
- Neglecting fluctuation and higher harmonics results in acceptably low errors (mainly for the currents)
- Arc reactances (increased operating reactances) from:
 - harmonics ? very low
 - phase shift [3] ? highest
 - fluctuations [4] ? medium

3.1 Origin of arc reactance



- The linear equivalent circuit diagram is restricted to periodic, fundamental frequency components
- Arc reactances result from
 - phase shift in fundamental frequency components of arc voltage vs. current because of non-linearity
 - increase of reactance (line reactance and first part of arc reactance) by fluctuation of electrical variables

3.2 Arc hysteresis and reactive power [5]



$$\frac{1}{2\pi} \cdot \oint u_L \cdot di + \sum_h h^2 \cdot X_0 \cdot I_h^2 = \frac{1}{2\pi} \cdot \oint u_{LG} \cdot di_G = Q_{LG} = X_L \cdot I_G^2$$

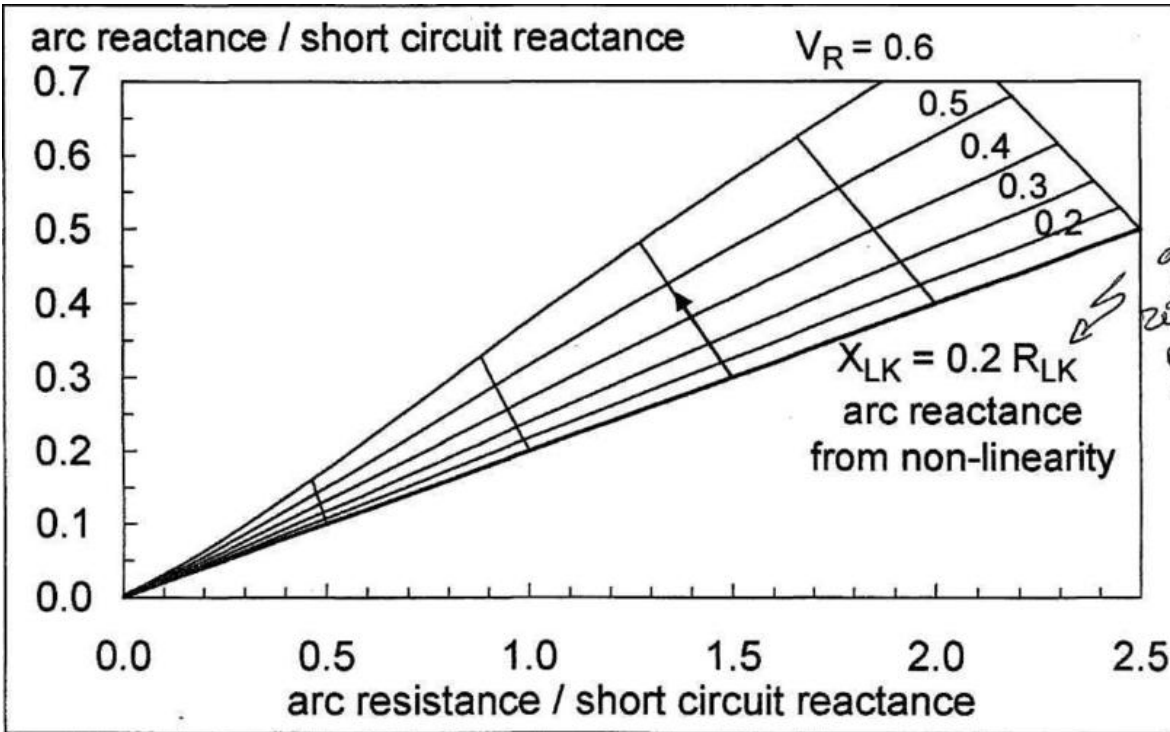
area of hysteresis
($\approx 90\%$ of X_L)

react, power
of current
harmonics at X_0

react, power
of fundamental
frequency comp.

arc reactance

3.3 Reactance increase from fluctuation



Fluctuation of resistances around mean values:

$$\overline{R_1} = \overline{R_2} = \overline{R_3} = R_K \quad \text{short circuit resistance } R_0 \text{ plus } R_{LK}$$

$$\text{corr}(R_n; R_m) = 0; \quad \delta(R_n) = \delta(R) \quad V_R = \delta(R)/R_K$$

$$X_1 = X_2 = X_3 = X_K \quad \text{short circuit reactance } X_0 \text{ plus } X_{LK}$$

$$X_{LK} = 0.2 \cdot R_{LK} \quad \text{arc reactance from non-linearity (assumed to be constant)}$$

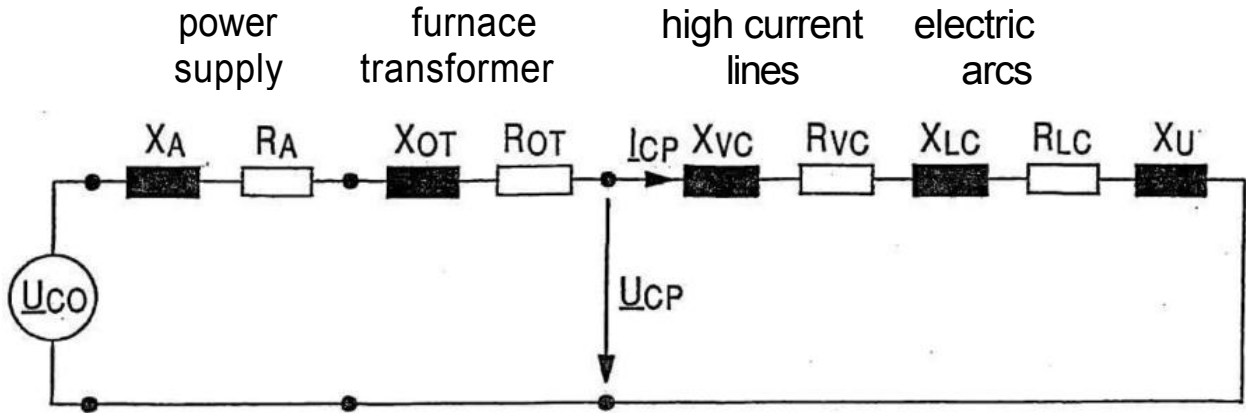
Periodic parts of fluctuating currents and voltages give:

$$R = R_K \cdot (1 - T) \text{ decreased} \quad X = X_K \cdot (1 + T) \text{ increased}$$

$$T = 2/3 \cdot \cos^2 \phi_K \cdot v_R^2 \quad \cos \phi_K = f(R_K; X_K)$$

More realistic calculation [6] with correlated fluctuation of arc resistances and arc reactances gives similar results

3.4 Single-phase equivalent circuit diagram



Values of the 3-phase linear equivalent circuit diagram summarised to collective values [7]:

$$U_{CP}^2 = 1/3 \cdot (U_{12P}^2 + U_{23P}^2 + U_{31P}^2)$$

$$I_{CP}^2 = (I_{1P}^2 + I_{2P}^2 + I_{3P}^2)$$

$$P = P_1 + P_2 + P_3 = I_{CP}^2 \cdot (R_{VC} + R_{LC})$$

$$Q_P = Q_{1P} + Q_{2P} + Q_{3P} = I_{CP}^2 \cdot (X_{VC} + X_{LC})$$

Total active power P and sum of reactive power Qp are measured on EAF transformer primary or secondary side

Calculated collective reactive power: from unbalance

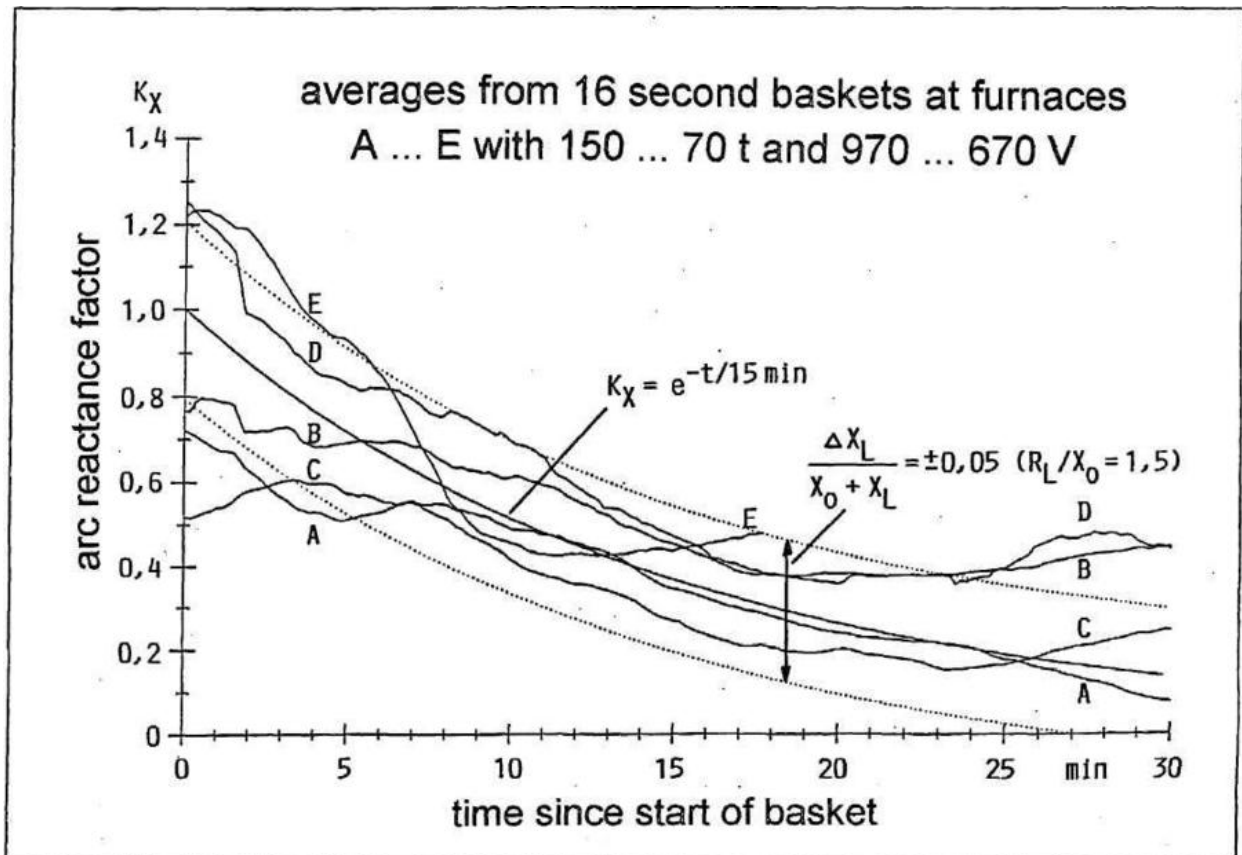
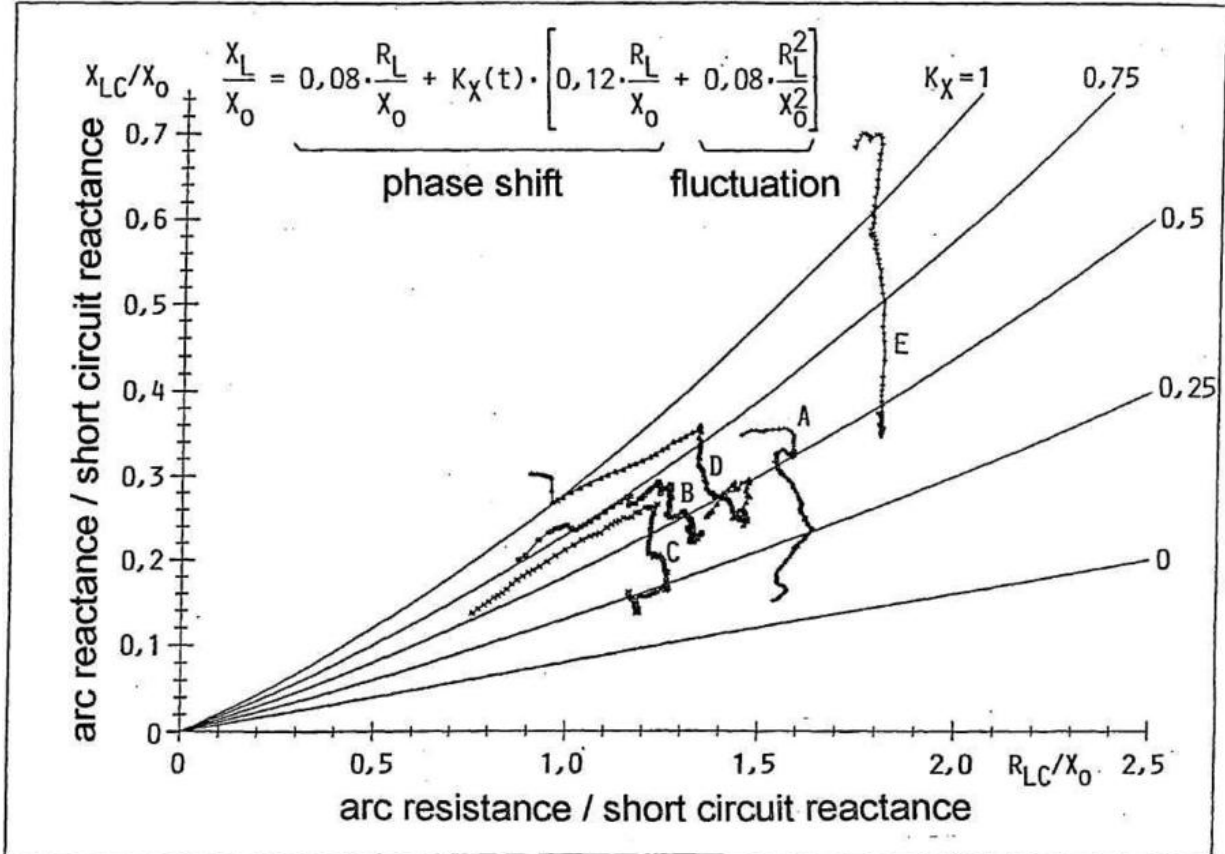
$$Q_{CP} = \sqrt{U_{CP}^2 \cdot I_{CP}^2 - P^2} = I_{CP}^2 \cdot (X_{VC} + X_{LC} + X_U)$$

Unbalance reactance is low under normal operation

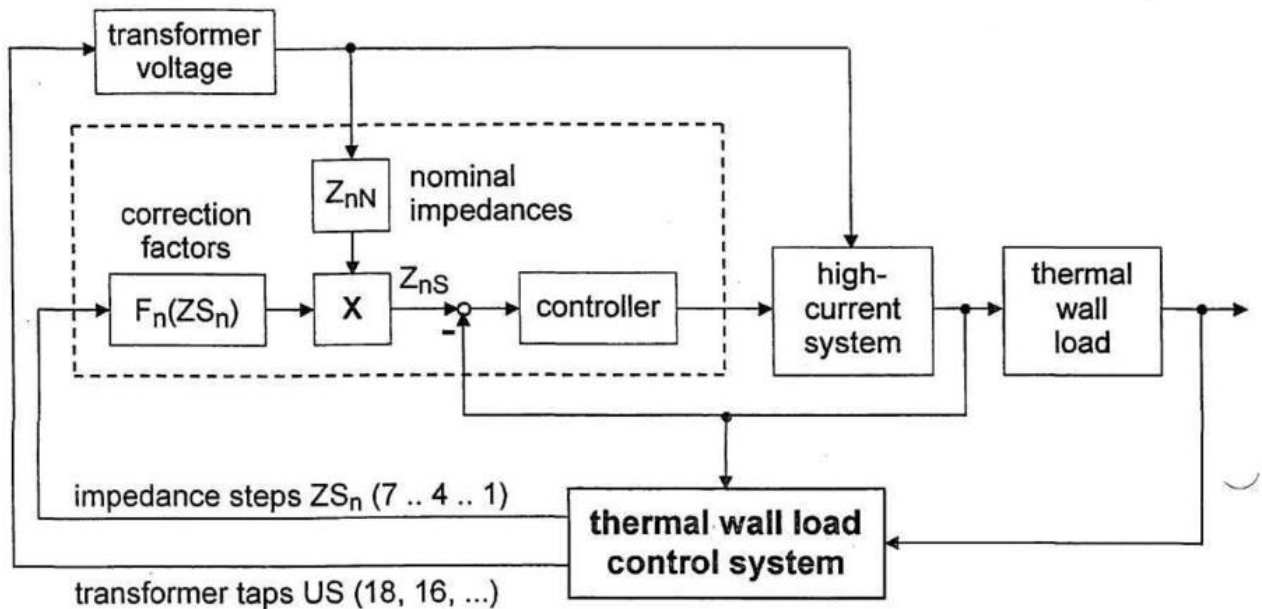
Power factors depend on applied reactive power:

- sum of reactive power Qp
- collective reactive power Qcp
- without / with harmonic and fluctuation components

3.5 Dependence of arc reactance [5]



4. Arc control for thermal wall load protection [8]



Criteria of control:

1. control of arcs to prevent high thermal wall load
2. supervisory current control for high power input

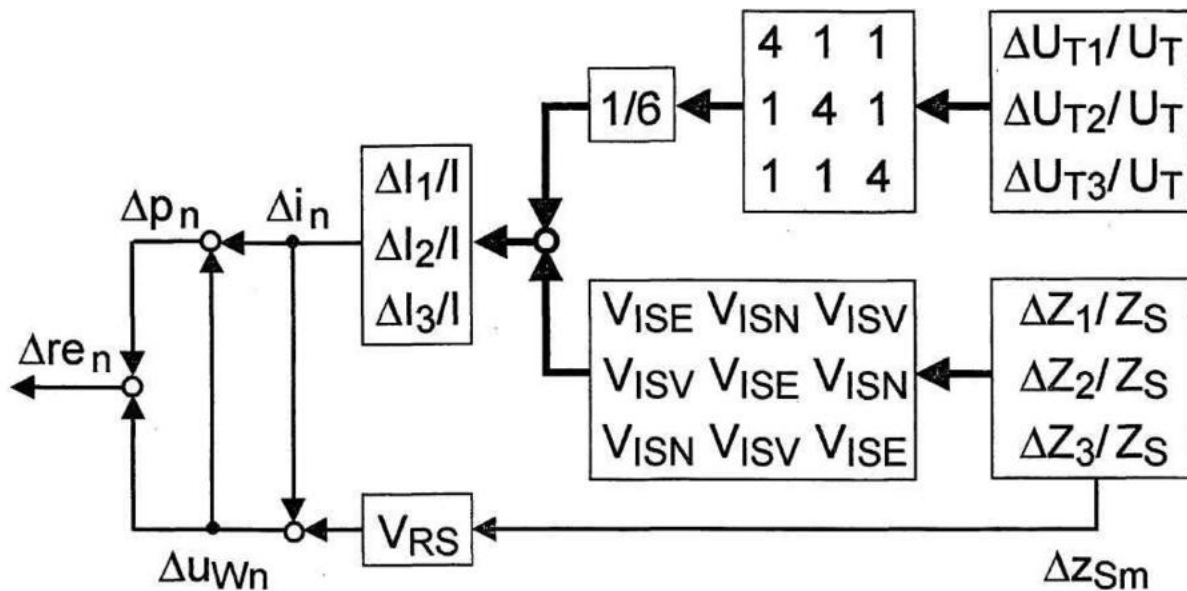
Available for control:

- impedance steps with correction factors (+/- 20%) for nominal impedance setpoint values per phase
- voltage taps of the furnace transformer (per phase if applicable)

Problems with asymmetrical control:

- coupling between electrical variables in three phases

4.1 Linearised model for electrical variables [2]



Linearisation for mean values (symmetrical operating points) describes effects of relative changes in input variables

- transformer voltages Δu_{Tm}
- furnace impedances Δz_{Sm}

on relative changes in output variables

- currents Δi_n
- active voltages $\Delta u_{Wn} \approx$ arc voltages Δu_{Ln}
- active powers Δp_n
- arc radiations Δre_n (power x voltage)

The matrix for the transformer voltages is simple

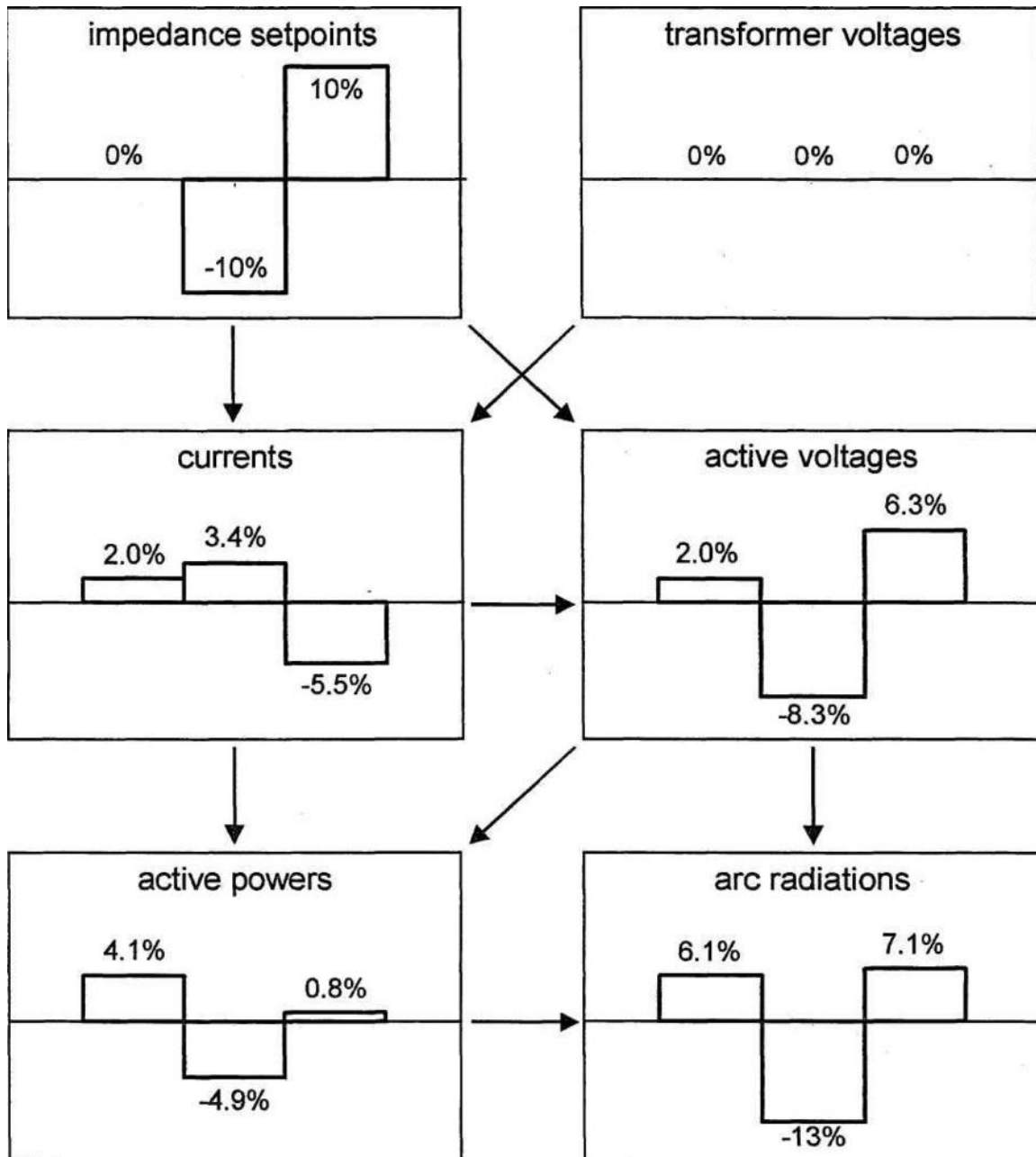
The matrix elements for the impedances depend on the operating point; typical gain for changes in the preceding... same... following phase:

$$V_{ISV} \approx 0 \quad V_{ISE} \approx -0.6 \quad V_{ISN} \approx -0.3$$

The linearised model has also been inverted to calculate relative changes of input variables necessary for control

4.2 Control by asymmetrical impedance setpoints

Change of impedances for lower arc radiation in phase 2



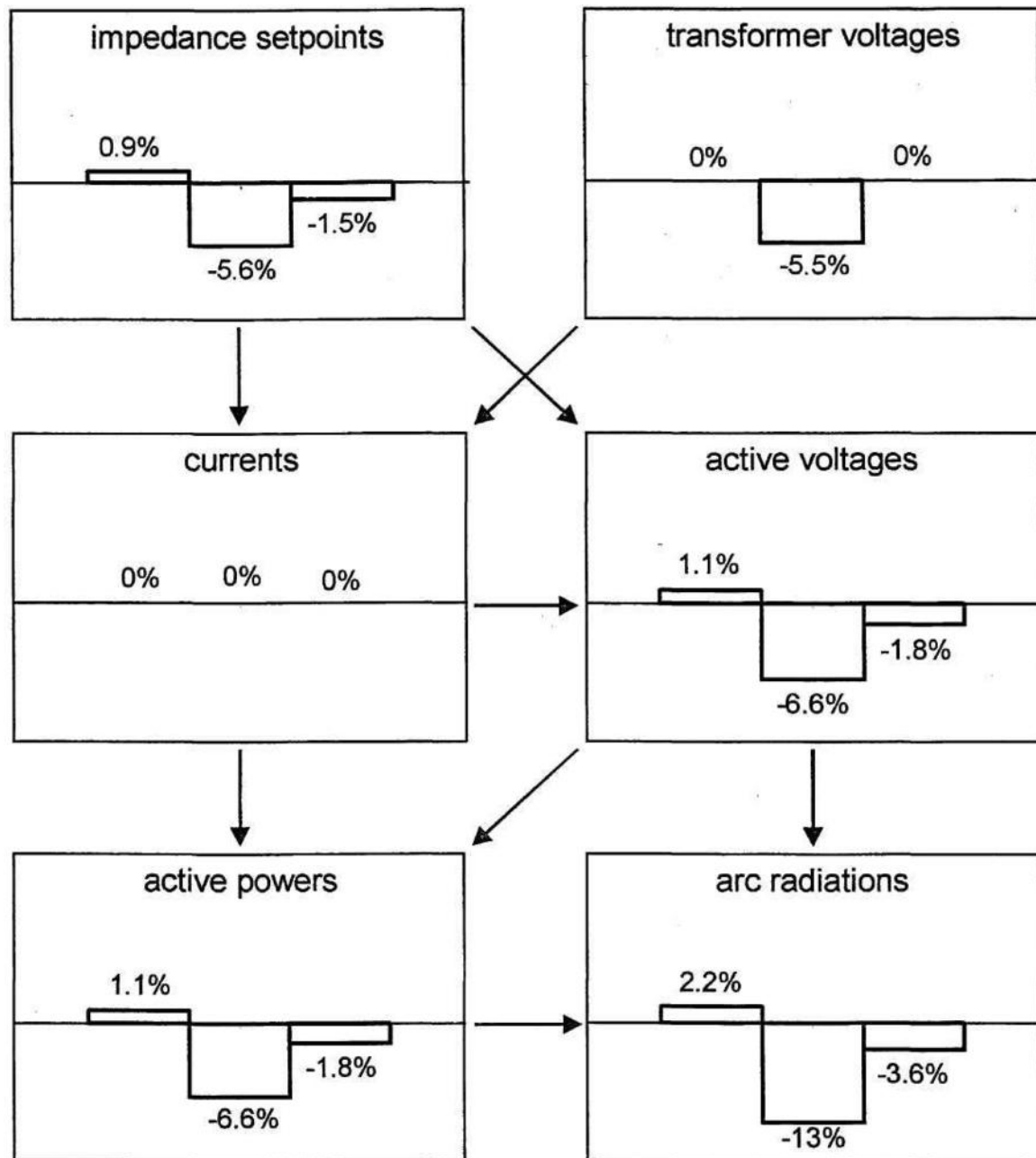
Operating point: 960 V, 63 kA, 82 MW, phase sequence 1 - 2 - 3

Arc radiation is distributed to protect the wall near phase 2

→ Total active power not reduced by this control action

4.3 Control by asymmetrical transformer voltages

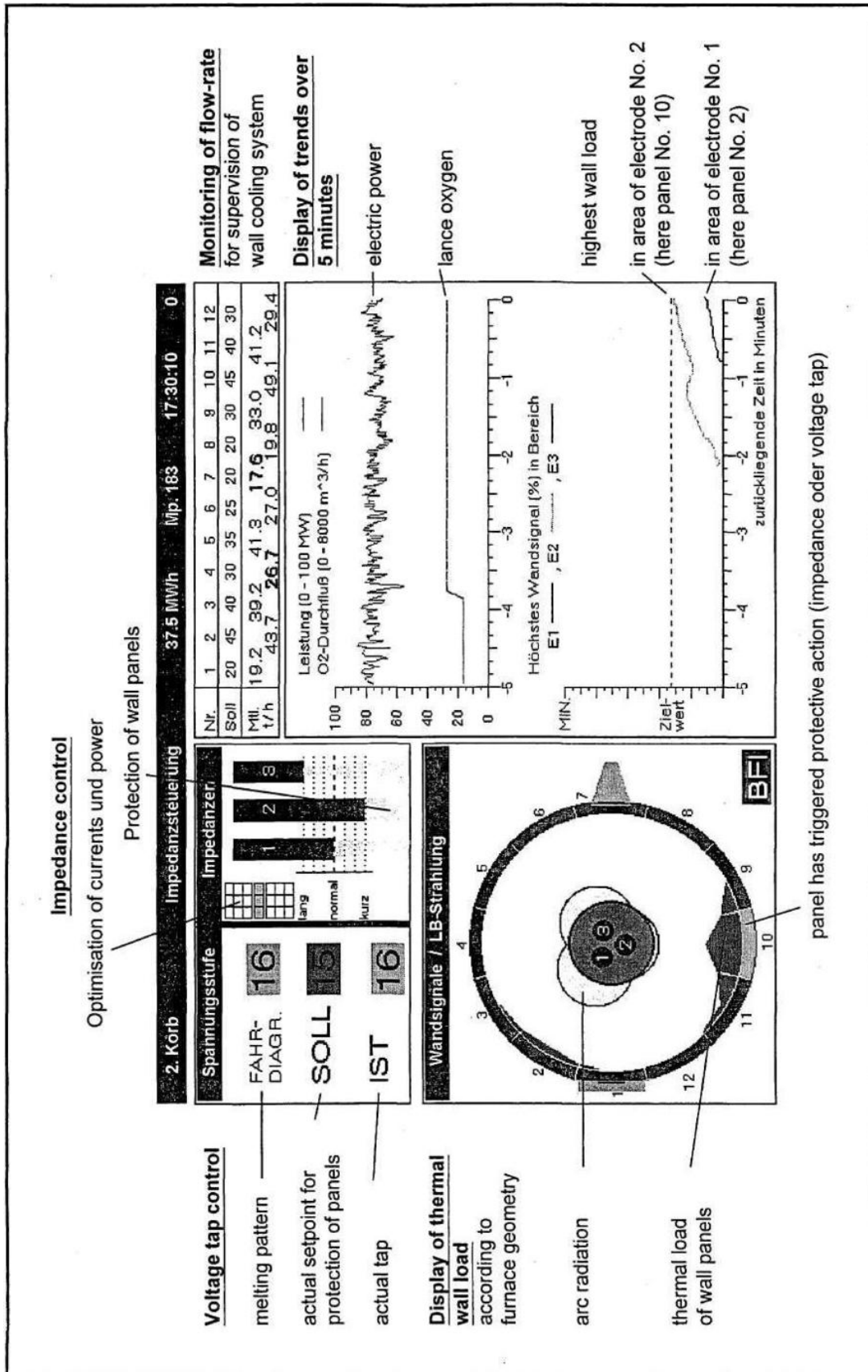
Change of voltages for lower arc radiation in phase 2
(impedances adapted by current controllers)



→ Total power reduced by 2.4% for same wall protection

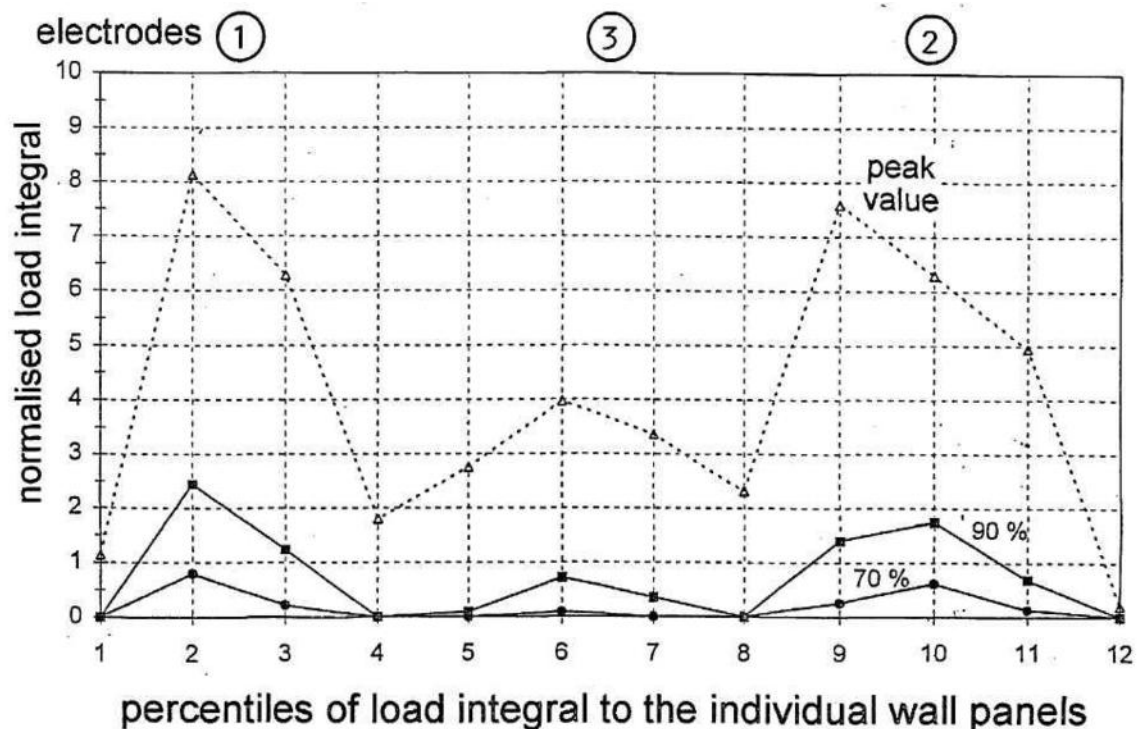
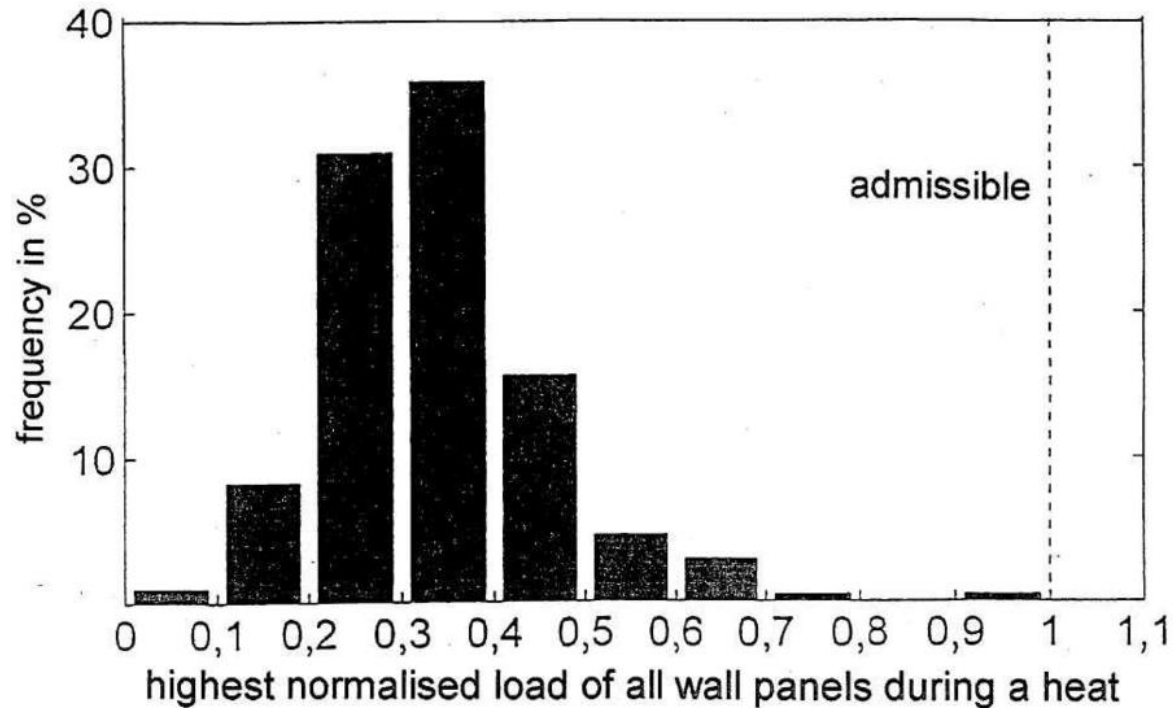
If transformer voltages can only be lowered symmetrically,
power is reduced by 6.6%

4.4 Operator display of wall protection control system

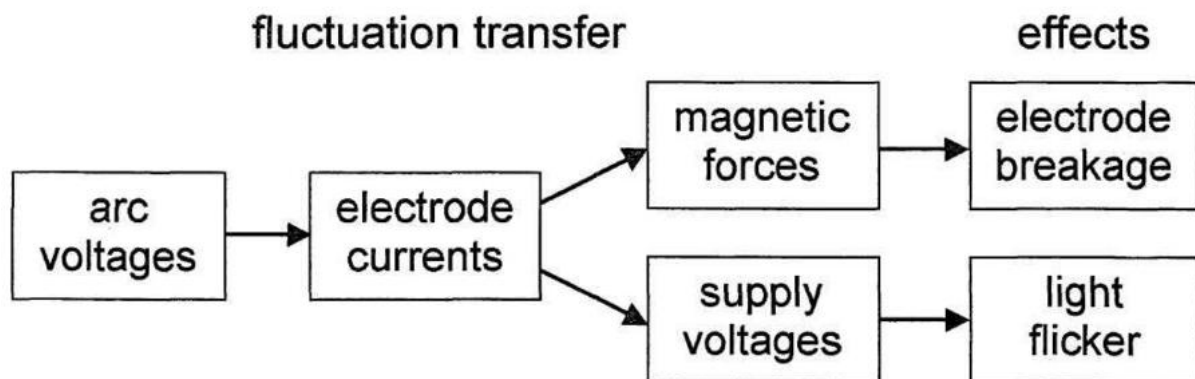
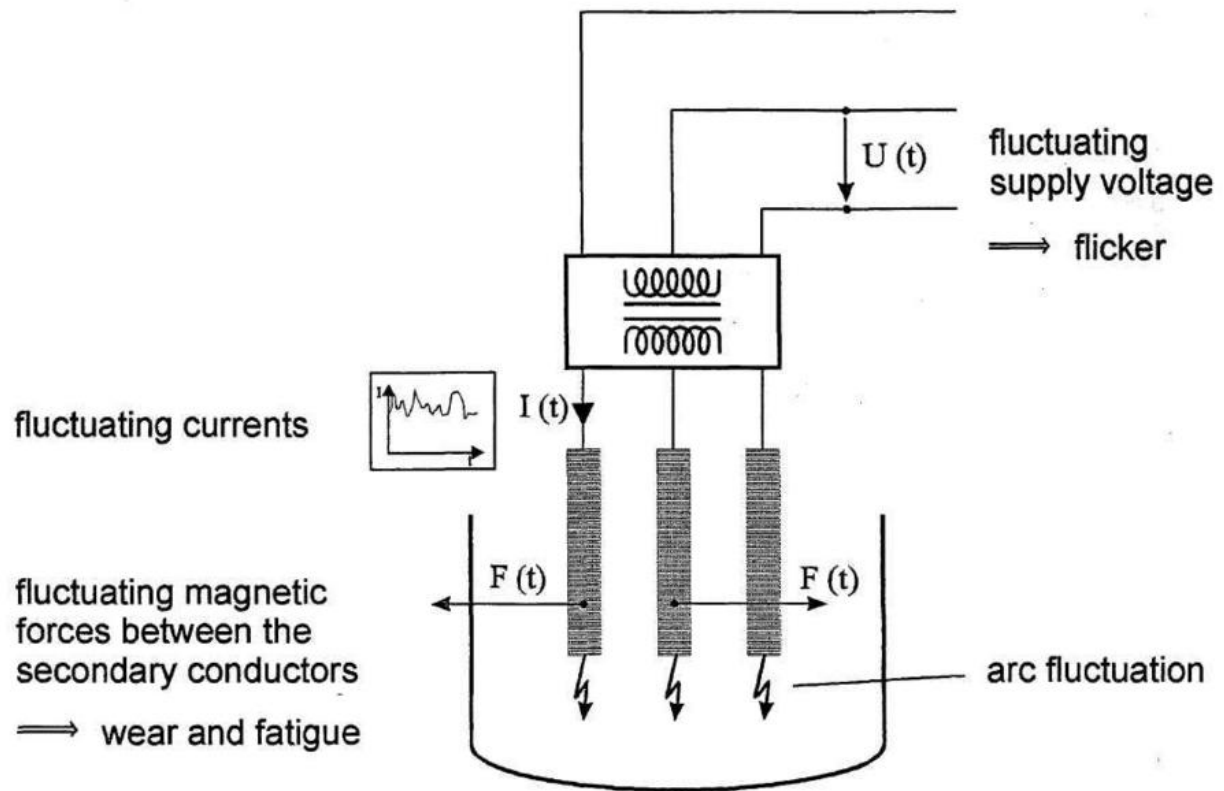


4.5 Statistical results of thermal wall load

Control system applied at an EAF with evaporation cooling
Water boils at high thermal load and lowers the in-flow rate



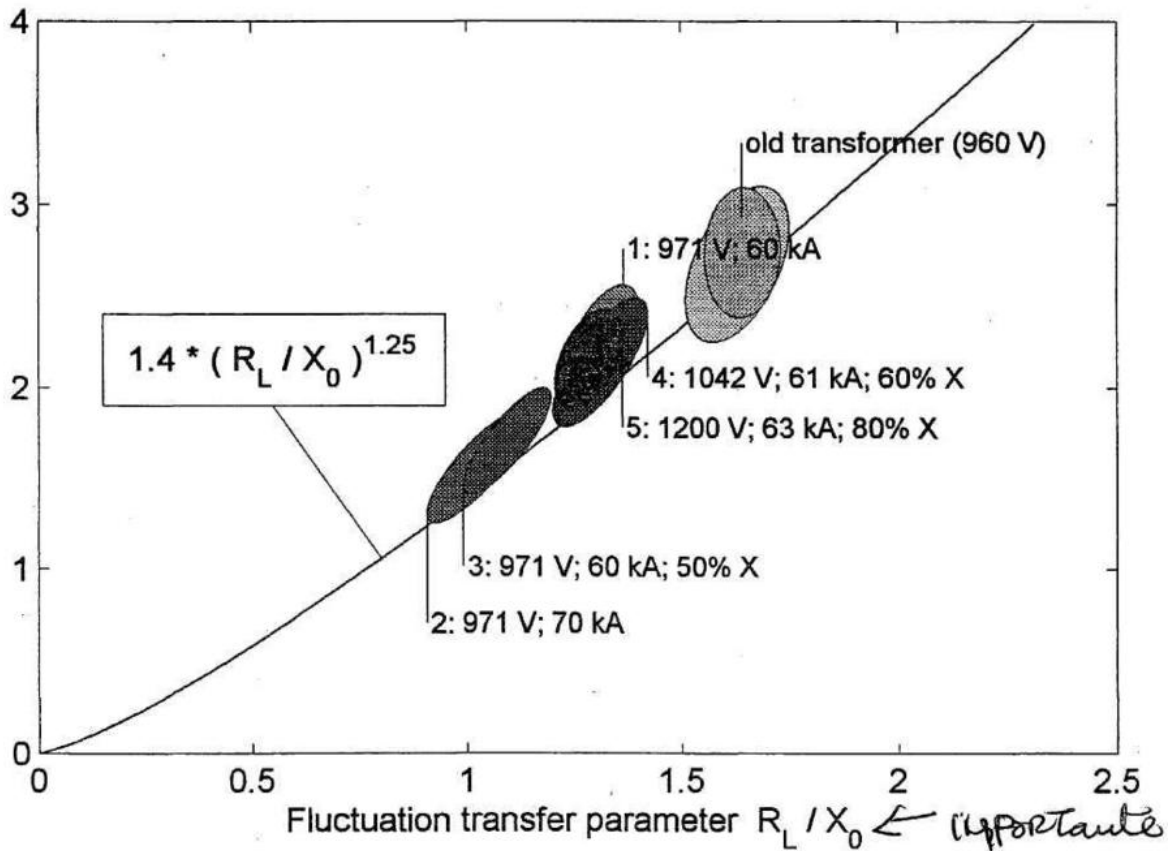
5. Control for electrical stability at high voltage [9]



→ Electrical instability has often been a severe problem especially at furnaces with higher transformer voltage

5.1 Transfer of arc fluctuation to current fluctuation [10,11]

Current fluctuation gain V_{I2} / V_{ULW}



Short time (20 ms) mean squares

$$I_{nK}^2 = \overline{i_n^2(t)}$$

Long time (e.g. 1 s) mean squares

$$I_n^2 = \overline{I_{nK}^2}$$

standard deviations

$$\sigma(I_{nK}^2)$$

relative fluctuation

$$V_{I2n} = \sigma(I_{nK}^2) / I_n^2$$

average over phases

$$V_{I2} = \overline{V_{I2n}}$$

Corresponding value for arc voltages

$$V_{ULW}$$

For currents and forces $V_{I2} \approx 1.4 \cdot (R_L / X_0)^{1.25} \cdot V_{ULW}$

→ Fluctuation transfer parameter $R_L / X_0 \leq 1.5!$ for stability

5.2 Selection of furnace operating points

At high voltage additional reactor required to adapt R_L/X_0

Thus three parameters to select for an operating point

- secondary no-load voltage by transformer tap **U**
- short circuit reactance by reactor tap **X**
- current by electrode controller setpoint **I**

The aim is to find a compromise between:

- electrical stability ($R_L/X_0 \leq 1.5$)
- high active power for short power-on time
- low arc radiation and thermal load to the panels
- low current for low electrode graphite consumption

Basic equations for electrical variables

Arc resistance $R_L = \frac{P_L}{3 \cdot I^2}$

P_L arc power I electrode current

Arc reactance $X_L = 0.08 \cdot R_L + K_X \cdot \left[0.12 \cdot R_L + 0.08 \cdot \frac{R_L^2}{X_0} \right]$

X_0 short circuit reactance

K_X arc reactance factor ($\approx 1.0 \rightarrow 0.2$ versus time)

Transf. voltage $U_{S0} = \sqrt{3} \cdot I \cdot \sqrt{(R_L + R_0)^2 + (X_L + X_0)^2}$

R_0 short circuit resistance

5.3 Voltage-reactance chart

AC EAF with 135 MVA /1200 V transformer and 20 MVA reactor

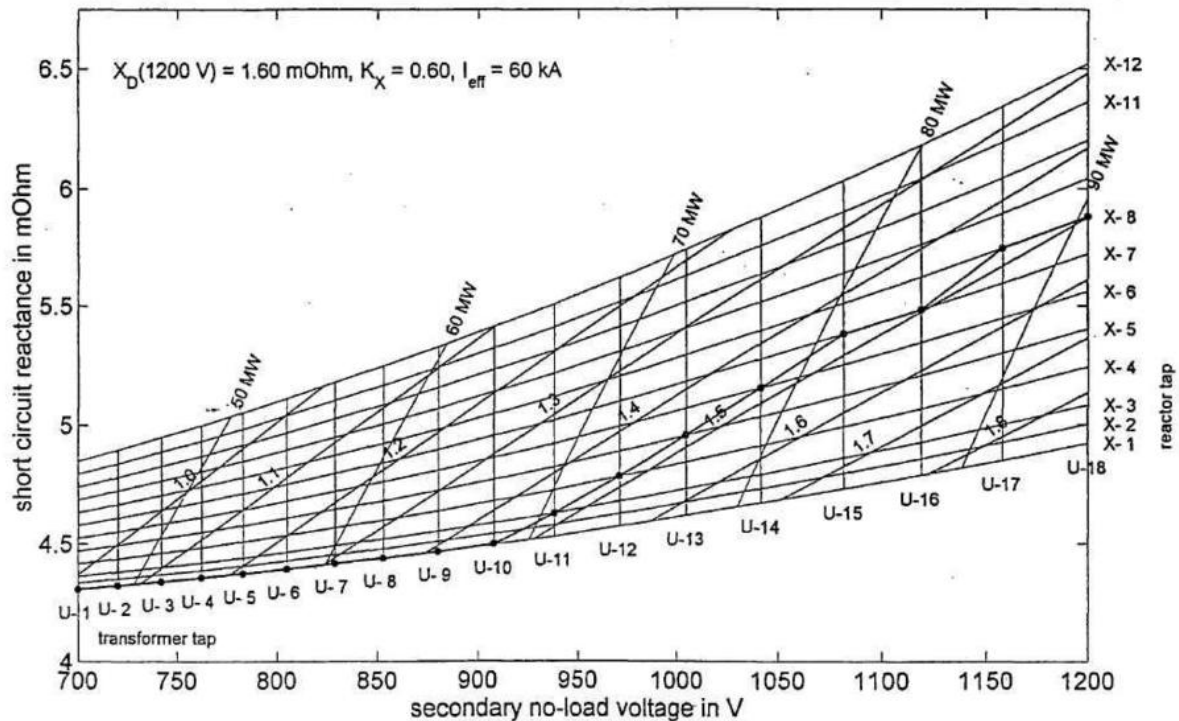


Chart at 60 kA with $R_L/X_0 = 1.0 \dots 1.8$ and $P = 50 \dots 90\text{ MW}$

→ reactor taps **X** for transformer taps **U** selected for
 $R_L / X_0 \leq 1.5$ with respect to electrical stability

Electrical furnace data:

$S_{\text{max}} = 135\text{ MVA}$ transformer apparent power

$U_{\text{So}} = 1200\text{ V}$ highest transformer voltage (18 taps)

$I_{\text{max}} = 83\text{ kA}$ highest current (below transformer tap 11)

$X_0 = 4.92\text{ m}\Omega$ short circuit reactance at 1200 V without reactor

$X_D = 1.60\text{ m}\Omega$ reactance of the reactor at 1200 V (12 taps)

$R_0 = 0.42\text{ m}\Omega$ short circuit resistance at 1200 V

$K_X = 0.60$ reactance factor during main melting

5-4 Current-power diagram

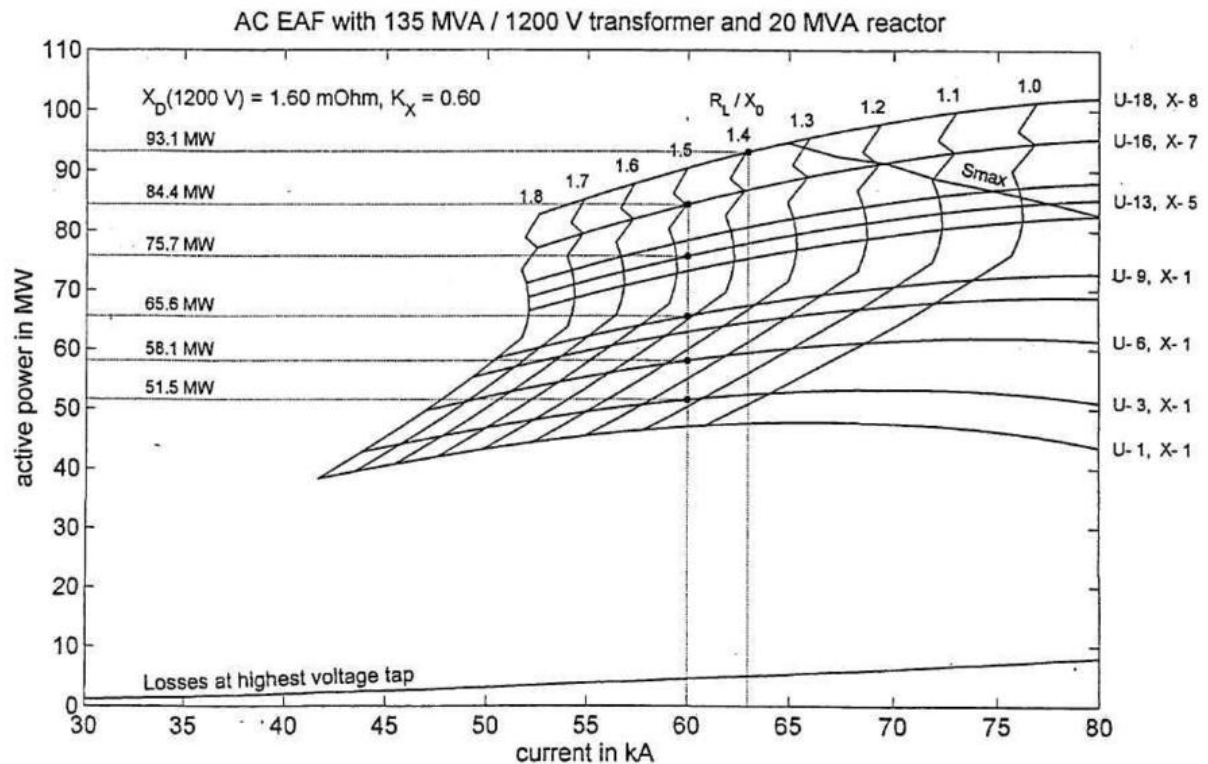
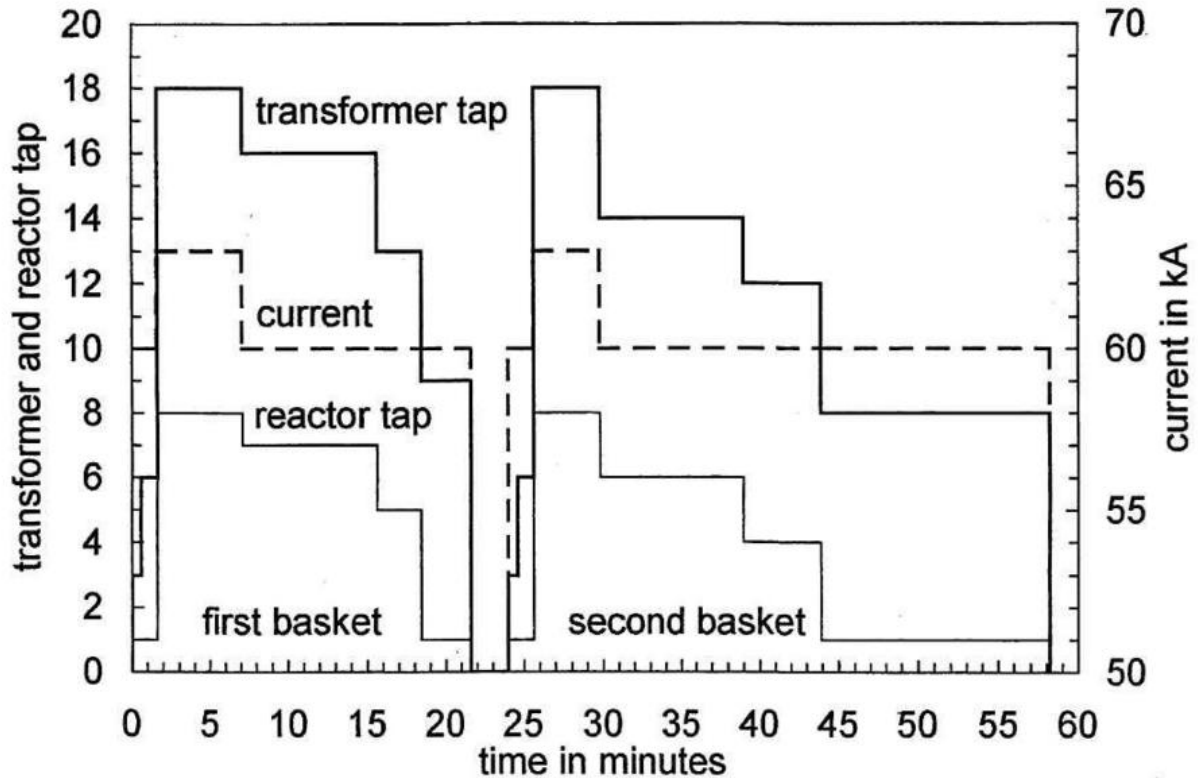


Diagram for selected transformer / reactor tap combinations

→ currents **I** for **U-X** combinations selected with respect to active power (also arc radiation, electrode consumption)

5.5 Furnace operating diagram

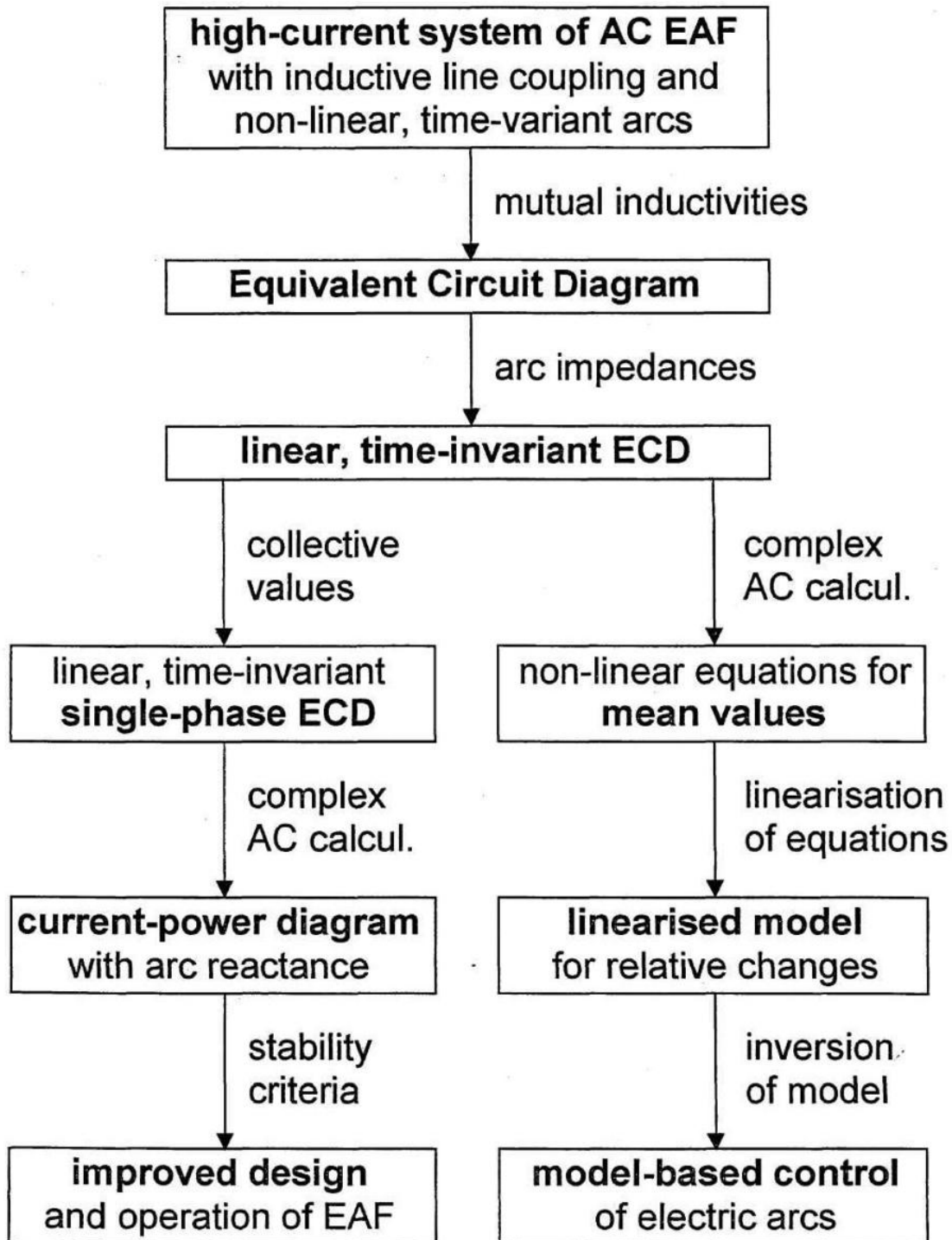


→ **U-X-I** combinations assigned to subsequent steps of the baskets according to the progress of melting

Results at the investigated furnace

- stable operation also at 1200 V and low currents of 60 kA if short circuit reactance sufficiently high
- more stable operation reduced electrode breakages
- this and lower currents reduced electrode consumption
- improved operating practice reduced wall defects

6. Summary of model development and application



7. References (and their highlights with respect to this lecture)

- [1] Bretthauer, K.; Timm, K.: Ober die Messung elektrischer Größen auf der Hochstromseite von Drehstromofen (About measurement of electrical variables at the high-current side of three-phase furnaces).
Elektrowarme international 29 (1971), p. 381-387
• *Non-linear equivalent circuit diagram (page 3)*
- [2] Kohle, S.: Ersatzschaltbilder und Modelle für die elektrischen Größen von Drehstrom-Lichtbogenofen (Equivalent circuit diagrams and models for the electrical variables of three-phase electric arc furnaces)
Verlag Stahleisen, Düsseldorf 1990
• *Compilation and extension of papers [2a - c]*
- [2a] Kohle, S.: Lineares Ersatzschaltbild des Hochstromsystems von Drehstrom-Lichtbogenofen (Linear equivalent circuit diagram of three-phase electric arc furnaces). Elektrowarme international 43 (1985) No. B1, p. B16-B25
• *Linear equivalent circuit diagram (page 4, 5) with arc reactance from phase shift between fundamental frequency components of arc voltage and current (page 6) and reactance increase from fluctuation of electrical variables (page 7)*
- [2b] Kohle, S.: Einphasiges Ersatzschaltbild und Leistungsdiagramme für Drehstrom-Lichtbogenofen (Single-phase equivalent circuit diagram and power diagrams of three-phase electric arc furnaces).
Elektrowarme international 46 (1988) No. B6, p. B318-B324
• *Single-phase equivalent circuit diagram (page 8) and power factor definitions for three-phase systems with distorted and fluctuating electrical variables*
- [2c] Kohle, S.: Linearisierte Modelle für die Kopplung der elektrischen Größen von Drehstrom-Lichtbogenofen (Linearised models of coupling between electrical variables in three-phase electric arc furnaces).
Elektrowarme international 46 (1988) No. B5, p. B264-B273
• *Linearised model (page 11 -13) for dependencies of output variables on input variables and inversion of these relations*
- [3] Kasper, R.; Jahn, H.-H.: Ein verfeinertes elektrisches Ersatzschaltbild des Drehstrom-Lichtbogenofens (A refined electrical equivalent circuit diagram of the three-phase electric arc furnace).
Elektrowarme international 36 (1978), p. B26-B29
• *Early description of phase shift between fundamental frequency components as a reason for increased operating reactance of arc furnaces*
- [4] Bowman, B.: Electrical characteristics of arc furnaces allowing for current swings.
8th UIE Congress, Liege 1976, Report Ia10
• *Early description of electrical fluctuation as a reason for increased operating reactance of arc furnaces*
- [5] Kohle, S.; Knoop, M.; Lichterbeck, R.: Lichtbogenreaktanzen von Drehstrom-Lichtbogenofen (Arc reactances in three-phase electric arc furnaces)
Elektrowarme international 51 (1993) No. B4, p. B175-B185
• *More detailed investigation of arc reactance from non-linear arc behaviour with hysteresis (page 6) and dependence of arc reactance on arc resistance and on time since start melting (page 9)*

- [6] Knoop, M.; Kohle, S.: Time varying loads in electric power systems - power input, equivalent circuit elements and disturbances.
European Transactions on Electrical Power 7 (1997) No. 1, p. 5-11
- *More detailed investigation of reactance increase from fluctuation (without some simplifying assumptions made on page 7)*
- [7] Buchholz, F.: Die Darstellung der Begriffe „Scheinleistung“ und „Scheinarbeit“ bei Mehrphasensystemen (Definition of „apparent power“ and „apparent work“ in multi-phase systems). Elektro-Journal 1 (1921), p. 15-18
- *Early definition of collective values and reactive power in three-phase systems applied for the single-phase equivalent circuit diagram (page 8)*
- [8] Knoop, M.; Lichterbeck, R.; Kohle, S.; Siig, J.: Steuerung des Einschmelzens im Drehstrom-Lichtbogenofen zum Schutz der Wandkuhlelemente (Dynamic control of the melting process in AC arc furnaces for protection of the water-cooled wall panels). Stahl u. Eisen 117 (1997) No. 2, p. 91-96
- *Description of the furnace control system (page 10-15)*
- [9] Kohle, S.; Lichterbeck, R.: Optimisation of high voltage AC electric arc furnace control. BFI Report 2.32.005, 2001; contribution to ECSC Report EUR 20176, 2002
- *Relevance of R_i/X_o for electrical stability of arc furnace operation (page 16-21)*
- [10] Knoop, M.; Kohle, S.: Schwankung der elektrischen Größen von Drehstrom-Lichtbogenofen (Electric fluctuations in AC arc furnaces). Elektrowärme international 54 (1996) No. B1, p. B32 - B39
- *Detailed investigation of fluctuation transfer from arc voltages to currents, magnetic forces and supply line voltages (page 16, 17)*
- [11] Knoop, M.; Kohle, S.: Electrical design of high voltage, high reactance AC arc furnaces. Iron and Steel Engineer (1998) No. 3, p. 39-43
- *Description of fluctuation transfer and relevance of R_i/X_o (page 16, 17)*

International Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Power Supply of AC Arc Furnaces

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2.2 Operation of arc furnaces

2.3 Network disturbances of AC furnaces

3. Reduction of network disturbances

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3.2 Use of compensation equipment

4. Construction and design of compensation equipment

4.1 Size of the compensator

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6. Conclusion

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1. Introduction

Talking about power supply of AC Furnaces, we have to take into account different aspects. Under the condition that a furnace installation creates in the supply network non tolerable disturbances, one step can be, to increase the short circuit capacity by additional interconnections or to define a so called "unsteady bus", where a higher level of disturbances can be tolerated. This has to be done by the utility company and is not possible in most cases.

The furnace supplier can use special electronic circuits, which enable low disturbances power supply. In the last years, there has been remarkable improvement.

The furnace operator can modify the furnaces process, but with negative influence on the production rate in many cases. If he wants to avoid this, he has to install additional equipment, e.g. a Static Var Control. It means additional investment costs and additional losses, especially if damped filter circuits are necessary.

If a furnace causes disturbances, which increases the permitted level, it makes no difference if only a fictive level is exceeded or if other customers are really disturbed. If the utility company insists on improvement, the furnace operator must do something which means additional costs and the risk of no sufficient success.

Besides the disturbances in the supply network, one must not neglect the influence of the network and network transformer impedance on the design of the furnaces transformer.

In order to be competitive, the furnace operators must try to increase the productivity of their furnaces. One way is to increase the transformer power. Because there is a relation between short circuit capacity of the supply network and the network disturbances, these problems are not limited the powerful furnaces, but can happen also to small furnaces. If the transformer power of a new furnace is in the range of 150 to 200 MVA, flicker compensation will be necessary in most cases and the costs are tolerable, compared with the total investment costs. If - in contrary - a small furnaces needs flicker compensation, the situation is completely different, due to the high basic price of this kind of installation.

Consequently it has to be asked, what conditions the supply network must fulfil that the disturbances of a connected furnace will be below the limits and what can be done if this is not the case. One big problem is the "forecast" of the level of the disturbances. They cannot be calculated exactly due to the unsteady furnace operation. Only estimations are possible.

2. Basic considerations

2.1 Voltage fluctuations in the supply network

The first question is, why arc furnaces are able to create voltage fluctuations in the supply network, which can be detected e.g. by a flicker meter. Normally arc furnaces are supplied via a medium voltage level - up to 30 kV - which comes from a high voltage level using a network transformer high voltage/medium voltage. That means that the Point of Common Coupling, that is the connection to the public network is on a high voltage level. On this level

the guarantee values due to disturbances have to be proved. Arc furnaces are highly inductive consumers, because they need a certain reactance to stabilise the arc. This kind of load causes great voltage fluctuations, because normally the ratio of network resistance to network reactance is 1:10 or smaller [3].

Fig. 1 gives an example. It shows an arc furnace installation and the 110 kV supply network and its equivalent network. It is a medium sized furnace at a relatively strong supply network (short circuit capacity 6000 MVA). The impedance of the network, the network transformer, the furnace transformer and the furnace are taken into account. They can be calculated using the information, given in *fig. 1* and related to the secondary voltage of the furnace transformer. How this has to be done, is described in [4] and [5]. The so-called "operational reactance" takes into account the difference between the theoretical approach and deviations in real existing installations.

Due to the fact that the Ohmic component of the network impedance can be neglected [3], a stationary voltage drop ΔU at the point of common coupling can be calculated approximately using the furnace current I as follows:

$$\Delta U / \sqrt{3} \approx I X_q \sin \varphi \quad (1)$$

	Offload	Border of arc stability	Nominal operation point	Short circuit
Transformer power 60 MVA network short circuit power 6000 MVA	0%	0,59%	0,97%	1,93%
Transformer power 60 MVA network short circuit power 3000 MVA	0%	1,18%	1,84%	3,73%
Transformer power 100 MVA network short circuit power 6000 MVA	0%	0,64%	1,10%	2,94%
Transformer power 100 MVA network short circuit power 3000 MVA	0%	1,28%	2,16%	5,7%

Table 1: Relative voltage drop at the 110 kV point of common coupling at different load cases of the furnace

Table 1 gives for the cases "electrode short circuit", "nominal operation point, border of arc stability and "off load" an estimation of the voltage drops in the HOkV level. Column 1 shows the situation given in *fig. 1*. During nominal operation the voltage drop is approx. 1% and doubles during electrode short circuit ($R_B = 0$, $\cos \varphi = 0,13$). The second row shows that in case of decrease of the short circuit capacity of the network to 3000 MVA the voltage in the 110 kV level drops about 3.73%. Row 3 and 4 show the situation after the furnace has got a

new transformer with 100 MVA instead of 60 MVA. In the worst case there is a voltage drop at the point of common coupling of about 5.7%.

2.2 Operation of arc furnaces

The behaviour of arc furnaces during operation strongly influences the supply network. There has to be made a difference between stationary and dynamic behaviour. The stationary behaviour gives an information about the influence of the impedance of the network and network transformer on the power input, while the dynamic behaviour is responsible for the influences on parallel connected other consumers. Problems occur mainly when the short circuit capacity of the supply network is not sufficient.

2.2.1 Arc furnace power profile

A power profile has different sections. An example gives *fig. 2*. After a scrap basket is charged, for a short time the power input is reduced - boring phase. After boring, the power input is increased to a maximum until the next basket has to be charged. Same procedure again until the scrap is completely charged. If the scrap is liquid the overheating phase starts with lightly reduced power if necessary. Some furnaces end with a fining phase (for metallurgical work) with small power input only. At the end of the power on cycle the power input is stopped several times for temperature measurements and taking samples.

Although furnaces are mainly used for scrap recycling, there are furnaces which use partly sponge iron or pig iron.

Other furnaces are continuously charging. In this case the power input is more or less continuously done with only a small number of stops.

According to the progress in melting res. overheating, different operation points in the circle diagram are used. Which operation point will be necessary, is depending on the process, if e.g. short arcs are required because the wall panels are not covered by scrap or foamy slag.

2.2.2 Stationary behaviour

The **stationary behaviour** of the furnace can be explained using the circle diagram, which is shown in *fig 3*. For the choice of the operation points, the field surrounded by a bolt line can be used. The borderlines are the maximum of the secondary current, the maximum transformer apparent power and of course the maximum voltage tap.

On the left hand side, the borderline is given due to the phenomena that an arc is loosing it's stability (continuous current flow by passing zero) when the power factor becomes to high (approx. $\cos \varphi = 0,86$) and can be cut completely (approx. $\cos \varphi = 0,90$). Operation points in this area shall be avoided. Modern furnaces are operated with power factors around 0.83, if the arcs can be covered by scrap or foamy slag. Is this not possible, the arc length has to become smaller. That means smaller power factors res. the operation points will go more to the left area.

Fig 4 shall show this, using results of power measurements at a great arc furnace. Active and reactive power have been measured during a relatively calm phase shortly before tapping. In order to get a circuit, the furnaces control was programmed to increase the arc length stepwise, which means that the power factor is increasing from $\cos \varphi = 0,65$ to $\cos \varphi = 0,95$. Nevertheless, it is easy to explain why in this range stable operation is possible. The instrument was connected at the primary side of the furnace transformer thus measuring only the reactive power the furnace was consuming. For the stability of the arc the overall power factor has to be taken into account. And this power factor is much smaller due to the additional reactances of the network transformer and the network itself.

From this stationary behaviour of the furnaces, it can be seen that the power factor must be increased using compensation equipment, because many power companies penalise low average power factors if they stay under a certain borderline.

The above mentioned stationary voltage drop can be calculated according to equation 2 as the relation of the network reactance X_n and the total reactance (network plus network transformer $X_{(q+a)}$ and furnace X_n):

$$\Delta U/U \approx X_n / (X_{(q+a)} + X_n) \quad (2)$$

The result of this stationary voltage drop is that the primary voltage of the furnace transformer is smaller than the rated voltage and therefore the transformer does not give its rated power although the rated current is flowing. A further result is that the power input of parallel connected consumers e.g. a ladle furnace is also decreased.

If according to *fig 1* a calculation of the power input is made, neglecting the network res. taking into account all additional reactances, it can be found that the operation point 60kA/600V changes as follows:

- the primary voltage at the furnaces transformer decreases to 28.4 V, the secondary voltage to 535.1 V and
- instead of 48.8 MW only 42,6 MW are taken by the system.

The example shows that during design of the furnace transformer, the additional reactances have to be taken into account, and that means higher secondary voltages and an adjusted transformer power are necessary.

2.2.3 Dynamic behaviour

To explain the dynamic behaviour of a furnace, the circle diagram of *fig. 3* shall be used again. The operation points will be fixed in the bolt surrounded area, but that does not mean that the area outside will not be met. Due to the variation of the furnace currents, operation of the

furnace can touch a much wider range. This area is fixed by the actual voltage tap and only limited by electrode short circuit condition rep. cut of the arcs.

The above described behaviour shall be explained using *Fig 5*. It shows the result of power measurements during minute 2 to 6 while melting the first basket. Each dot is an rms. value over 480 ms. The great deviation from the operation point, which has been fixed during the measuring period as well as the voltage tap, shows the unsteady operation during scrap melting.

The most critical situation for the supply network is the period after charging a basket, in which the cold scrap is melting. Typical for this period are numerous cuts of the arcs followed by immediate re-ignition, strong variation of the load currents due to arc movements and the danger of short circuits due to collapsing scrap. The results are phase wise non symmetrical currents, non continuous currents etc. According to the variation of the currents, voltage variations are caused at the network impedance *III*. *Fig 6* shows, how this looks in reality *121*. The arc currents and voltages of an 801 furnace during second 135 to 138 after start of scrap melting can be seen. It can be easily seen that the behaviour is totally unsteady and for prediction statistical methods must be used.

According to *fig 7* the voltage drop at the network impedance can be split in tow components. Its magnitude is mainly influenced by the component along the longitudinal axis *III* and *161*. Due to the ratio resistance to reactance of 1:10 in supply networks the voltage change can be calculated, using the change of reactive power over the short circuit power.

A good approximation is equation 3:

$$\Delta U_{dyn}/U \approx \Delta Q/Sk \quad (3)$$

Q reactive power of the furnace

Sk network short circuit power

This voltage changes are influencing all other consumers, which are connected to the same area of the supply network.

2.3 Network disturbances of ac furnaces

Form the above it is obvious, that network disturbances cannot be explained using a simple sentence. This means that the requirements to the compensation equipment will be numerous. In order to give a description of the network disturbances, caused by an arc furnace the following differences can be made:

*Voltage fluctuations (flicker, trafo inrush, voltage drop in case of short circuit),
harmonics,
non symmetrical operation*

and the already mentioned

*stationary voltage drops and
low power factors.*

The most critical disturbances are voltage fluctuations which cause **flicker** in low voltage networks. The so called flicker is a variation of the brightness of lamps due to voltage variations, which are most dominant in filament lamps. The human eye is very sensitive against this variations. Many tests with people have shown, that the two things are important. The magnitude of the relative voltage change $\Delta U/U$ and the frequency of this fluctuation. It has been found that the same magnitude of voltage fluctuation and the resulting fluctuation of the light are most disturbing at a frequency of 9 to 10 Hz.

Internationally standardised - except in some Asian countries - is a flicker definition using so called Pst and Plt values (Pst=Perturbation Short Term and Plt=Perturbation Long Term). In Germany also Ast and Alt values are used. A means Annoyance and the relation to Pst values is the power of three $/3/, /7/, /8/$

$$Ast = Pst^3 \quad (4)$$

$$Alt = Plt^3 \quad (5)$$

st = short term means "average" values during a 10-Minute-Interval, while Lt = long term is normally related to 2-hour-Intervals. The relation between short term values and long term values is given by *relation 6*:

$$Plt = \sqrt[12]{\sum_{i=1}^{12} p_{sti}}$$

The level when the light flicker will be detectable by human eyes is a *Pst value of 1*. Therefore the value of 1 should not be exceeded in low voltage supply networks. The internationally used visibility curve is shown in *fig. 8*.

As flicker meter an internationally standardised so called UIE flicker meter is used (UIE = International Union for Electricity Applications) *111, 191, 110/*. It is standardised in IEC 868. Meanwhile there are many suppliers of this kind of instruments. *Fig 9* shows a block-diagram of the UIE flicker meter. In block 1 to 4 the voltage signal is transferred to the momentary flicker (output 4). Block 5 is a statistical evaluation to get e.g. 10 min Pst values.

It is very difficult to give an estimation which Pst-values can be expected by arc furnace operation, because numerous things are influencing the flicker, the mechanical arrangement, the system reactance, the quality of the scrap, the choice of the operation points of the furnace, i.e. the arc stability and many other things. In the second edition of the German " VDEW-

Grundsätze für die Beurteilung von Netzruckwirkungen" dated 1986 the following approach can be found:

$$P_{st} \approx 0,6 \cdot k \cdot S_{kA} / S_k \quad (7)$$

S_{kA} furnace short circuit power

S_k network short circuit power

A factor k of about 80

UIE's approach is similar, but without the factor 0.6 but k between 48 and 80

Later approaches do not give any equation for P_{st} values any longer. Only the German VDEW gave 1992 an estimation for P_{lt} values [3]:

$$P_{lt} \approx 35 \cdot S_{kA} / S_k \quad (8)$$

Currently a modification of *equation 7* is used. Instead of $0.6 \cdot k$ a new factor called k_{st} is used with k_{st} between 40 and 50 for ladle furnaces and 50 to 80 for ac arc furnaces.

$$P_{st} \approx k_{st} \cdot S_{kA} / S_k \quad (9)$$

fig 10 shows the results of flicker measurements at the 30 kV bus of a furnace with a transformer power of 100 MVA. Clearly visible are 3 tap to tap cycles. Heat 1 and 3 use 2 scrap baskets, while heat 2 used 3 baskets. It can be seen, that the flicker values are extremely different from each other and therefore also the k_{st} -factor according to *equation 3*. At the beginning of a new basket they are around $k_{st} \approx 50$.

There are for sure other possibilities for a flicker estimation. All need without doubt a great portion of experience with furnace operation.

What happens now if more than one furnace are operated at one supply bus ? In this case, it is assumed that the events in the furnace which cause flicker will not occur simultaneously. Therefore a resulting P_{st} value can be calculated as follows:

$$P_{st} = \{ \sum (P_{st})^m \}^{1/m} \quad (10)$$

The exponent may be between 2 and 4. UIE recommends a value of $m=3$ for the majority of the cases.

There is another important method to measure voltage flicker, the Japanese AVio -Method *III*. In this case the values are detected minute wise. The reference value is the 4th highest after one hour. Comparative measurements between Pst values and AVio values gave the following relation:

$$\Delta V_{io} (4 \text{ th}) / P_{st \text{ max}} = 1/3 \quad (11)$$

This method is mainly used in Asia (Japan, Korea, Taiwan)

A further kind of disturbances are **harmonics**. It can be said that an arc furnace acts as a generator of harmonic currents which are inserted in the supply network. These currents cause at the network impedance harmonic voltages, which are overlapping the fundamental thus influencing all other consumers. During operation of an arc furnace, a continuous spectrum can be measured with peaks on the even and again higher odd harmonics. *See Fig. 11*. AC arc furnaces do not generate remarkable harmonics above the 10th / *I II*.

Non symmetrical currents give non symmetrical voltage drops at the network impedances and thus non symmetrical supply voltages for other consumers. There is a difference between 1 phase active and reactive loads, due to short circuit resp. cut of an arc. One phase active loads do not change the value of the voltage in the load phase but increase resp. decrease the voltage in the other phases. With one phase reactive loads, it is just the other way round / *I II*.

3. Reduction of network disturbances

3.1 Without use of compensation equipment

Following a UIE investigation from 1973, there will be no disturbances, if the network short circuit power is equal or higher than 80 times of the rated transformer power / *131*. This estimation is still used.

If problems occur, the furnace operator can negotiate with the power company to increase the short circuit capacity at the point of common coupling in order to get the above mentioned ratio between short circuit capacity and transformer power. In most cases this is not possible because furnace power of 140 MVA require short circuit capacities of 14 GVA and more. *What can be done instead?*

According to *fig 12* a **series reactor** can be used on the furnace primary side. The figure gives a comparison between a classical furnace and a furnace with a 25% series reactor. The reactor reactance is expressed as a relation to the transformer power.

The purpose of the series reactor is to increase the reactance in the furnace circuit in such a way that operation points can be chosen which enables the operator to bring in the same active power as before, but now using more stable arc operation which is represented by the lower power factor. The second advantage is the lower secondary current, which gives a decrease in electrode consumption.

On the other hand, more apparent power and - very important - higher secondary voltages are necessary.

A further effect shall also be mentioned. One can see that the arc length is increasing and therefore also the refractory wear index. This is wanted, when foamy slag operation is possible but in case of uncovered arc it can become a problem.

There is another reason to use a series reactor. This is to decrease the secondary current as much as possible in order to minimise the electrode consumption. In this case the power factor is similar to operation without reactor and therefore the flicker would also be similar.

If the flicker of an existing furnace is too high, the additional use of a series reactor would be no solution, because higher secondary voltages are necessary, which are normally not existing.

Series reactors are normally built in the transformer tank. This is the most economical solution. Alternatively external iron core or air core reactors can be used, if space enough is available.

The reactors can be equipped with tap changers in order to adjust the reactance if necessary. Another possibility to adjust the reactance is shown in *fig 13*. Here DC premagnetisation is used [21]. By this the reactive power can be controlled in a certain way, which leads to a further reduction of flicker.

Another possibility to stabilise the consumption of reactive power of a high impedance furnace is the use of a thyristor controller in series with the furnace. This is also shown in *fig. 13*. The first installation of this kind can be found at Co-steel Lasco in Canada. This furnace operation is very similar to DC furnace operation, i.e. operation with nearly constant current. The supplier states the flicker is reduced significantly [23].

3.2 Use of compensation equipment

3.2.1 Principles of compensation

If the tolerable flicker in the supply network is exceeded by a consumer, it is possible to run a flicker compensation in parallel. The basic purpose of all compensation equipment is however to supply the necessary reactive power in order to increase the average power factor. A usual value required by many utility companies is 0.9.

The necessary compensation power Q_c can be calculated using the average active power:

$$Q_c = P (\tan \varphi_1 - \tan \varphi_2) \quad (12)$$

φ_1 average phase angle before compensation

φ_2 average phase angle after compensation

The main task of the compensator is however to minimise periodical voltage fluctuations especially in the range of the critical frequencies. Further tasks are to limit harmonics and the effects of non symmetrical operation.

Fig. 14 shows all methods of reactive power generation [15]. The classical compensator is a synchronous condenser, but due to the inertia of the machine it is not possible to use it for flicker compensation. Also the attempt to use a saturated reactor was not very successful. Only one plant was built in Nigeria.

More successful are TCR's (TCR = Thyristor Controlled Reactor) and TSC's (TSC = Thyristor Switched Capacitors) both in combination with filter circuits.

3.2.2 Thyristor Switched Capacitors

Thyristor switched capacitors are using the *direct compensation principle*, i.e. much inductive by the furnaces means much capacitive compensation power which can be switched on dynamically [1]. Although the direct solution looks very simple, there are immense problems. The reason is that capacitors generate transient currents when they are switched. In order to avoid this, the capacitor voltage has to be adjusted by a pre-firing pulse. The switching delay is around one period and thus limits the dynamic. Another problem is that the network resonance is changed if additional capacitors are switched. Because of these disadvantages TSC's are not used any longer for the compensation of arc furnaces.

3.2.3 Thyristor controlled reactors

The compensation equipment, which is used for arc furnace compensation nowadays is consisting of thyristor controlled reactors and filter circuits. Such a compensator is using the *indirect compensation principle* which means much inductive power of the furnace requires low inductive power of the TCR and the other way round. If the capacitive power of the filter circuits is great enough, the overall power factor can be kept near $\cos \varphi = 1$. *Fig. 15* shows the basic arrangement of an SVC. The TCR consists of antiparallel operating thyristor and split reactors. The delta connection suits best, because the currents are smaller and certain harmonics are eliminated in case of symmetrical operation. The currents can be controlled between zero and rated values. *Fig. 16* shows currents and voltages for different firing angles. Concerning the harmonics the TCR acts like a 6-pulse Graetz bridge. Additionally a third harmonic is generated in case of non symmetrical operation. These harmonics are overlapping the furnace harmonics and have to be eliminated by the filter circuits.

3.2.4 Electronically realised synchronous condenser

A further possibility of dynamic compensation is offered by Siemens-Westinghouse. It is a statcom system (Static Synchronous Compensator). A statcom system acts like a synchronous condenser, i.e. it can supply reactive and capacitive power as well. In contrary to a mechanical synchronous condenser its control speed is extremely high, because it is realised by using GTO's (Gate Turn-off Thyristors) /20/. This gives also remarkable advantages compared to a classic TCR. *Fig 17* shows a statcom system.

ABB has developed a similar system /27/ which is called SVC light. Its basis is the VSVC technology (= Voltage Source Var Compensator) and it uses IGBT's (= Insulated Gate Bipolar Transistor) as switching elements. The response time is smaller than a millisecond, which enables this type of compensator to reach much higher flicker improvement factors than conventional TCR's. *Fig 18* shows a simplified connection diagram and a comparison of the current flow in a TCR and a VSVC. The alternating voltage can be controlled very fast in amplitude, phase and frequency, so that reactive power can be generated resp. consumed. The active power transfer is zero. Therefore no DC source is necessary, a relatively small DC capacitor is sufficient.

4. Construction and design of compensation equipment

4.1 Size of the compensator

It is not possible to determine the size of an SVC as easy as it is to calculate filter circuits. Each SVC is individually projected by the supplier. During design phase has to be taken into account:

- The supply network (especially the short circuit capacity),
What kind of consumer has to be compensated,
- Which guarantees regarding the limitation of disturbances have to be given

Each supplier has his individual design philosophy, which may lead to completely different solutions, although the boundary conditions are the same.

This shall be demonstrated in *table 2*. The table contains data of already existing plants.

4.2 Construction of an SVC

Filter circuits are consisting of capacitor banks and air core reactors. They are connected in double star in order to make the use of non symmetry protection possible. Filter circuits of the order 2 are normally equipped with damping resistors.

For TCR reactors normally air core reactors are used. If there is a lack of space or a limitation of noise, also iron core reactors can be used /28/.

The cooling can be made by water-water cooler res. water-air cooler. The primary circuit needs de-ionised water.

Except the thyristor controller, the equipment is for outdoor installation. It has to be checked that near the reactors no iron shall be in the foundations due to the induction of eddy currents.

Fig 19 and 20 show examples of SVC's. The SVC of *fig. 19* has a power of 130 MVar while the SVC in *fig 20* has a power of 60 MVar. The space requirement of the greater compensator is 40 by 50 meter. Some dimensions and weights can be found below:

- TCR reactor: approx. 91 per Phase
 Diameter approx. 3,5 m
 Total height ca. 6 m
- Filter reactors weight ca. 0,5 to 1,61 per reactor
 Diameter 1 to 2,3 m
- Capacitor banks total weight ca. 45 t
- Resistors ca. 200 kg per piece

Installation	Dynamic part	Filter circuits	Type	Supplier
AC furnace 48 MVA (KIA, Korea)	60MVA _r	50MVA _r 2. 3. 4. 15 10 25MVA _r	SVC	ABB
Rolling mill (Sollac, F)	66MVA _r	66MVA _r 5. 5. 7. 33 16,5 16,5 MVA _r	SVC	ABB
AC furnace 37.8 MVA Ladle furnace 7.7 MVA (Hagfors, S)	±22MVA _r	22MVA _r 3. 5. 8 14 MVA _r	SVC light	ABB
DC furnace 140 MVA (Arbed, L)	110 MVA _r	HOMVA _r 3. , 5., 7., 12. 10, 30, 45, 25 MVA _r	SVC	Ansaldo
DC furnace 140 MVA With free wheeling diode and phase shifting (Arbed, L)	60MVA _r	32 MVA _r 3. , 5. 13, 19 MVA _r	SVC	Cegelec
AC furnace 96 MVA (Arvesta, S)	120 MVA _r	120,4 MVA _r 2. 3. 4 5. 7. 11. 22,8 7,7 7,3 19 32 31,6MVA _r	SVC	Nokia
Cold rolling mill (Krakatau, Indonesien)	50MVA _r	50 MVA _r 5. 7. 11. 20 15 15 MVA _r	SVC	Siemens
Hot rolling mill (EKO, D)	70MVA _r	70 MVA _r 3. 5. 7. 11 10 20 20 20 MVA _r	SVC	Siemens
Cycloconverter (Nucor, USA)	80MVA _r	80 MVA _r 3. 5. 7. 10 25 45 MVA _r	SVC	Siemens
AC furnace 137 MVA (ISPAT, Indien)	190MVA _r	180 MVA _r 2. 3. 4. 5. 50 30 30 70 MVA _r	SVC	Siemens
AC furnace 66 MVA (Feralpi Riesa, D)	80MVA _r	80 MVA _r 2. 3. 4. 5. 15 35 20 10 MVA _r	SVC	Siemens

Table 2: Existing compensators of different suppliers

4.3 Improvement factors

The improvement factor is the ratio of the Pst values without compensation to the Pst values with compensation. A TCR can realise an improvement factor of approx. 2, if the short circuit capacity is not too small. It requires however an experienced supplier. Malfunction of the TCR control can lead to improvement factors smaller than 1.

Fig. 21 shows the results of flicker measurements in a steel plant with an arc furnace and an SVC. The power company required a Pst value of 1 as a 99% value, which the compensator fulfilled. For test reasons the SVC was switched off. It can be seen, that the improvement factor is around 1.8, that means without SVC, the operation of the furnaces is not allowed by the power company.

The improvement factor of an SVC light system is approx. 3.3 to 3.8 (There are only two installations up to now).

5. Flicker planning levels in supply networks

Very often the question rises, which maximum flicker generation of an arc furnace installation is permissible. This question cannot be answered generally although it looks simple, because as said above, the borderline of visibility is the $P_{st}=1$ curve. But one must not forget that this curve is talking about flicker in low voltage supply networks with private households as customers and that this borderline is the result of all generated voltage fluctuations and not only the result of the generated flicker of one single consumer installation. That means that the tolerable flicker, generated by a single installation connected to low voltage networks must be lower than the borderline. This is the philosophy of most utility companies res. national standards.

On the other hand it is clear that steel plants are high voltage customers for the utility companies, because the input lines are always high voltage lines. That means there is no direct connection to the low voltage supply networks of the neighbouring cities. It is known from recent research work, that there is a so called flicker transfer factor.

From measurements it is known, that flicker which is e.g. caused by industrial sources and can be detected in the local HV system is transferred to the LV system by a factor smaller than one. This factor is called transfer coefficient between two points in the network and is defined as the ratio of the Pst values, measured synchronously in both locations /8/

Measurements made in /17/ have shown that

- the flicker transfer coefficient from MV to LV is equal to 0.99
- the flicker transfer coefficient from HV to MV is equal to 0.92

This should give to the network operator some room for higher tolerable flicker generation of industrial high voltage customers, but it must be said that this fact is not known by many utility companies up to now.

In reality planning levels given by international res. national standards or by nation-wide power companies can differ very much from each other and are very often relatively low, although all are using the same flicker definition, which is given by IEC 61000 or by a Japanese standard (i.e. Avio)- Some examples:

Standard resp. Power company	Planning level	Remark
Germany/VDEW	$P_{st} < 0.8$ $P_{it} < 0.59$	Percentile not specified
England / P28	$P_{stmax} < 1$	Successes former P7/2
Russia / GHOST	$P_{st} \quad 1.3$	Percentile not specified
China /National Standard GB 12326-2000	$\Delta v_{io} < 0.4$ $P_{st99} \quad 0.8$ $P_{lt99} \quad 0.6$	old new
Korea /KEPCO	$\Delta v_{io} \quad 0.45$	4 th highest of 60 per hour
Taiwan/TPC	$\Delta v_{io} \quad 0.4$	Can be less according to the number of furnaces connected
France	$P_{it} \quad 1$	Percentile not specified
EEC 61000-3-7	$P_{st99} \quad 0.8$ $P_{lt99} \quad 0.6$	Emission levels in HV-EHV, indicated value
EN 50160	$P_{it95} \quad 0.95$	Must apply to all European networks, i.e. must suit weakest zone

Table 3: Planning levels 725/

Some standards allow that in single cases the utility company can negotiate with their customer and allow for single installations higher values than the standard required (e.g. German VDEW). Others are going for single installations to much lower values than the standard require as planning level, if more than one flicker relevant load is connected or shall be connected in the future (e.g. China, Taiwan). This approach leads in single cases to extreme low guarantee levels for single installations and thus to great risks for the equipment suppliers.

6. Conclusion

Arc furnaces are critical consumers for the supply network because remarkable network disturbances may occur. This is evident if the short circuit capacity of the supply network is not sufficient, in this case, the utility company can try to change the network configuration.

If this is not possible, the installation of a high impedance furnace may help. But the improvement is only limited. The further step will be the installation of flicker compensation equipment, which allows dynamic reactive power control

The classic flicker compensator is a combination of TCR and filter circuits. This installation is able to reduce the flicker of a factor of 2. If this is not enough the furnace operator can use compensators of the latest generation, called statcom res. SVC light. They are using GTO's or IGBT's instead of thyristors and their control speed is much higher with the result that they reach flicker improvement factors above 3.5. The problem is that the price is nearly double, compared with a classical solution.

The flicker planning levels can be very different from each other although all utility companies are using the same flicker definition given by IEC. The supplier of arc furnaces res. the operator should contact the local network operator in order to find out which standard is applicable.

7. References

- /1/ D. Grünberg, W. Reiche
Netzruckwirkungen von Lichtbogenofen und ihre Kompensation
BBC Druckschrift Nr. MD 0790017D
- /2/ H. Faber
Ein Beitrag zur Ursache periodischer Spannungsschwankungen in Drehstrom-Lichtbogenofen
PhD-thesis Hochschule der Bundeswehr Hamburg, 1979
- /3/ Grundsätze für die Beurteilung von Netzruckwirkungen 3.
überarbeitete Ausgabe 1992, VDEW
- /4/ R. Roeper
Kurzschlussströme in Drehstromnetzen Verlag
Siemens AG, Berlin, 6. Auflage 1984
- /5/ VDE 0102 Teil 2, VDE-Leitsätze für die Berechnung der Kurzschlussströme
- /6/ R. Brehler, W. Kaufhold, D. Schumacher
Operational Characteristics and Design Criteria for Isolated Power Supply Systems of Electric Arc
Furnaces and Rolling Mills
Siemens Druckschrift A19100-E264-B167-X-7600
- /7/ Flicker Measurement and Evaluation
Second Revised Edition 1991, UIE Disturbance Working Group
- /8/ VDE 0838, Teil 3
Rückwirkungen in Stromversorgungsnetzen, die durch Haushaltsgeräte und ähnliche elektrische
Einrichtungen verursacht werden
- /9/ Flickermeter - Functional and design specifications IEC
Publication 868, 1986
- /10/ Addendum to IEC Publication 868 Flickermeter - Funktional and design specifications
IEC 77A(Central Office) 28. May 1989
- /11/ E. Wanner, R. Mathys, M. Hausler
Kompensationsanlagen für die Industrie
BBC Druckschrift CH-IT 123 090D
- /13/ J. Lemmenmeier, P. Meynaud, H.J. Shepard, K.B. Nevries
14. revised report on UIE/UNIPED enquiry about effects of electric arc furnaces on power systems -
A.I.M. - C.B.E.E., 1973
- /14/ Engineering recommendation P28 "Planning limits for voltage fluctuation caused by industrial,
commercial and domestic equipment in the UK" System Utilisation Consultancy Group,
September 1989
- /15/ H. Pesch, W. Schulz
Controlled Reactive Power Compensation- A Comparison of the Possible Alternatives -
AEG-Telefunken Firmenschrift A52 VI.8.49/0583 EN
- /17/ A. Robert, M. Couvreur
Recent Experience of connection of big arc furnaces with reference to flicker level
UIEPQ-9430, 1994

- /20/ STATCOM, Field-Proven Electronic Controller for transmission Voltage
Westinghouse Firmenschrift PGBU-59660, USA 1997
- /21/ L. Poggi, G. Di Palma
Transformatoren für Drehstrom- und Gleichstromlichtbogenofen,
Stahl und Eisen 117 (1997) Nr. 3
- /23/ SPLC A modern Technique for Controlling AC Electric Arc Furnaces J.
Mulcahy Enterprises, Whitby, ON, Canada
- /24/ E. DEJAEGER, G. BORLOO, W. VANCOESTSEM, Flicker Transfer Coefficients from HV to MV
and LV Systems, UIE Publication 1997
- /25/ Arlt, D., Eberlein, Ch. Examples of International Flicker Requirements in high Voltage Networks and real
world Measurements, to be published in Electra in 2002
- /27/ SVC Light
A breakthrough in power quality
ABB power Systems, Vesteras, Sweden
- /28/ Produktivitätssteigerung im Elektrostahlwerk durch Netzstabilisierung auf engstem Raum
Siemens Druckschrift, Bestell-Nr. A19100-E264-B198

8. Figures

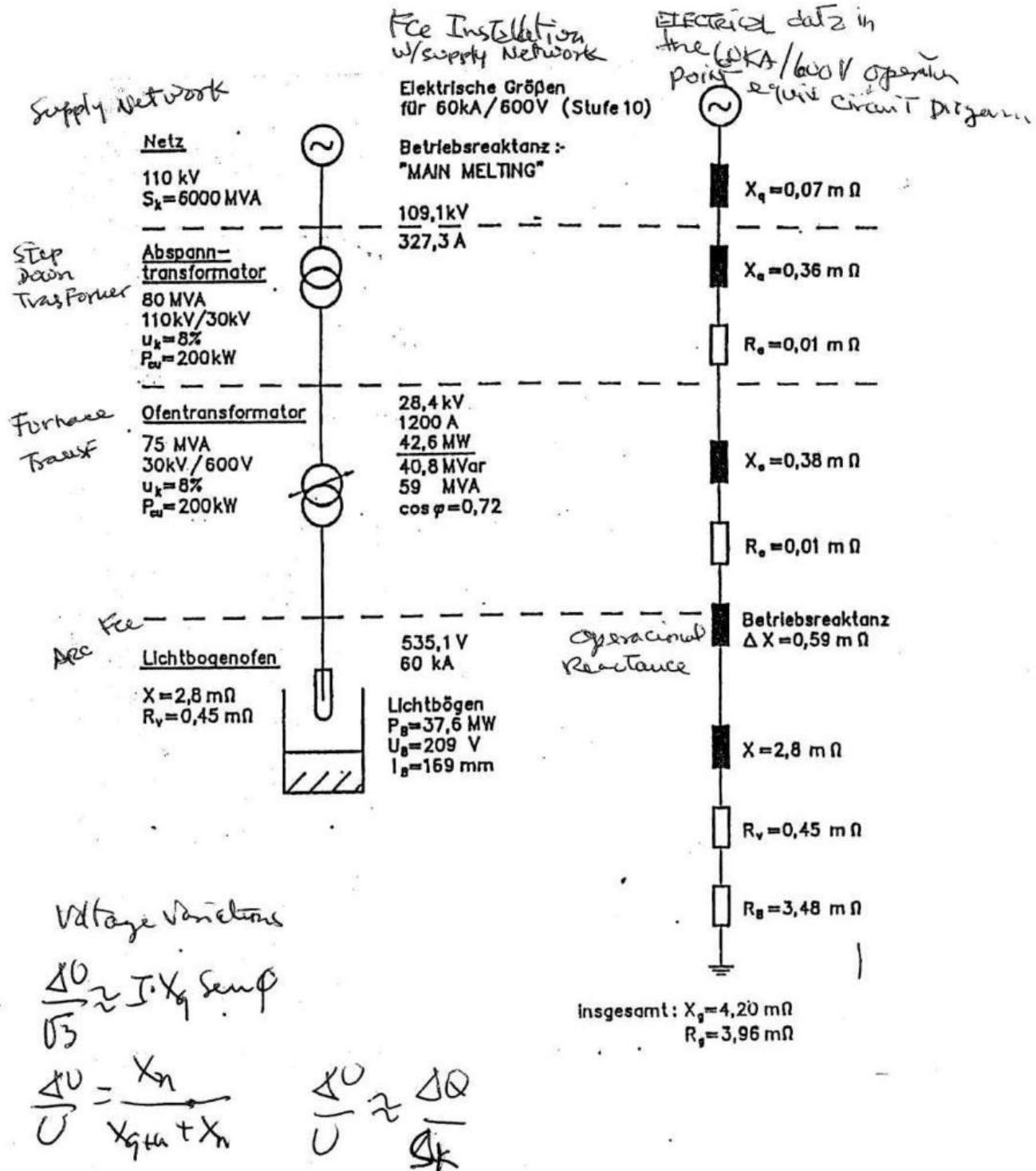


Fig 1: Arc Furnace with supply network, Electrical data at the operation point 60 kA/600 V
Equivalent network of the total system

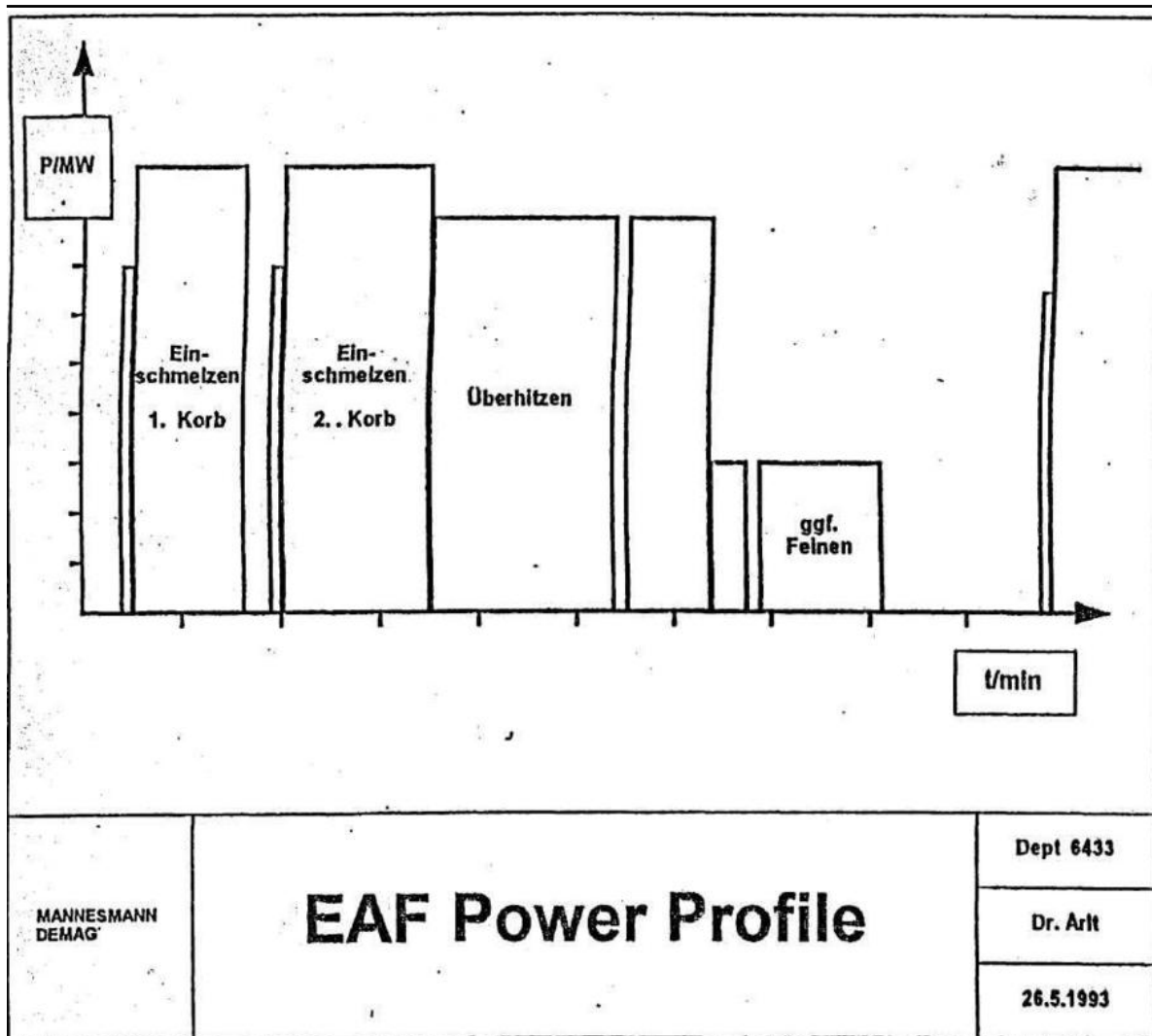


Fig. 2: Arc furnace power profile

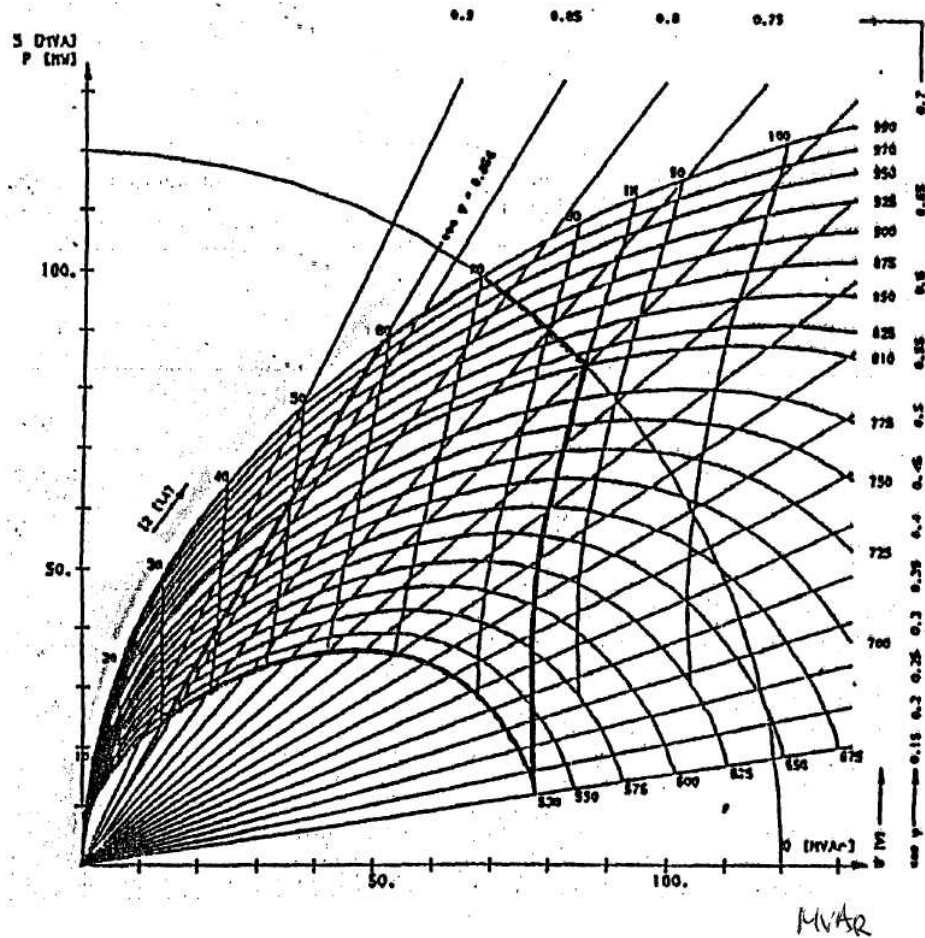


Fig. 3: AC arc furnace circle diagram

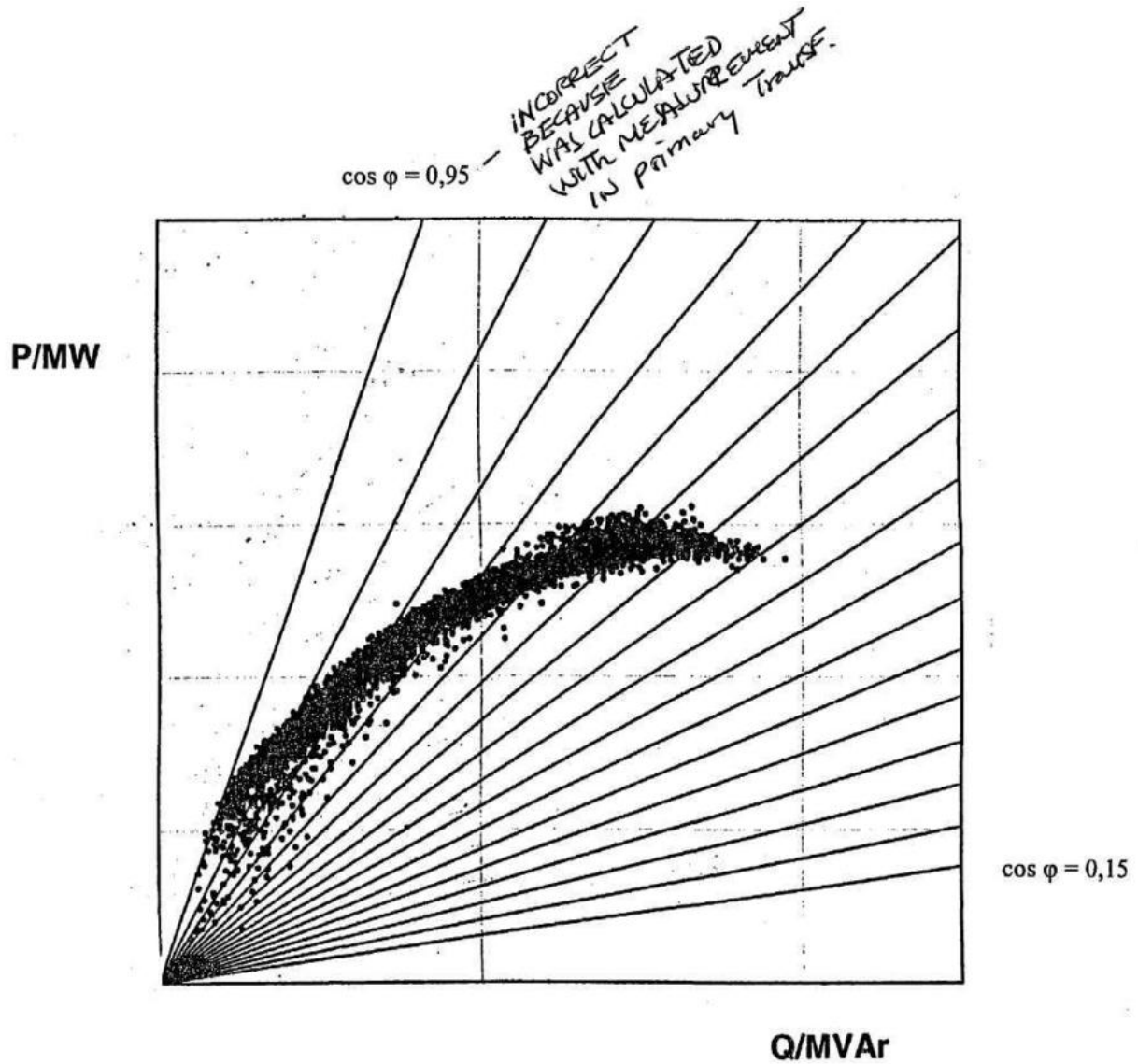


fig 4: „Measured circle diagram of a AC furnace (created by increasing the arc length step by step)

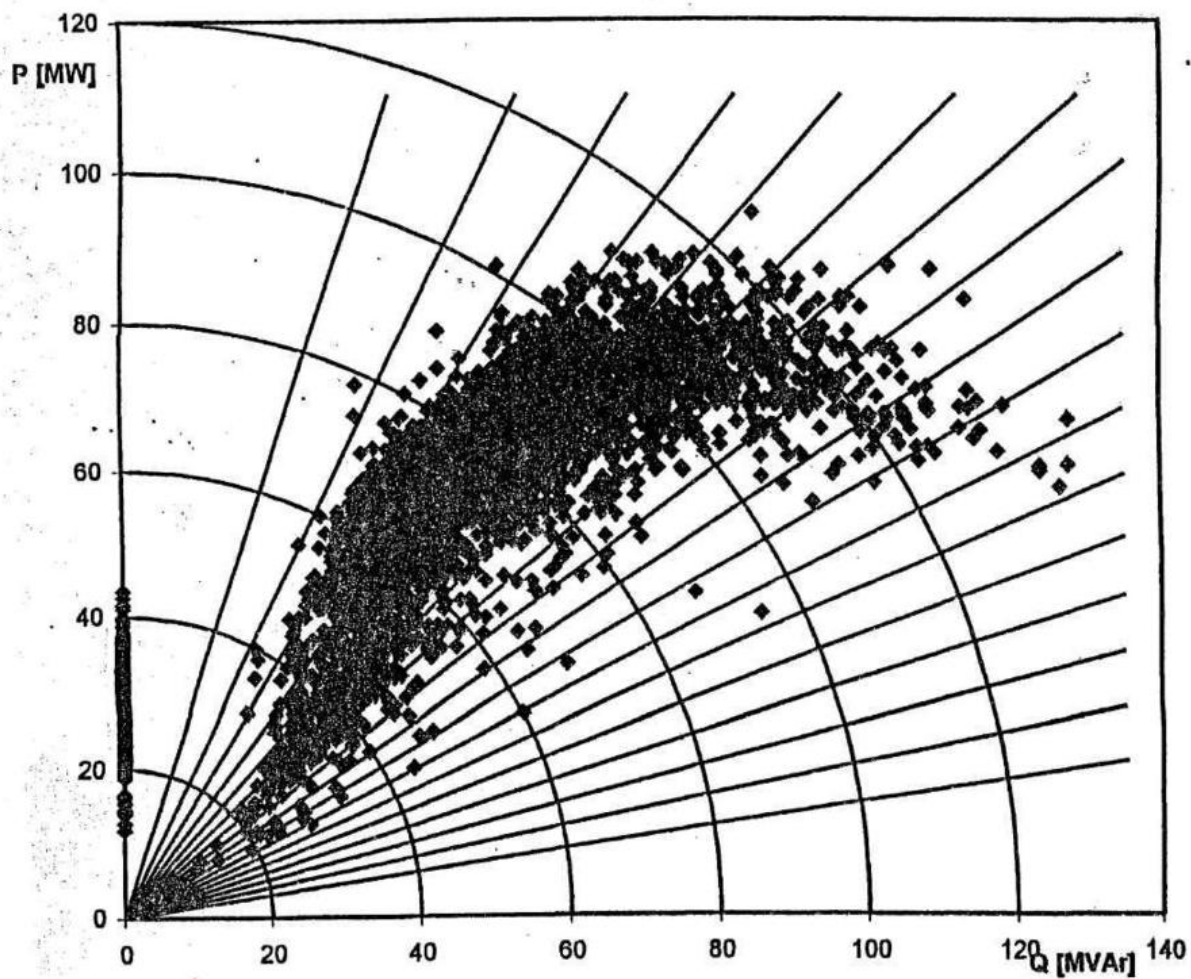


fig 5: Power measurements of an AC furnace with 80 MVA transformer power
(1. basket, minute 2-6, voltage tap 780 V)

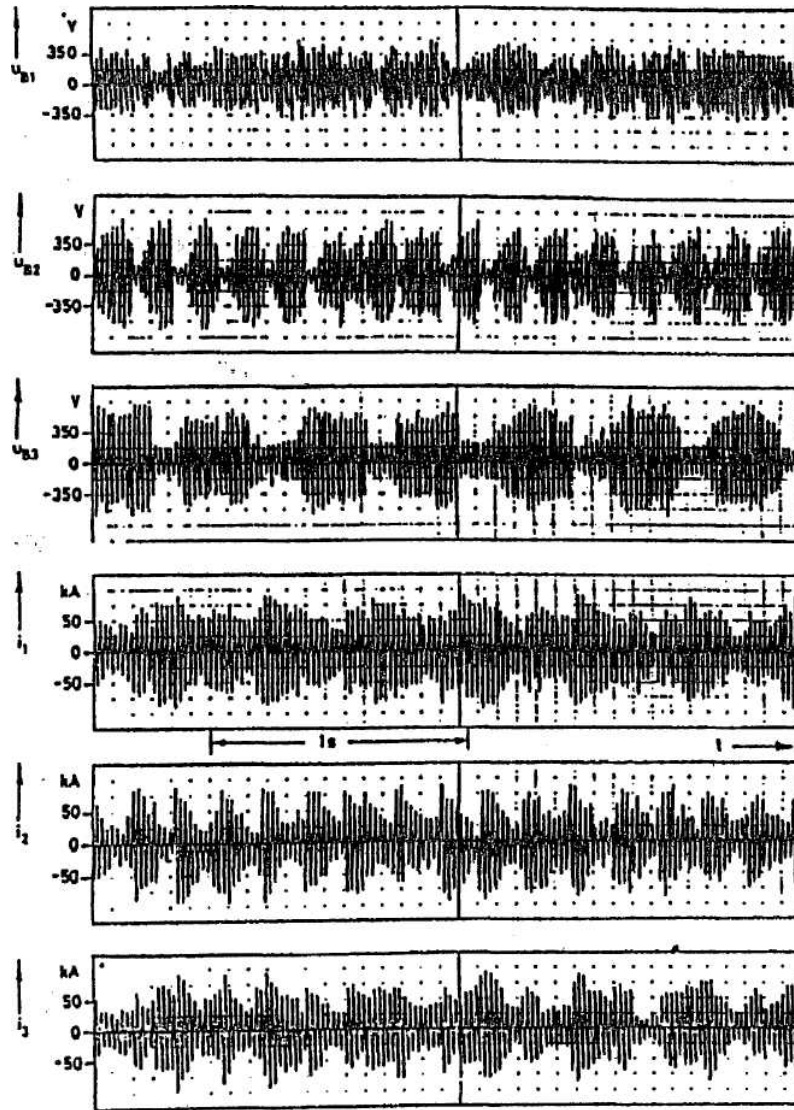


fig 6: Measured arc currents and voltages III . During second: 135. to 138. after power on

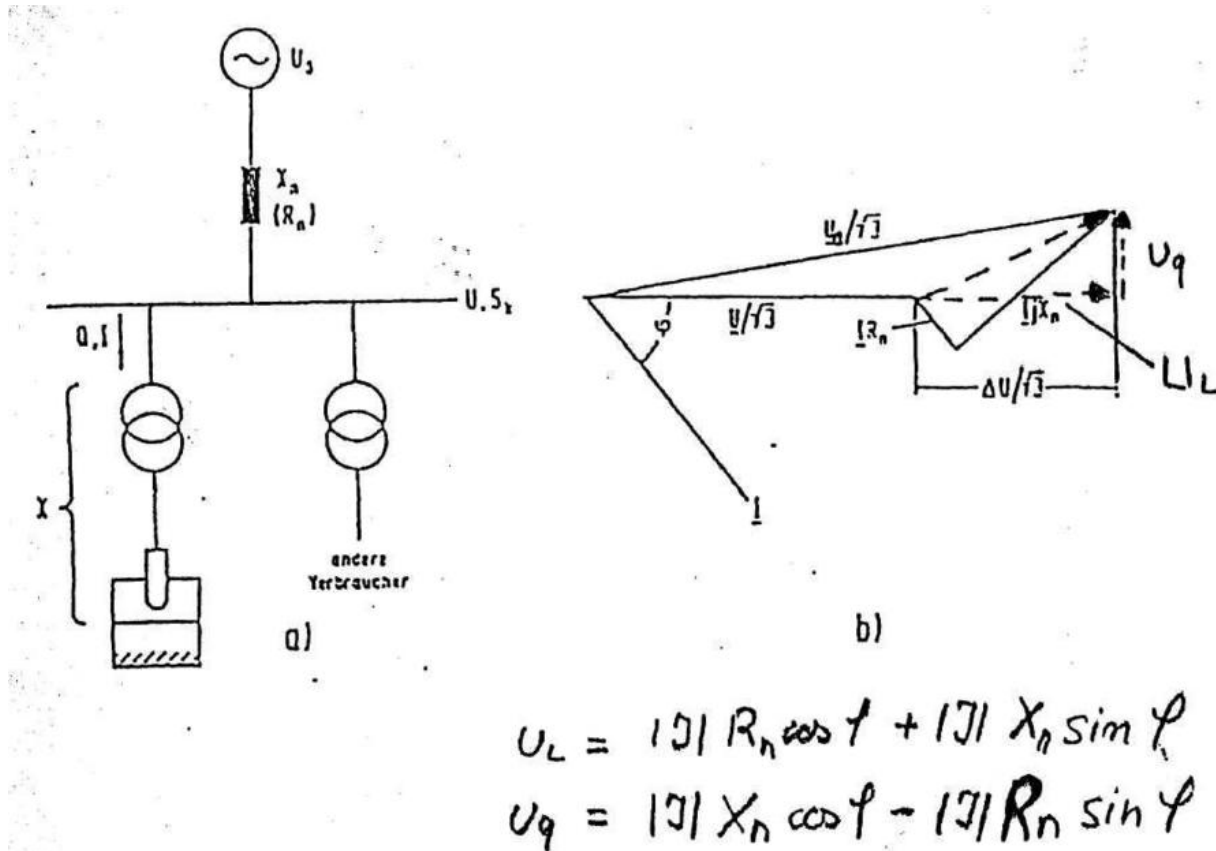


fig 7: Arc furnace at a power supply network (a) and resulting vector diagram (b)

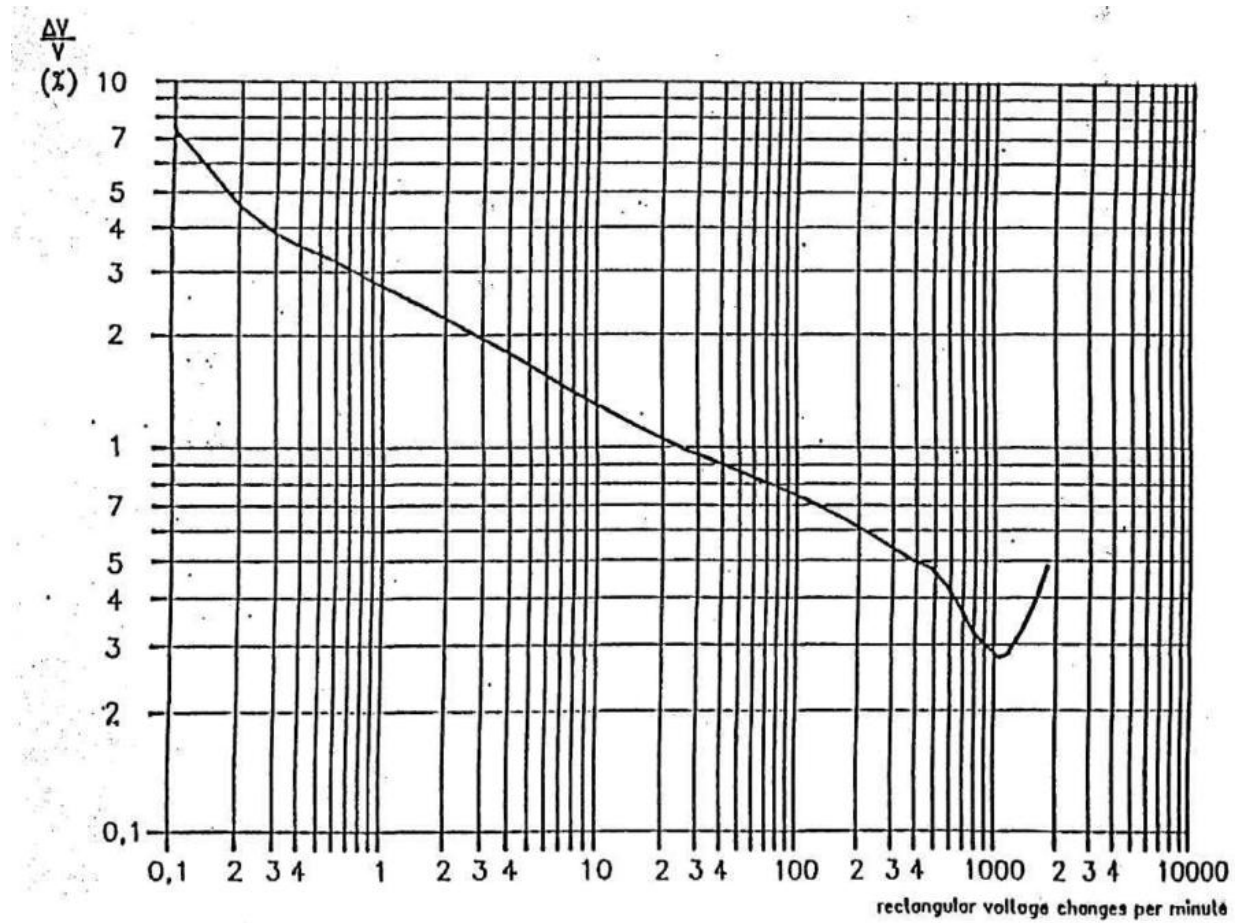


fig 8: Limit of visibility for rectangular voltage changes (Pst 1 curve)

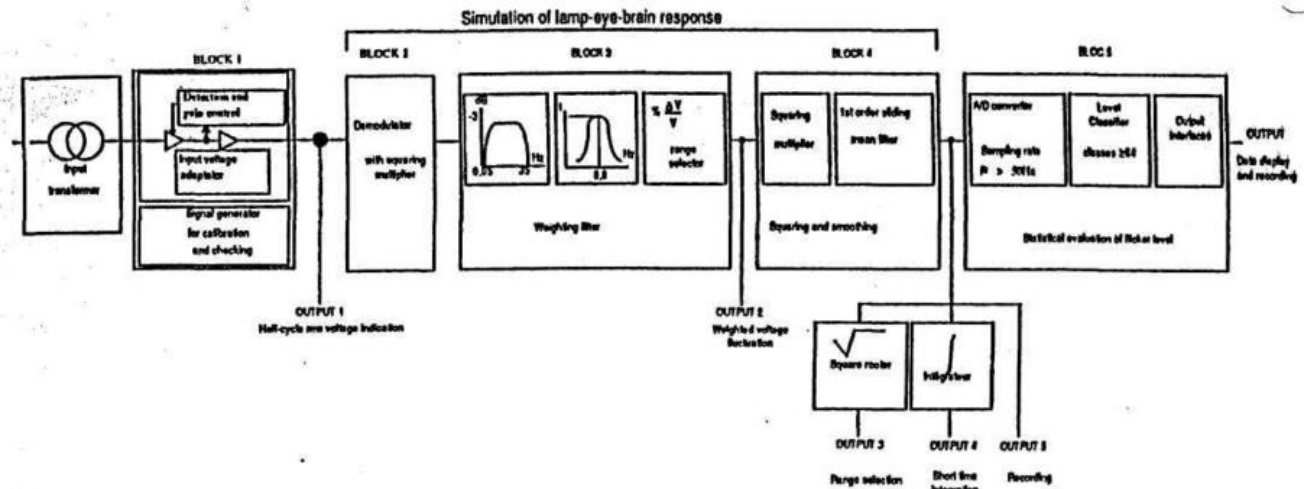


fig 9: Block diagram of the UIE-Flicker meter

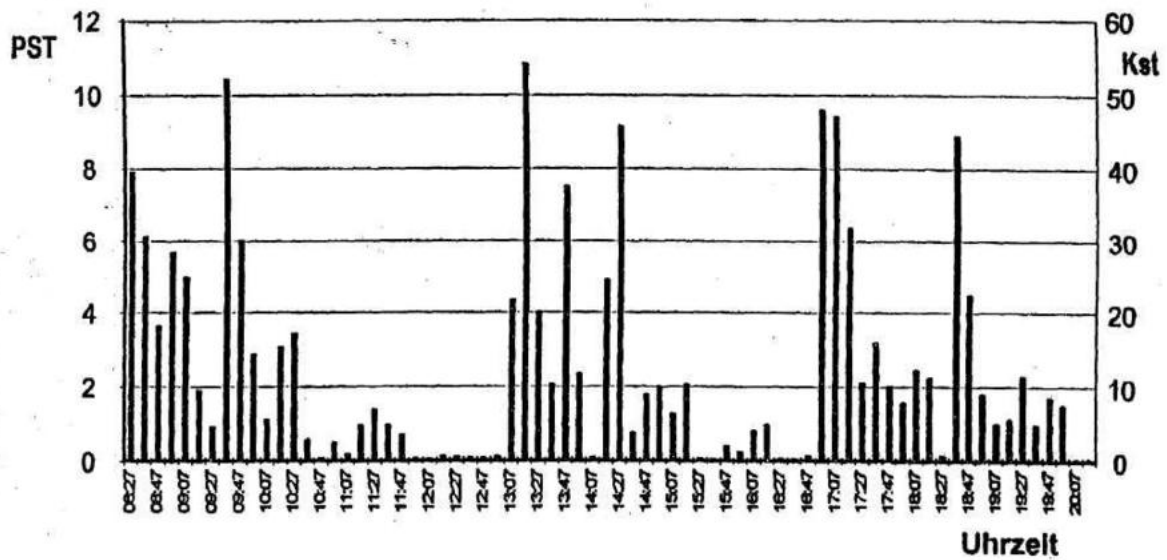
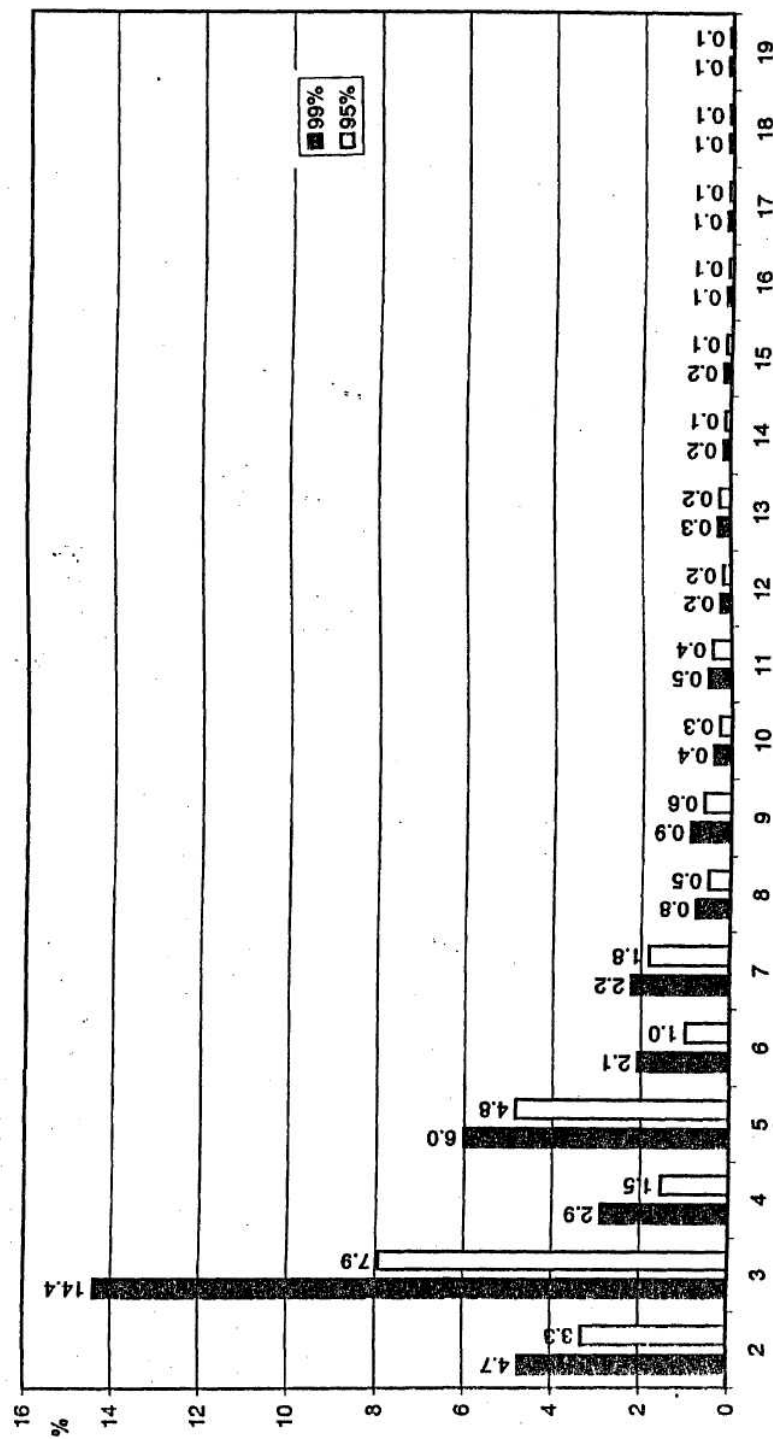


fig 10: Flicker measurements at the 30 kV furnace bus of an AC furnace with a transformer power of 100 MVA



figl: Harmonic spectrum of the primary currents of an AC furnace

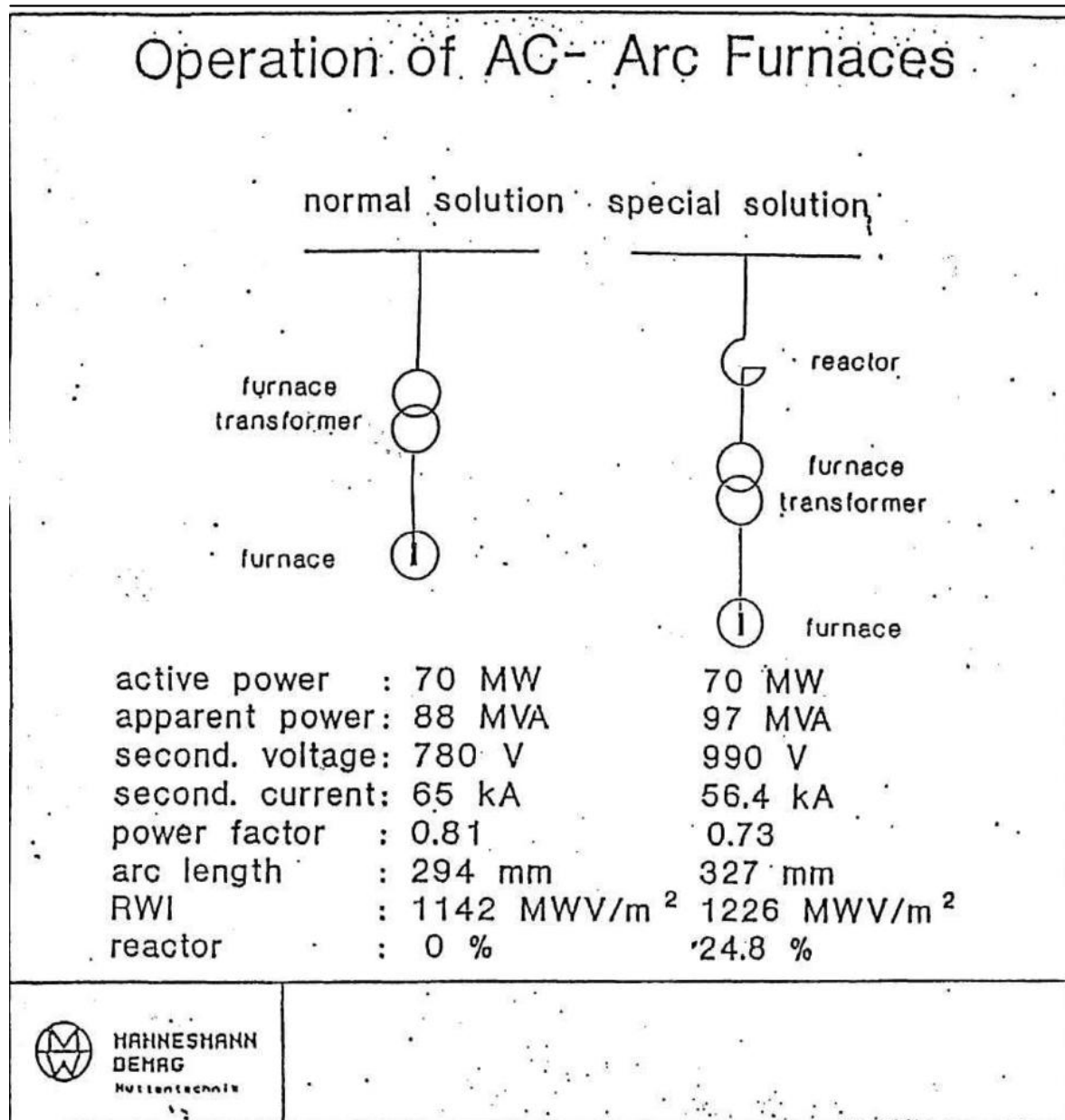
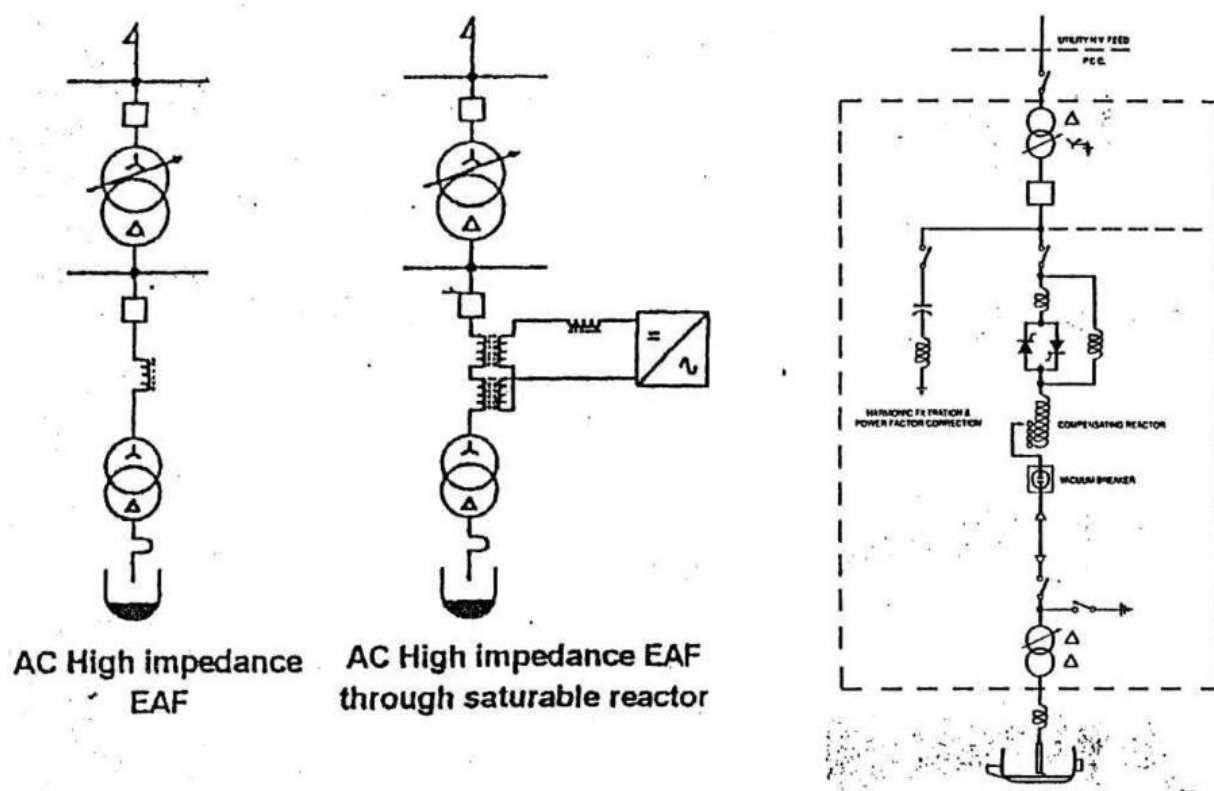


fig 12: Classic AC furnace (left) and high impedance furnace with series reactor (right) and basic technical data



$$Q_c = P(\tan \phi_1 - \tan \phi_2)$$

ϕ_1 = w.g. phase angle without compensation
 ϕ_2 = desired w.g. phase angle

fig 13: High impedance furnace, high impedance furnace with DC pre-magnetisation and high impedance furnace with series thyristor controller

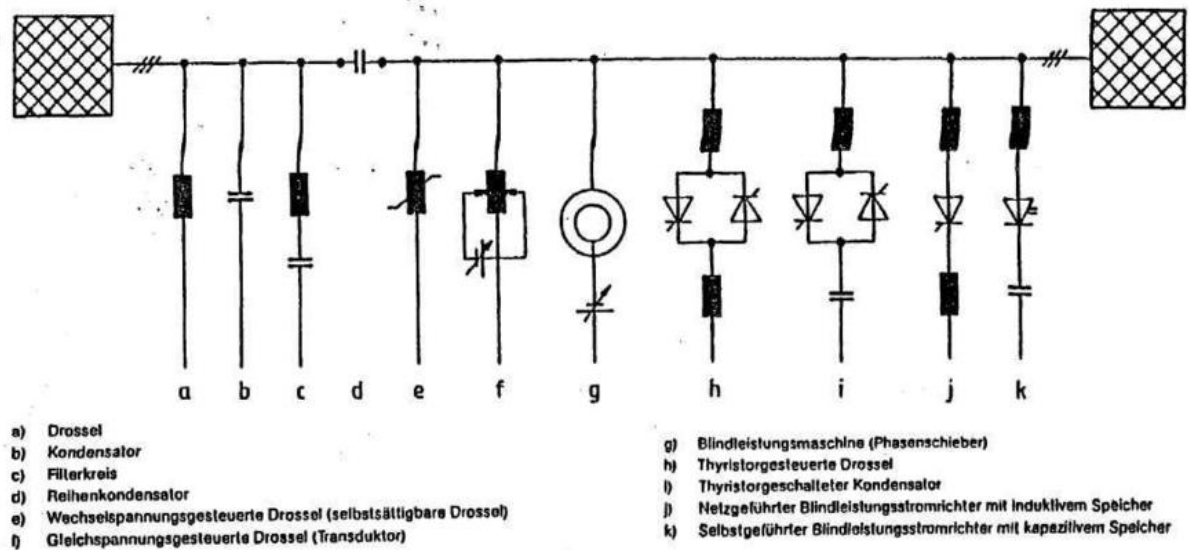


fig 14: Different methods of reactive power generation

- | | |
|--------------------------|--------------------|
| 1 - Air core reactor | 4 - Filter circuit |
| 2 - Thyristor controller | 5 - TCR |
| 3 - Control unit | 6 - arc furnace |

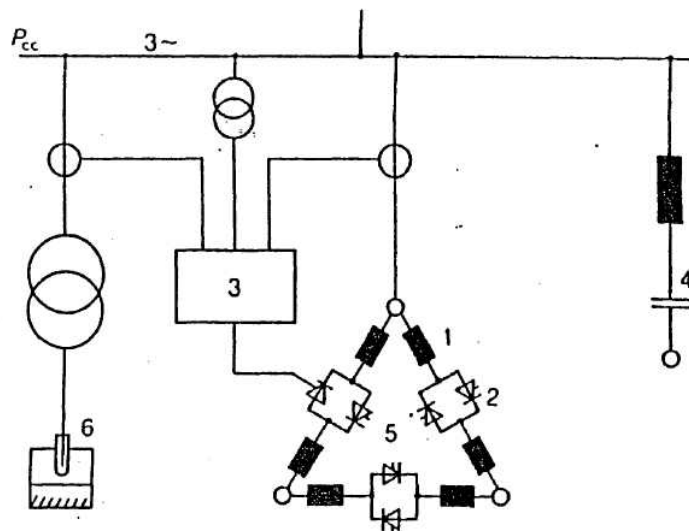


fig 15: Basic arrangement of an SVC, consisting of TCR and Filter Circuits

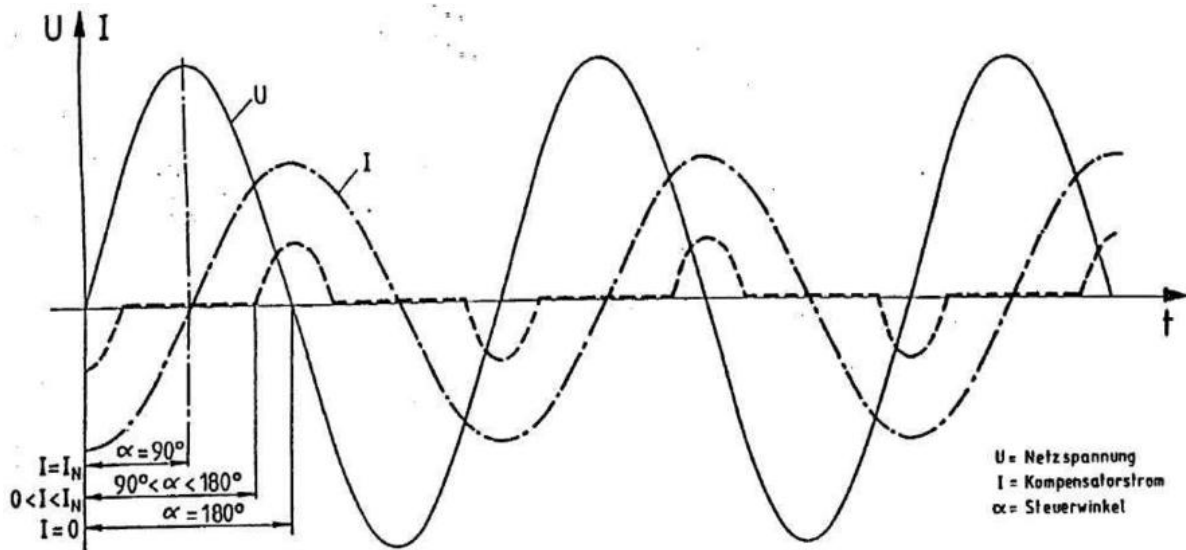


Fig 16: Current and voltage of a thyristor controlled reactor for different firing angles

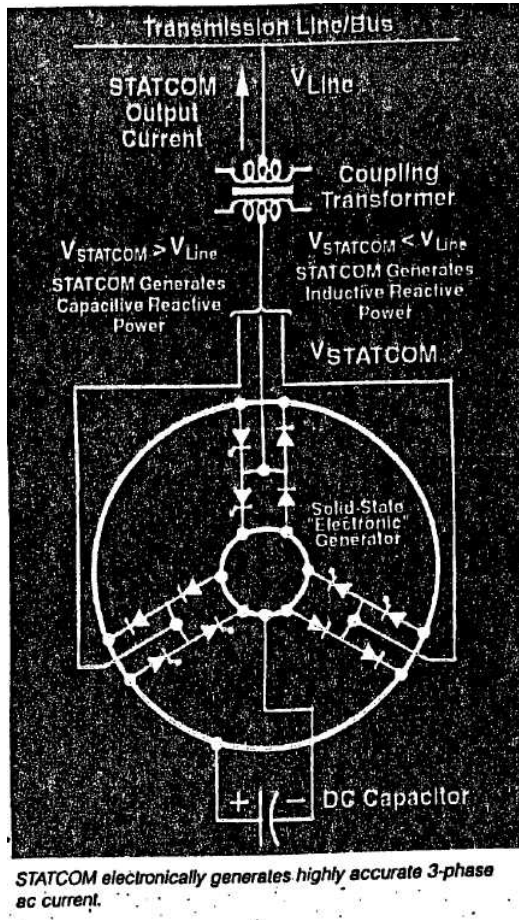


fig 17: Statcom installation by Siemens-Westinghouse

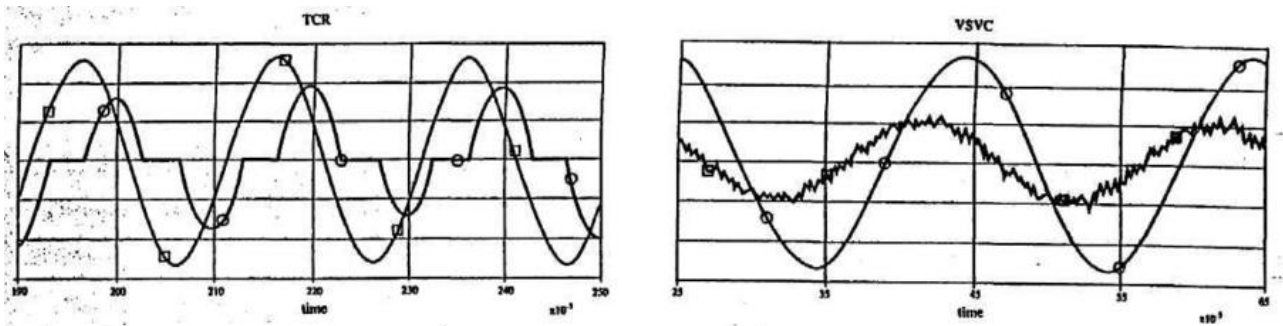
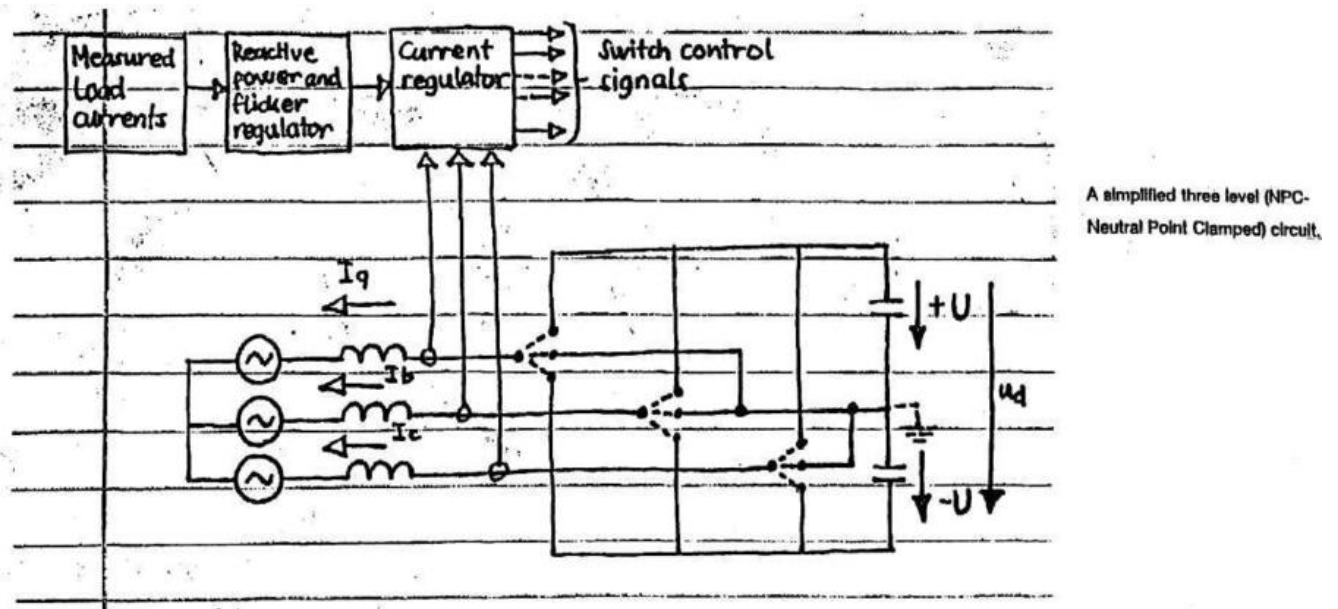


fig 18: SVC light by ABB, Comparison of current and voltage in a classic TCR with a VSVC

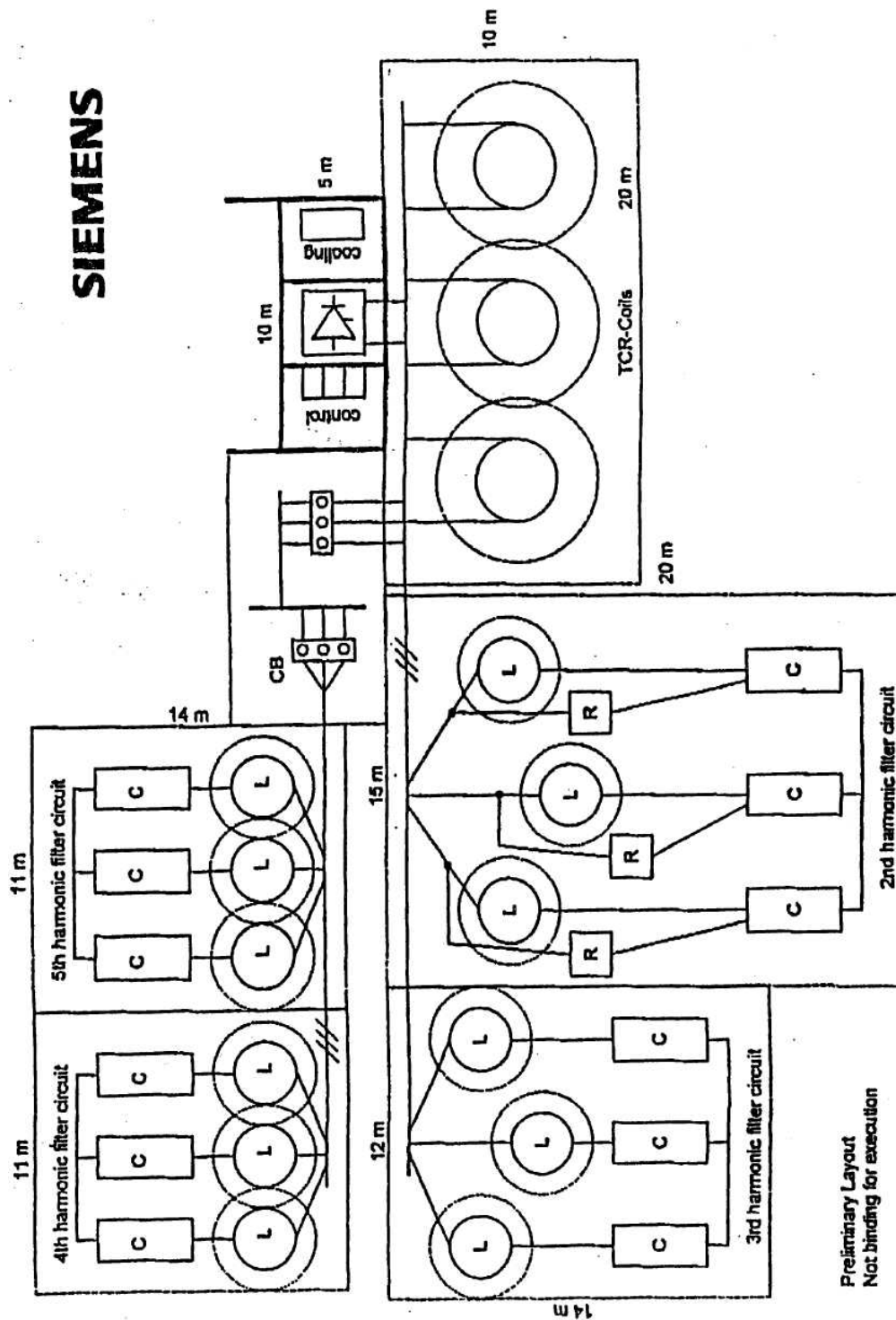


fig 19: Arrangement of an SVC

ABB Power Systems

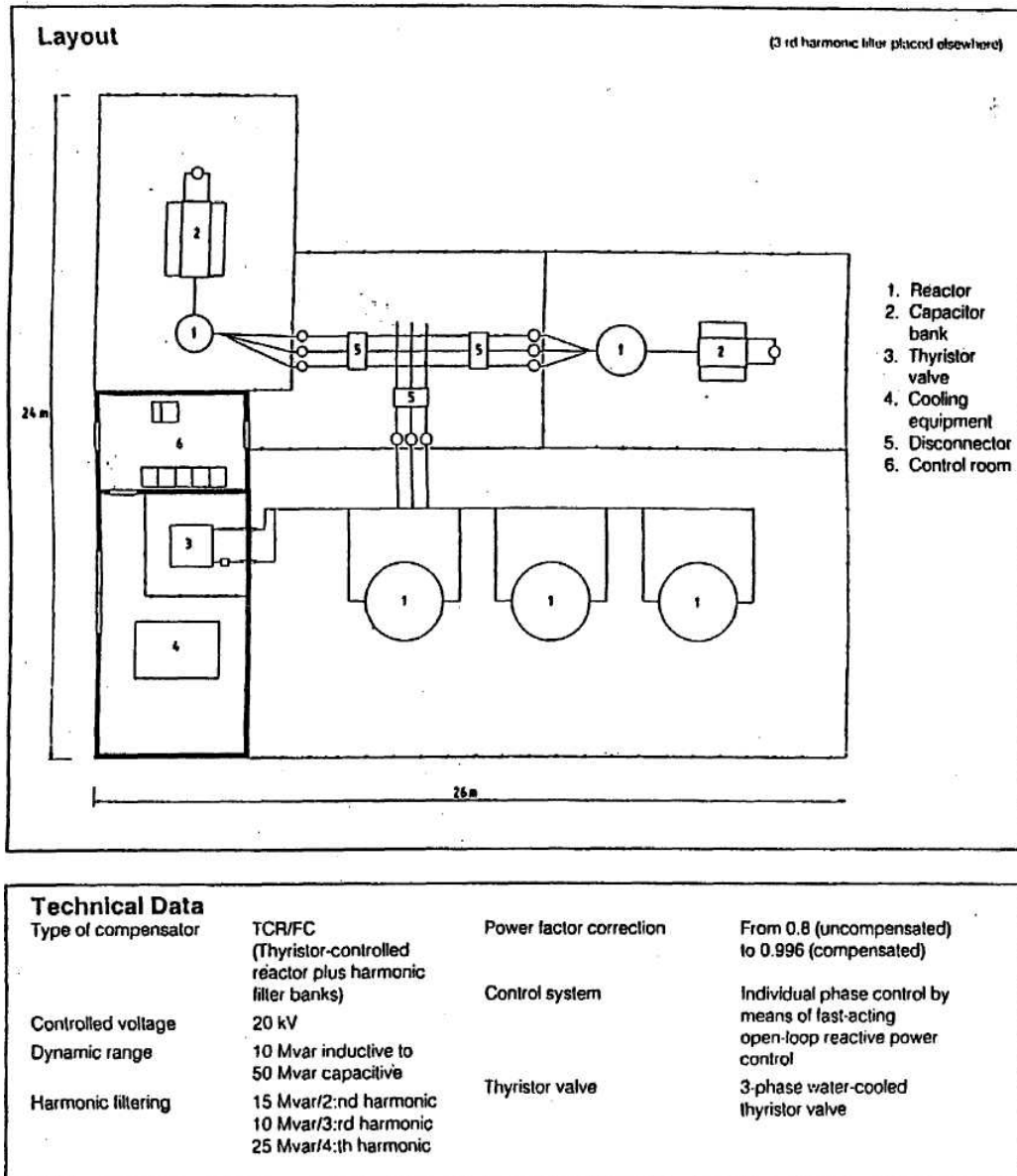


fig 20: Arrangement of an SVC



International Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Electric Principles of DC Furnaces

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Electric Principles of DC Furnaces

1. Historical Development
2. Layout Concept
3. Rectification
4. Closed-loop Voltage and Current Control
5. Arc Deflection
6. Industrial Importance
7. Considerations for Decision-Making

Prof. Dr.-Ing. Klaus Krüger
Institute of Automation Technology
Helmut-Schmidt-University/University of German Armed Forces Hamburg

14.09.2008

Electrical Engineering of Arc Furnaces

1

Historical Development

1880

William Siemens presents the principle of the DC arc furnace.

1905

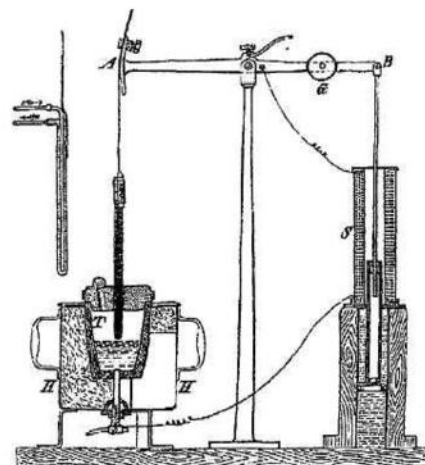
Start of industrial steel production with electric arc furnaces, using AC-EAF.

1982

First DC-EAF for industrial steel production (6 MW, 12 t).

1996

Height of the DC-EAF technology, DC-EAF reaches capacity of the AC-EAF.



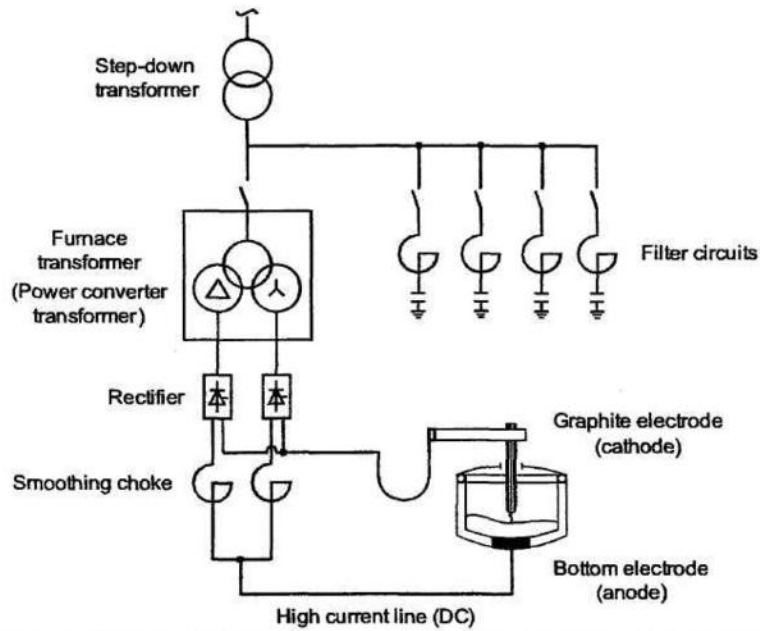
DC Electric Arc Furnace
William Siemens 1880

14.09.2008

1. Historical Development

2

Electrical Energy Supply

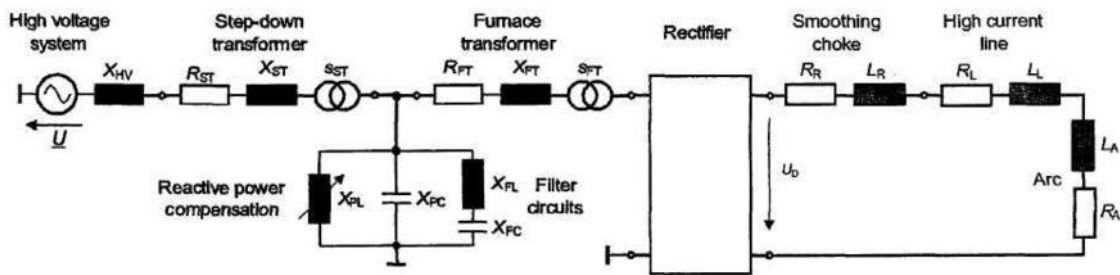


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2. Layout Concept

3

Network Topology

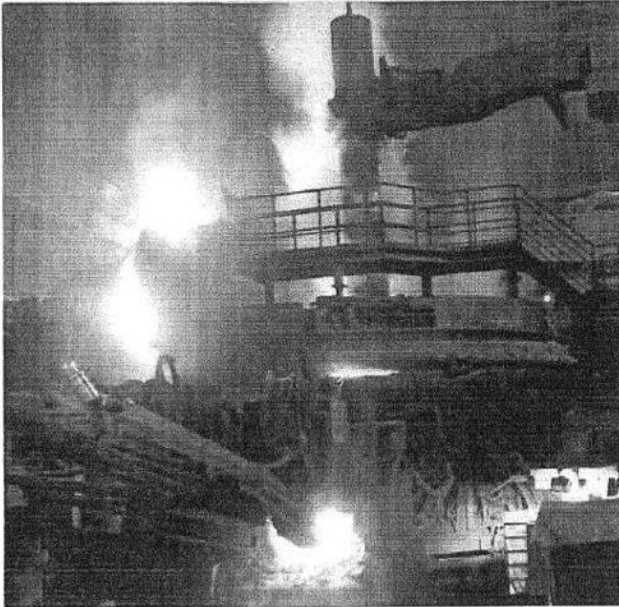


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2. Layout Concept

4

Arc Furnace in Operation



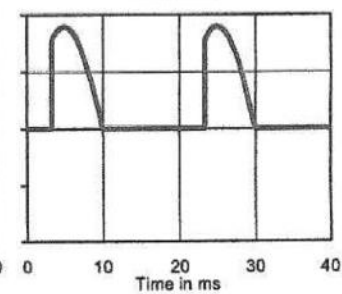
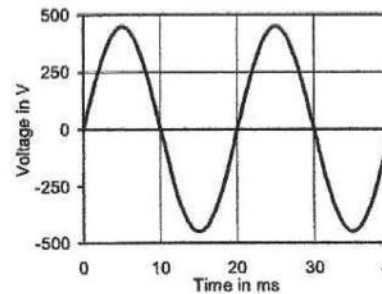
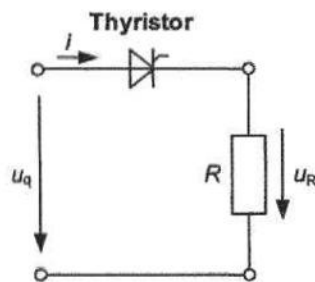
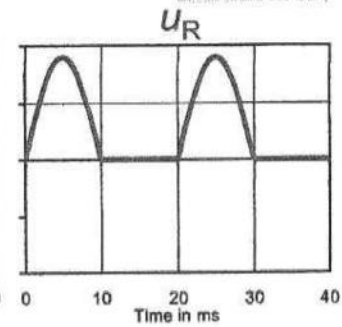
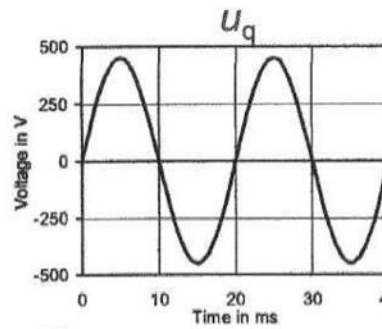
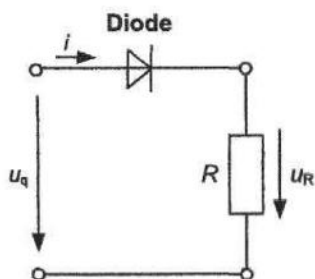
DC Electric Arc Furnace
130 t, 130 MVA

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2. Layout Concept

5

One-Way Rectifier

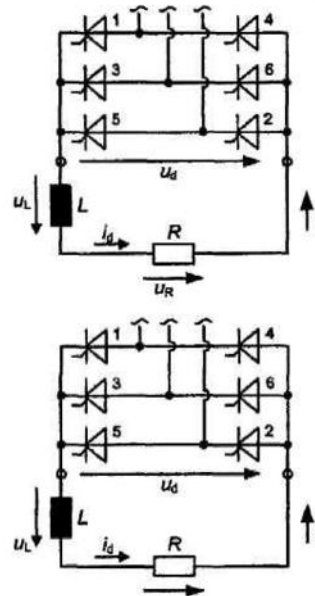
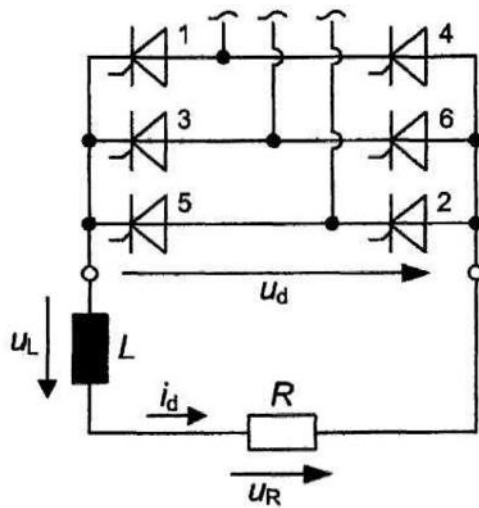


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3. Rectification

6

Three-Phase Bridge Rectifier (6 Pulse)

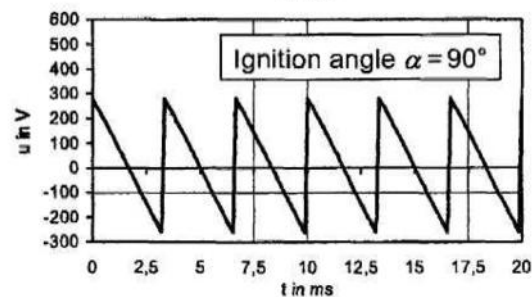
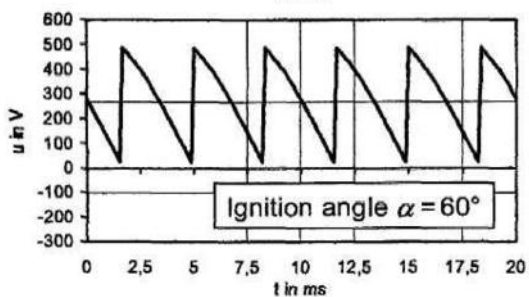
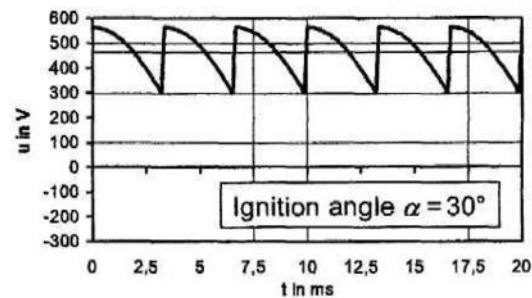
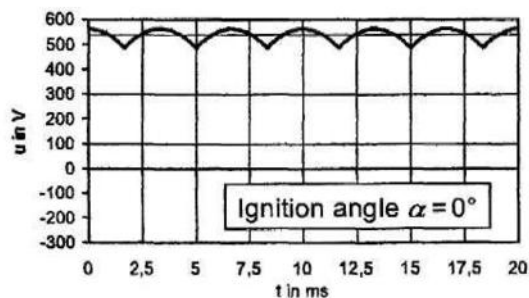


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3. Rectification

7

Three-Phase Bridge Rectifier (6 Pulse)

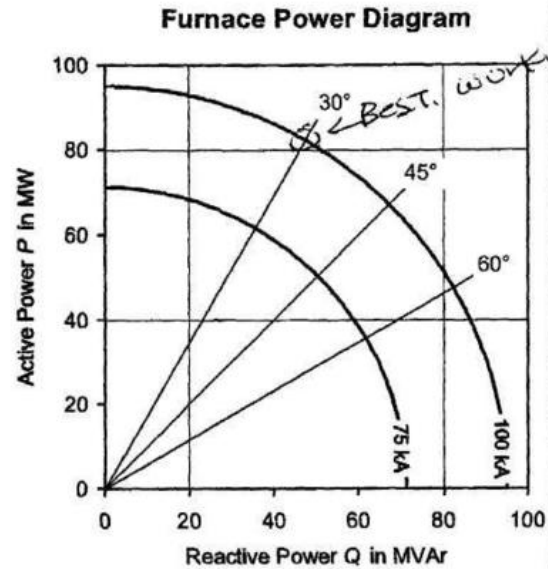
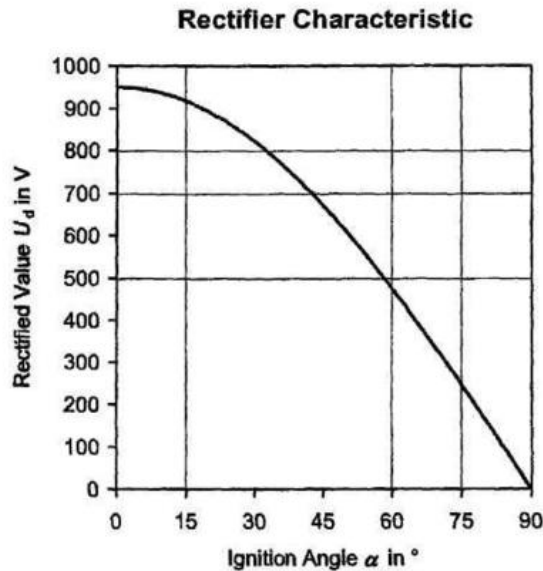


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3. Rectification

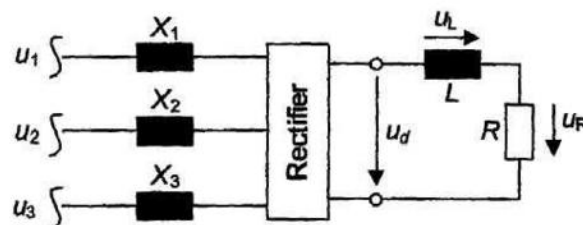
8

Ideal Characteristic Curves

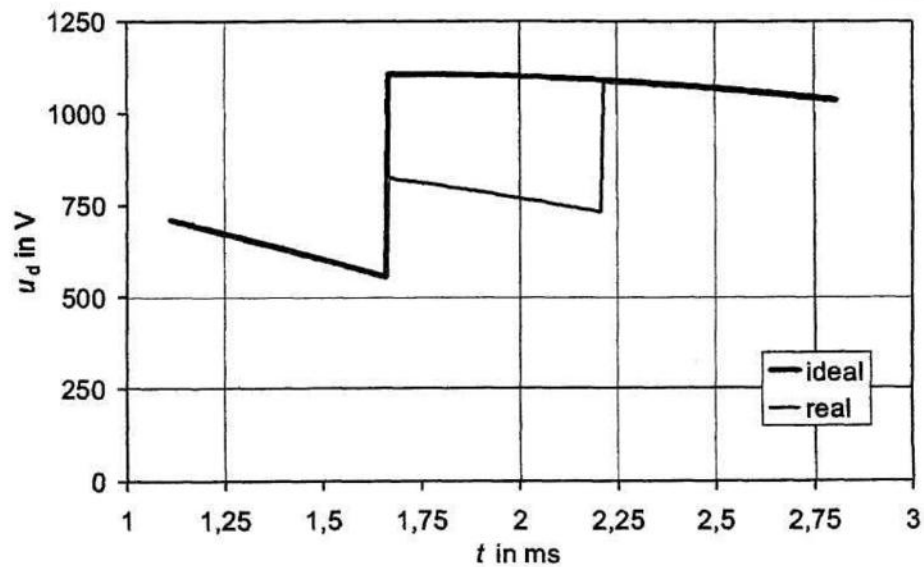


Real Characteristic Curves

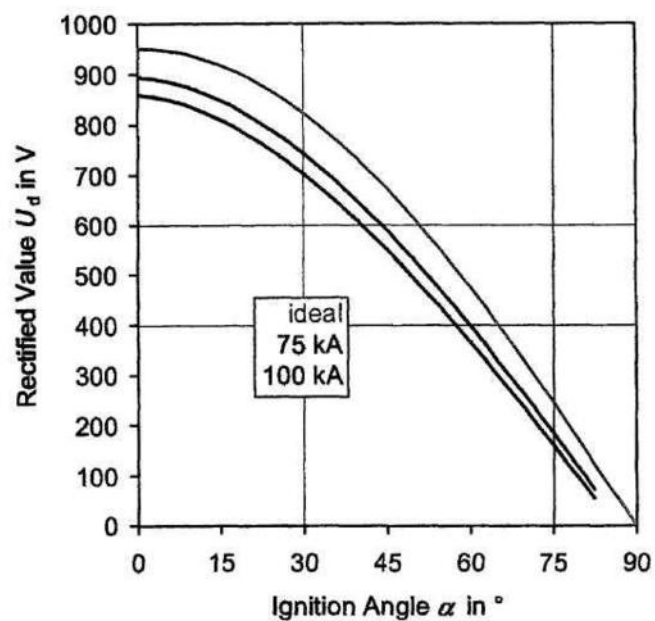
- Voltage drop at the network reactances
- Extinction of the arc at small voltages
- Commutation process



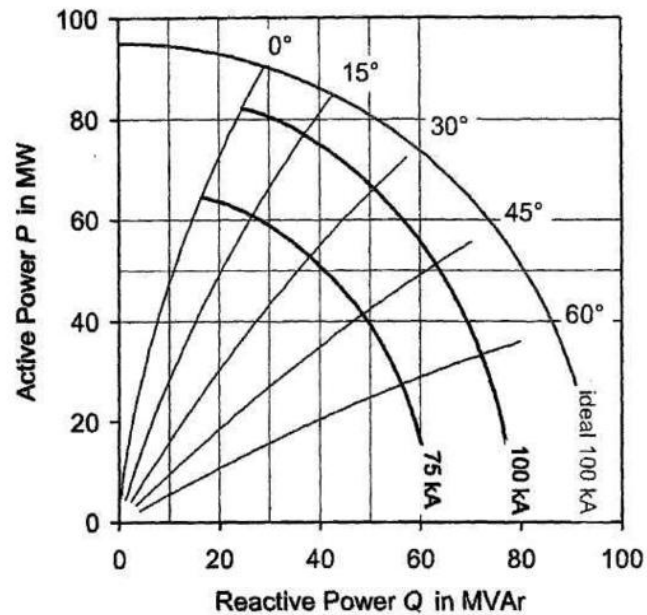
Commutation Process



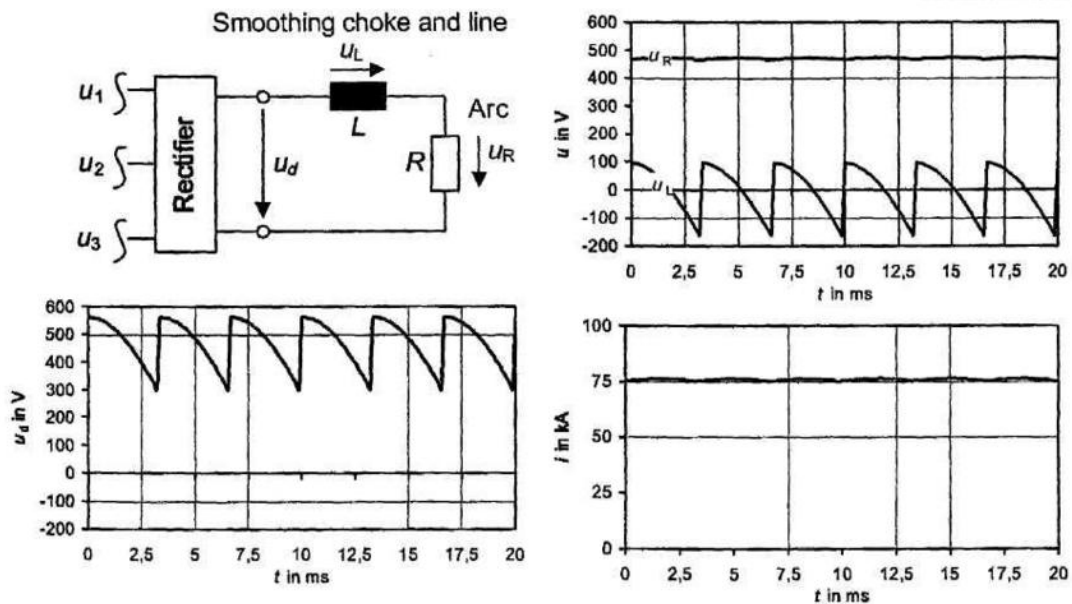
Real Rectifier Characteristic



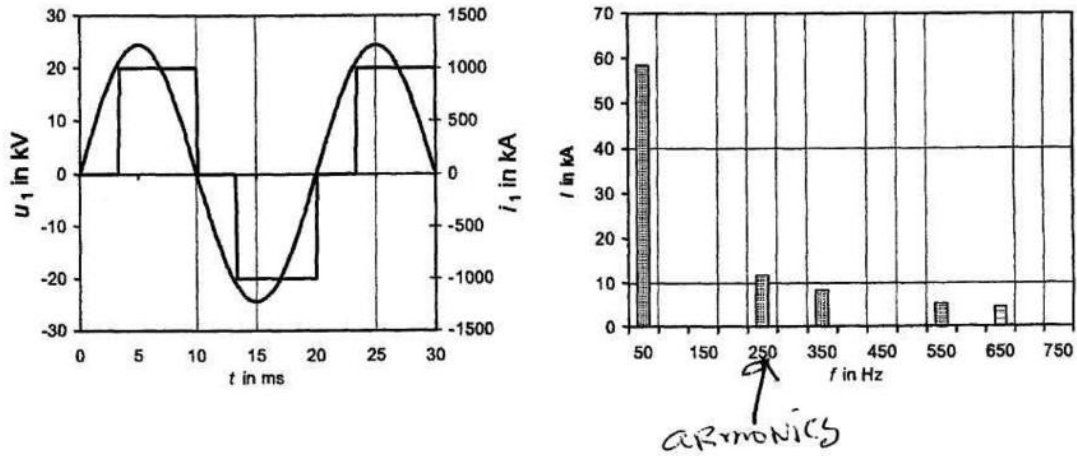
Real Furnace Power Diagram



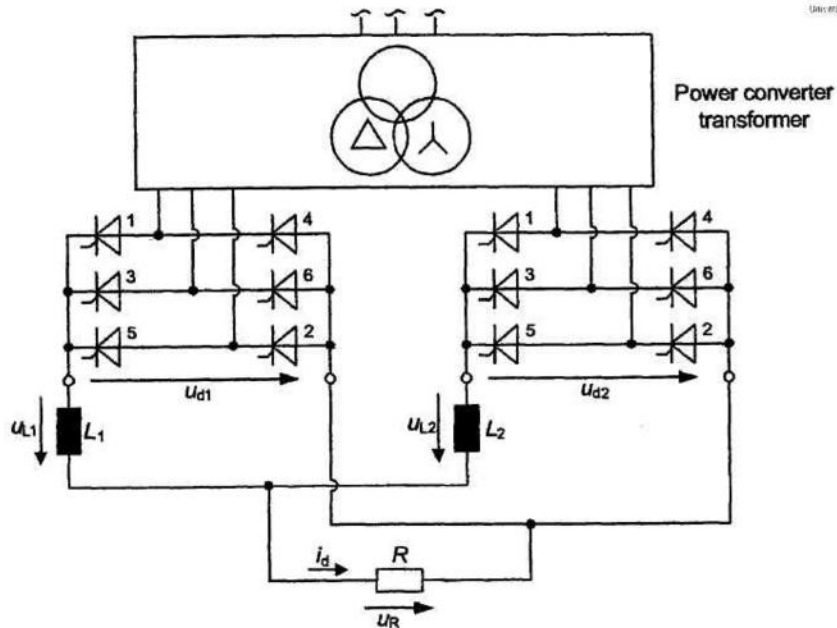
Current Shape (DC Line, $\alpha = 30^\circ$)



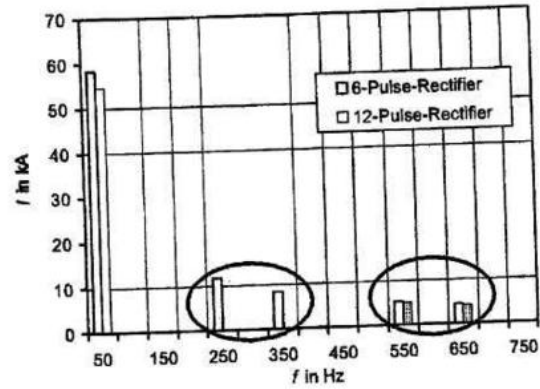
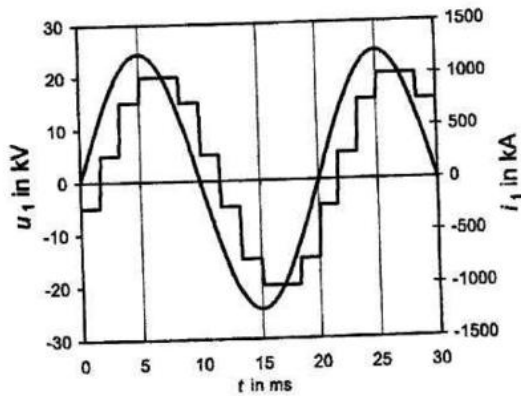
Current Shape (AC Line, 6 Pulse, $\alpha = 30^\circ$)



12-Pulse Three-Phase Bridge Rectifier



Current Shape (AC Line, 12 Pulse, «=30)

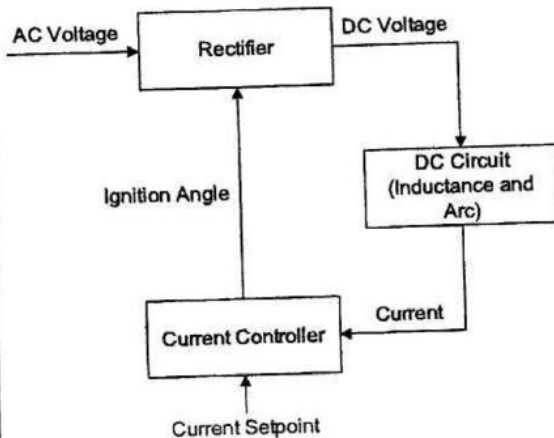


3. Rectification

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Current Control

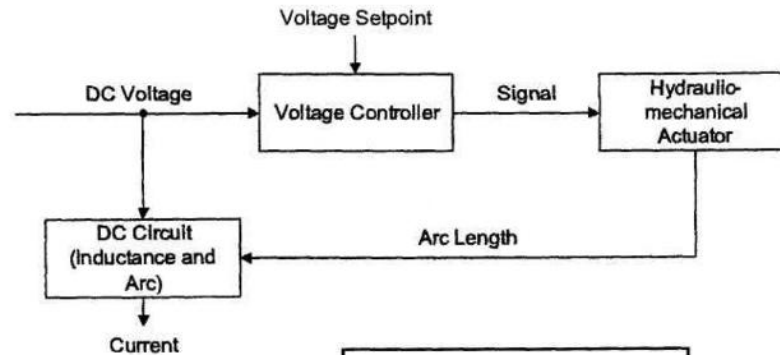


4. Closed-loop Voltage and Current Control

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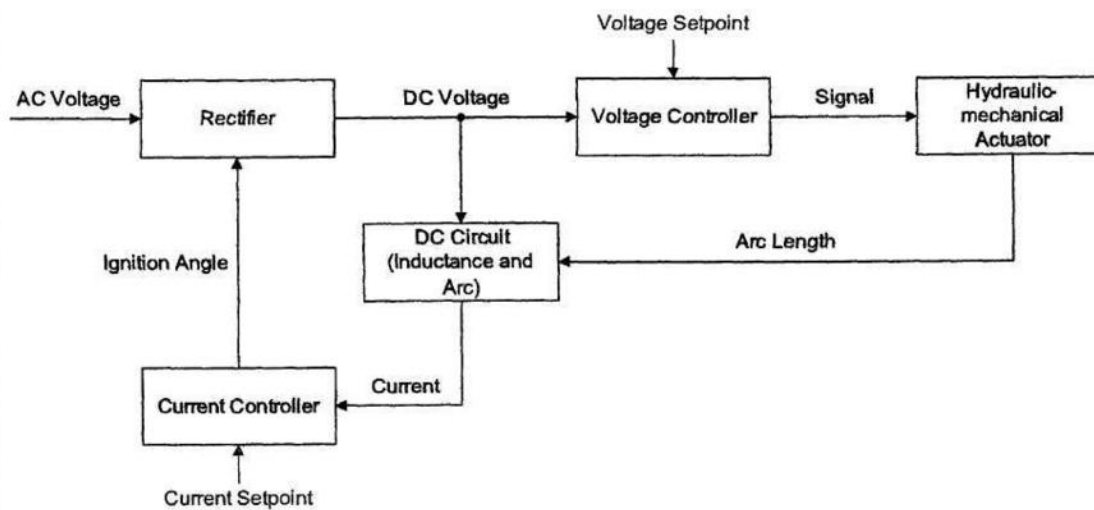
Voltage Control



Attention:

The arc field strength is not a constant parameter, $E = 1\text{V/mm}$ is not valid generally!

Coupled Control Loops



Current Control

- Typically realised as PI-controller
- Averaging of actual current value
- Time constants in the range of 20 ms

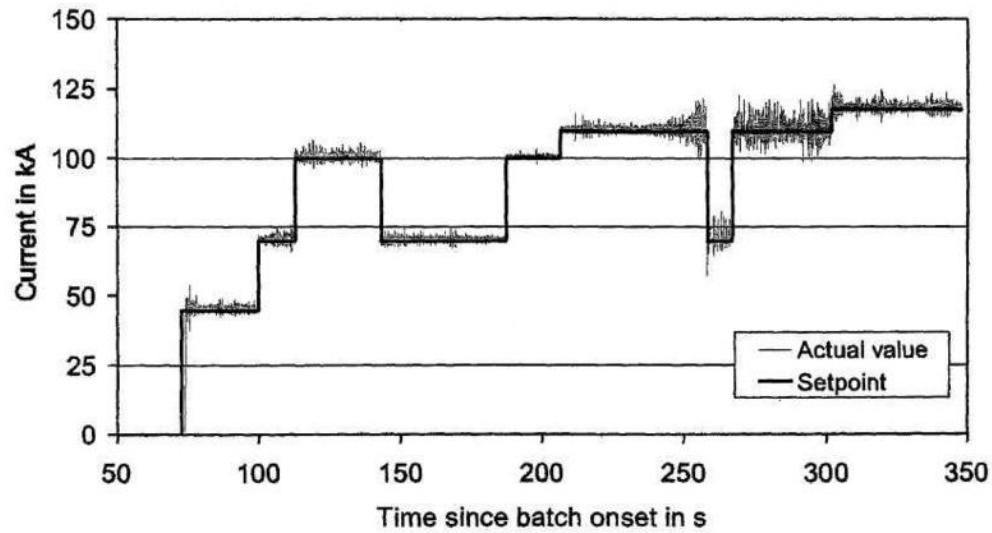
⇒ **Fast control**

Voltage Control

- Typically realised as P-controller
- Hydraulic actuator shows integrating behaviour
- Averaging of actual voltage value (current control presents a significant disturbance)
- Time constants in the range of 200 ms

⇒ **Slower Control**

Real Current Run (100 ms Averaging)



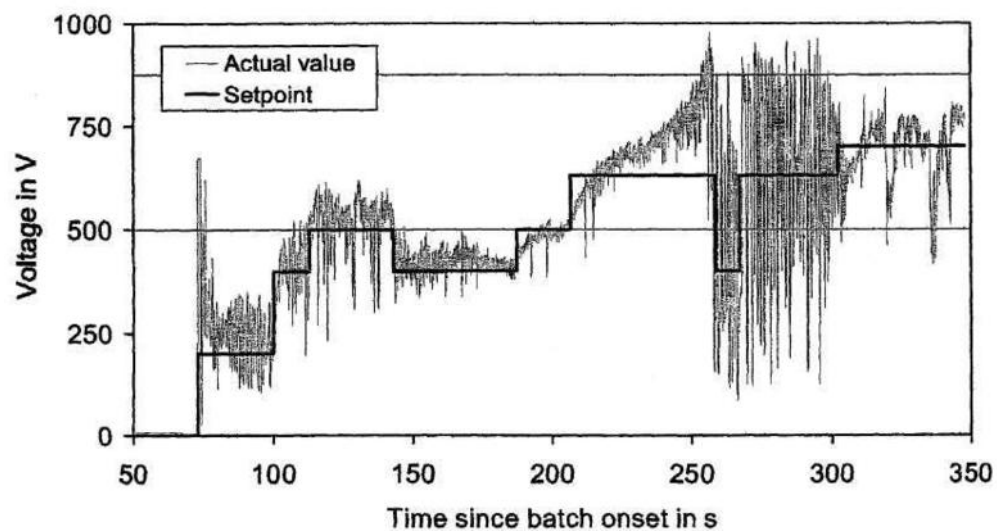
8th European Electric Steelmaking Conference, Birmingham, 2005

14.09.2006

4. Closed-loop Voltage and Current Control

23

Real Voltage Run (100 ms Averaging)



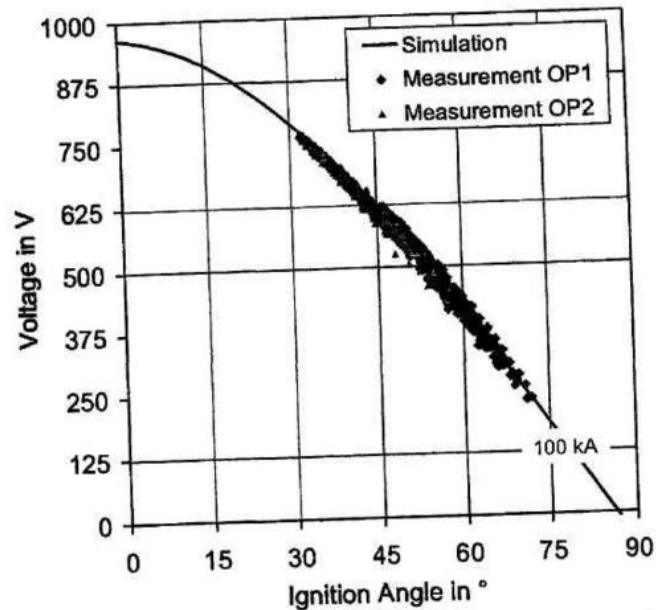
8th European Electric Steelmaking Conference, Birmingham, 2005

14.09.2006

4. Closed-loop Voltage and Current Control

24

Voltage Operating Point (100 ms Averaging)



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4. Closed-loop Voltage and Current Control

25

Innovative Voltage Control

- Suitable averaging time
- Avoidance of unnecessary electrode movements by applying an inactive neutral range
- Feedback of the real electrode movement
- Reaction to scrap collapses, detection based on the current run
- Consideration of the non-linear arc field strength

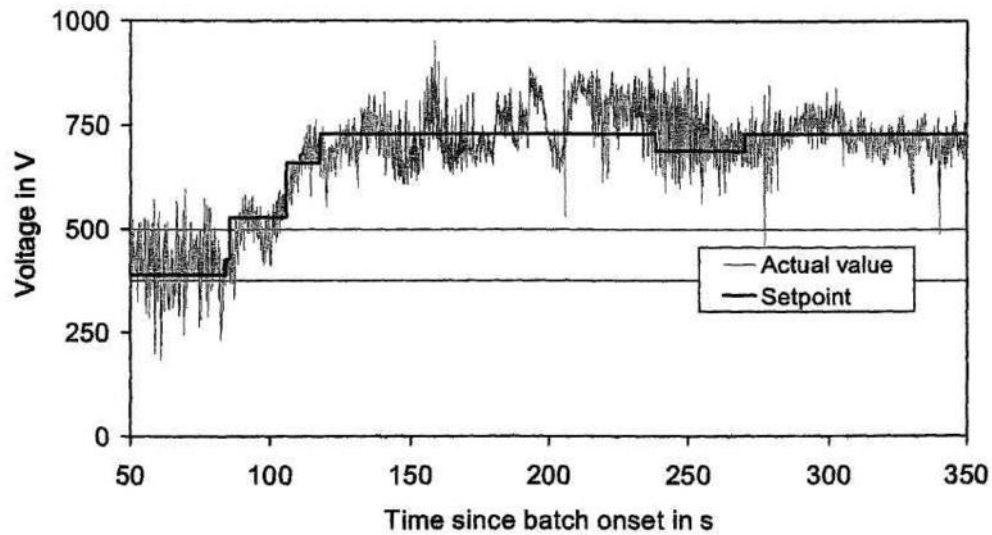
GMH, VDEh-Unterausschuss, 29.09.05

14.09.2006

4. Closed-loop Voltage and Current Control

26

Optimized Voltage Control



GMH, VDEh-Unterausschuss, 29.09.05

14.09.2008

4. Closed-loop Voltage and Current Control

27

Lorentz Force

Within a magnetic field, any electrical load in motion and any current-carrying conductor is effected by a force, the so called Lorentz force.

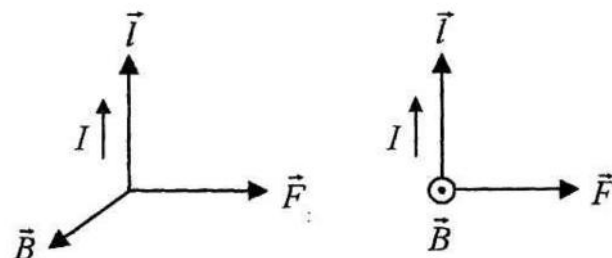
$$\vec{F} = I \cdot (\vec{l} \times \vec{B})$$

$\vec{F}$ Force onto the conductor

$\vec{l}$ Line length (direction of current flow)

I Current

$\vec{B}$ Magnetic flux density



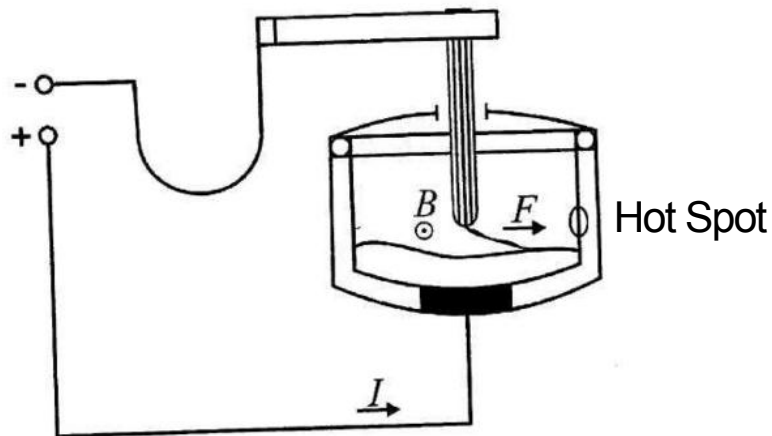
Right-Hand-Rule, Screw-Rule

14.09.2008

5. Arc Deflection

28

DC Supply Line without Adaptation



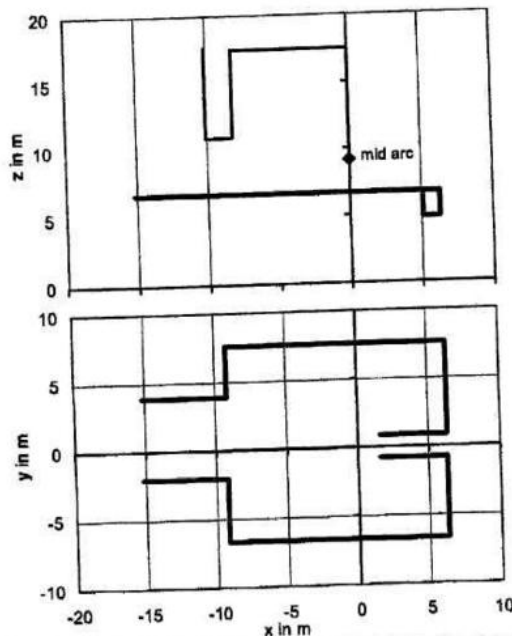
DC supply line in the form of simple loop
 $\Rightarrow$ Arc deflection
 $\Rightarrow$ Hot spot and unsymmetrical melting down

5. Arc Deflection

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Optimized DC Supply Line



Optimised supply line

- $\Rightarrow$ No magnetic field within the area of the arc
- $\Rightarrow$ No arc deflection
- $\Rightarrow$ Very symmetrical melting down

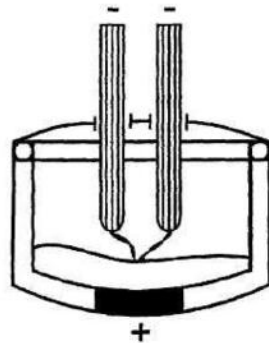
VAI Fuchs

5. Arc Deflection

14.09.2006

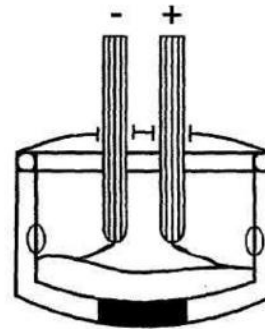
30

Furnaces with two Electrodes



Both electrodes used as Cathode

- Arcs attract each other
- Hardly suitable for scrap melting
- Suitable for continuous DRI melting



One used as cathode, one as anode

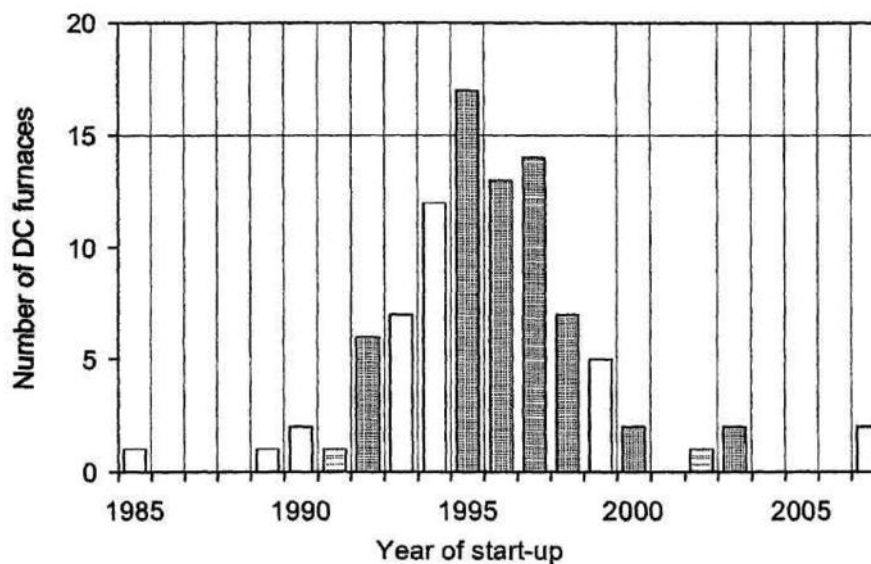
- Arcs repel each other
- Two hot spots
- No bottom anode required
- High graphite consumption

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5. Arc Deflection

31

DC Plants (more than 60 t, still in operation)



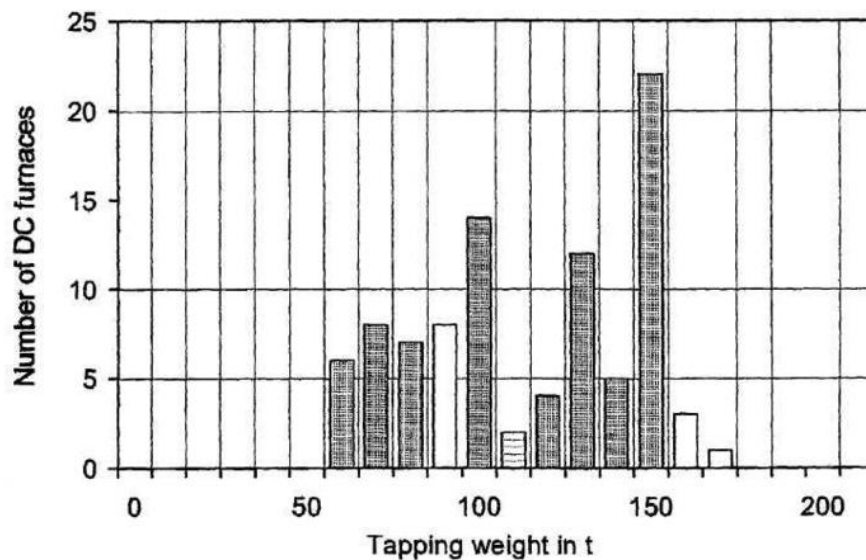
VDEh

14.09.2006

6. Industrial Importance

32

Operating DC Arc Furnaces (more than 60 t)



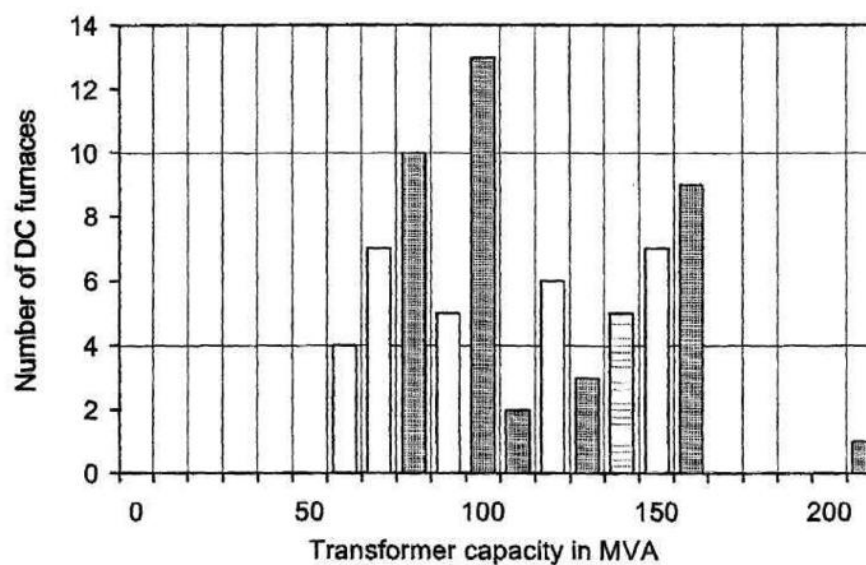
VDEh

14.09.2006

6. Industrial Importance

33

Operating DC Arc Furnaces (more than 60 t)



VDEh

14.09.2006

6. Industrial Importance

34

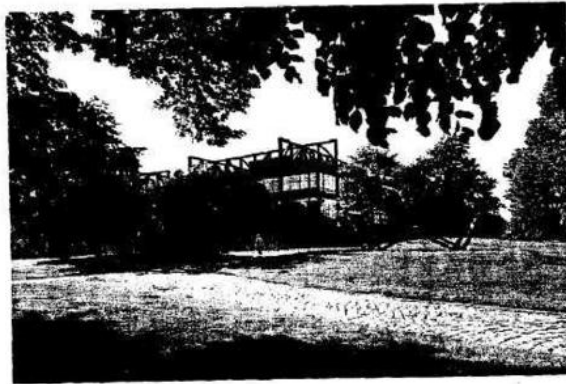
General Advantages of the DC Arc Furnace

- **Concentric energy source**
 - ⇒ Symmetrical melting down
 - ⇒ Reduced thermal losses
- **Continuously burning arc using the graphite electrode as a cathode**
 - ⇒ Lower graphite consumption
 - ⇒ More stable arc
- **Fast control allows for almost constant current**
 - ⇒ Less network disturbances
 - ⇒ Operation at weak networks is possible
 - ⇒ Reactive power compensation may be dispensable
- **No skin effect in the high current lines (DC)**
 - ⇒ Lower ohmic losses

General Disadvantages of the DC Arc Furnace

- **Rectifier required**
 - ⇒ Higher investment expenditure
- **Bottom electrode required**
 - ⇒ Higher maintenance effort
- **Just one arc**
 - ⇒ High voltage and current required
 - ⇒ Longer arc may cause higher thermal losses
 - ⇒ High current requires bigger electrode diameter
- **Rectification causes harmonics in the network**
 - ⇒ Filter circuit may be required
- **Possible arc deflection through external magnetic field**
 - ⇒ Where appropriate unsymmetrical melting down

Contact



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international Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Static Power Converters for DC Arc Furnaces and it's Network Disturbances

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info@steel-academv.com * www.steel-academv.com

Static Power Converters for DC Arc Furnaces and their Network Disturbances

Prof. Dr.-Ing. D. Arlt

Symposium "Electrical Engineering of Arc Furnaces"

Prof Dr.-Ing. D. Arlt
University of applied Sciences Duesseldorf, D-40474 Duisseldorf, Josef-Gockeln. Str. 9
Tel: 0172 260 6642, Fax: 02151 389776, e-mail: arlt@fh-duesseldorf.de

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0	Content	2
1	Introduction	3
2	Power semiconductors and power converters	4
2.1	Power semiconductors	4
2.2	Power converter circuits	4
2.2.1	The classic B6 bridge	4
2.2.2	Three phase bridge circuits with phase shifting control	7
2.2.3	Three phase bridge circuits with free wheeling diodes	8
2.2.4	Chopper circuits	9
3	Network disturbances	10
3.1	Flicker	10
3.2	Harmonics	11
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1 Introduction

Although the idea to built arc furnaces as DC furnaces is very old, the breakthrough of this technology came only some years ago. The reason is that the progress in development of powerful power semiconductors made it possible to verify the theoretical knowledge. There are many possibilities to built power converters, but only a few of them are able to fulfil the requirements given by an operating arc furnace.

In this contribution, the power converter circuits, which are currently used for arc furnace power supply are explained as well as some future developments.

A short chapter explains the different types of power semiconductors.

During the start up phase of the first DC furnaces, many people thought that the problems with network disturbances have been solved by using this new technology. Unfortunately this did not happen. Network disturbances - although a little bit different - are still a problem. Therefore a separate chapter deals with network disturbances and gives the differences to AC arc furnaces.

2 Power semiconductors and power converters

Power converters can be seen as special electrical circuits, which contain electric valves which are for one current direction either always conducting or always non conducting. Or they contain valves, which are - up to the choice of the operator - conducting or non conducting in one direction, while they are always non conducting in the other direction. Nowadays only semiconductors are used as valves, that are diodes, transistors, thyristors, GTO's and IGBT's.

To make it a little bit clearer: The idealised valves have in conducting direction a resistance of zero, i.e. a conducting connection in the equivalent circuit diagram, while the non conducting direction has the resistance infinite, i.e. are not present in the equivalent circuit diagram *III*.

In reality there is of course a difference in the characteristic features of idealised or real semiconductors.

2.1 Power semiconductors

In the information technique the transistor was in the beginning of the semiconductor age the most important element. In contrary to this in the power electronic the former mercury-vapour-converters have been replaced by thyristors. Later on there have also been developed transistors, which are able to carry higher currents at sufficiently high voltages.

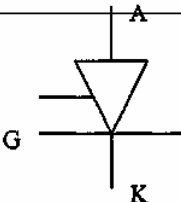
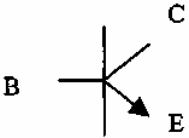
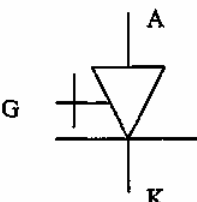
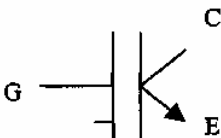
The further development of thyristors lead to GTO's and as the latest new element of semiconductors further development of transistors lead to IGBT's. *Table 1* is summing up the elements and their characteristic features.

2.2 Power converter circuits

There are different possibilities to use semiconductors in power converters and to control them. But only a few of them are suitable for DC furnace rectifiers.

2.2.1 The classic B6 bridge

For nearly all high power converters the classic B6 bridge is used. The bridge is a combination of two 3-pulse circuits with neutral and consists of in total 6 thyristors and a ripple filter choke. In case of non controlled valves and good smoothing of the DC current by the ripple filter choke, two valves are simultaneously conducting the current i for one third of a period, i.e. $t = 2T/3$. *Fig. 1* shows a classic B6 bridge as well as currents and voltages *III*.

Thyristor	2 Transistor
	
Up to 5000 V and 3000 A	Up to 1200 V and 500 A
Characteristic features: Very low driving power Only low switching frequency (<500 Hz) High blocking voltage High current only switch on possible (blocking only possible when the current is passing zero) - robust cell technology	Characteristic features: - high driving power necessary - Only low switching frequency (500 Hz) - limited blocking voltage - low current - switch on and off possible - Module technology
3 GTO (Gate Turn Off Thyristor)	4IGBT (Insulated Gate Bipolar Transistor)
	
Up to 4500 V and 3000 A	Up to 4500 V and 1200 A
Characteristic features: Higher driving power Only low switching frequency (<500 Hz) High blocking voltage High current switch on and off possible robust cell technology	Characteristic features: - low driving power - high switching frequency (some kHz) - High blocking voltage - High current - switch on and off possible - Module technology
Table 1: Characteristic features of different semiconductor elements	

With the rms value three phase voltage U the direct voltage U_{di} in fig 1 is the mean value of the so-called ideal no-load direct voltage u_d :

$$U_{di} = \frac{3}{\pi} \cdot \sqrt{2} \cdot U \quad (1)$$

The direct voltage at the load is depending on the firing angle α . This angle expresses the time delay between the natural firing point and the chosen firing point.

$$U_{di\alpha} = U_{di} \cdot \cos \alpha \quad (2)$$

The relation between RMS value of the phase current I and the rated direct current I_{dN} is:

$$I = \frac{\sqrt{2}}{\sqrt{3}} \cdot I_{dN} = 0.8165 \cdot I_{dN} \quad (3)$$

The fundamental current I_1 is:

$$I_1 = \frac{\sqrt{6}}{\pi} \cdot I_{dN} \quad (4)$$

the power factor can be calculated as follows:

$$\lambda = \frac{3}{\pi} \cdot \cos \alpha \quad (5)$$

the consequence of the above equation is that these circuits are consuming a lot of reactive power, if they are operated e.g. with setpoints for the firing angle of 40° , i.e. $X = 0.73$.

The above described Graetz bridge is a so-called 6-pulse bridge circuit. The majority of all DC furnaces however is equipped with two B6 bridge circuits in parallel connection. Electrically the voltages on the AC sides are phase shifted by 30° , thus giving a 12-pulse operation. One way to realise this is e.g. to use a converter transformer with two secondary windings. One winding is delta connected while the other is Y connected. The advantage of the 12-pulse bridge circuits is a reduced amount of generated harmonics. Fig. 2 shows a 12-

pulse bridge circuit (top). Below it can be seen a 12-pulse interphase transformer connection, which are used for plasma furnaces or for electrochemical installations.

12-pulse bridge circuits show a slightly smaller ratio of phase current to direct current than 6-pulse bridge circuits. Equation (3) changes to:

$$I = \frac{1 + \sqrt{3}}{2} = 0.7887$$

$$I_{dN} = 2\sqrt{3}$$

The question is now how the circle diagram of a DC furnaces looks like, which is using a classic bridge circuit?

In contrary to an AC furnace the DC furnace allows two ways of control. This shall be shown using *fig 3*. The so-called voltage controller is responsible for the electrode position. It keeps the electrode in a position that the arc voltage is in the average in it's desired value so that the furnaces operator gets the desired power input. This part of the controller corresponds to the controller of an AC furnace. The second part of the controller, the so-called current controller is extremely fast - compared with the voltage controller - and thus it's purpose is to keep the furnaces current nearly constant by permanent adjustment of the firing angles.

Fig. 4 shows the circle diagram of a DC furnace, which is controlled as above described. The basic difference to the circle diagram of an AC furnace is easy to detect. The circle diagram of an AC furnace consists of circles representing constant voltage while the circles in a circle diagram of a DC furnace are representing constant current and are therefore approximately circles of constant apparent power. The AC furnace has a fixed secondary voltage, which can be adjusted by a very slowly acting onload tap changer. The current can only be controlled by the position of the electrode arms. The DC furnace does not have this limitation due to the extremely fast firing angle control. It is possible to control the current in such a way that there are really circles of constant current.

Fig. 5 shall prove, how "perfect" such a controller works. The figure shows power measurements from a great DC furnace in Belgium. Each dot is a mean rms. value of 480 ms. Three sections of the melt cycle are shown: Boring, melting 1 with slightly reduced power and melting 2 with full power. I can be seen that

there are really circuits of constant current and constant apparent power respectively
the values of the active power have only small deviations from the desired values
the power factor is very low because it is one of the first great DC furnaces and therefore
was operated with a large firing angle to get a better controlability.

2.2.2 Three phase bridge circuits with phase shifting control

The further step in the development of the power supply for DC furnaces are three phase bridge circuits with phase shifting. This technology is e.g. used by Ansaldo and with special

control of the half-bridges by Siemens /41/. *Fig. 6 (top)* shows a bridge circuit which consists of two half-bridges. The difference to the classic bridge can only be found in the control itself. The power of the converter is split to the two half-bridges /1/, /2/.

Normally the bridge circuit is controlled in such a way that one half-bridge is permanently fully fired and acting as a rectifier, i.e. $\alpha = 0^\circ$, while the other half-bridge is fired according to the control task. The result is that in this case only one half-bridge needs phase control reactive power and thus the reactive power consumption is reduced drastically.

Fig. 6 (bottom) shows the function of the reactive power without and with phase shifting control. The borderlines are given if there is a maximum difference in firing angle setpoints, i.e. $\alpha_1 = 0^\circ$ and $\alpha_2 = 90^\circ$ (curve 2) or both half-bridges are fired with the same firing angle, i.e. $\alpha_1 = \alpha_2$ (curve 1). In the second case operation is according to the classic bridge control. *Fig. 7* shows the voltages for two cases: $\alpha_1 = 90^\circ$, $\alpha_2 = 0^\circ$ and $\alpha_1 = 30^\circ$, $\alpha_2 = 0^\circ$ respectively.

Siemens developed a special highly dynamic digital control, which works in such a way that both half-bridges are controlled but with different firing angles ($\alpha_i \neq 0:2$). See *fig. 7a*. The reactive power consumption is constant as long as the setpoint is on the horizontal line of the circle diagram (*fig. 7b*). Even in the case of electrode short circuit, the consumption of reactive power remains constant. This could be proved by measurements at an existing furnace /14/.

2.2.3 Three phase bridge circuits with free wheeling diodes

Another way to reduce the consumption of reactive power is the use of an additional free wheeling diode. *Fig. 8* shows as an example a M3 circuit with free wheeling diode (top) and the voltage and currents (bottom) *III* in the circuit. The free wheeling diode is taking the current in case that the instantaneous value of the voltage becomes zero and is conducting the current until the main valve which is following in the cycle gets a firing pulse. *Fig. 9* shows the function of the reactive power. It can be seen that the reactive power does not increase any longer if the firing angles go above 30° . The dotted line is the function of the reactive power without free wheeling diode.

Cegelec /5/ is using a Graetz bridge with two free wheeling diodes according to *fig. 10*. It should be mentioned that it is necessary to have access to the converter transformer secondary neutrals. That means a converter transformer which feeds a classic bridge cannot be used as spare. In addition to the free wheeling diodes Cegelec uses phase shifting control. The result is a circle diagram as shown in *fig. 11*. The area of operation will be within the bolt lines which are the result of using free wheeling diodes and shift control. It should be noted that this area is an *area of constant current*. (The classic bridge has *lines of constant current*).

In the meantime several furnaces are equipped with bridges with free wheeling diodes and shift control. *Fig. 12* shows the results of power measurements at a 150t furnace with a transformer power of 140 MVA. The area of constant current can be clearly seen and looks very similar to the theoretical calculations of *fig. 11*. The reactive power consumption is

reduced, because the area of constant current is not identical with the circuits of constant apparent power. This leads to higher power factors compared with classic bridge.

2.2.4 Chopper circuits

A very interesting approach is coming from Robicon, a company located in Pittsburgh/USA /6/. They use very fast switching transistor chopper circuits or buck converters. The power of this circuits is already in the range of Megawatts due to the development of powerful IGBT's.

Fig. 12 shows an elementary chopper cell. If the IGBT is fired, there is a power flow from the capacitorbank to the load. If the IGBT is blocked the reactor forces a current through load and diode. Therefore the load current is nearly constant. Reactive power will not be consumed, because the chopper gets chopped direct current from the capacitor bank. And the capacitor bank gets active current via the rectifiers from the voltage source.

Real installations are consisting of several chopper units which are connected in parallel. Their firing signals are phase shifted. Due to the transformer and source reactance, there will be a certain reactive power consumption which cannot be avoided. Copper system are operating with power factors between 0,95 and 0,97.

Comparing chopper circuits with thyristor bridge circuits shows another advantage. IGBT's a much higher control speed, because they are not bound to the fundamental. That means that reactive power fluctuations in the range of the critical flicker frequencies can be nearly eliminated. The manufacturer states that he does not expect any flicker problem, if his technology is used for arc furnace power supply. He has already experiences with plasma furnaces and a fist arc furnace application is in the start up phase.

3 Network disturbances

The disturbances in supply network caused by DC arc furnaces are only in a limited way comparable with the disturbances caused by AC furnaces. Relatively similar are the flicker problems. Harmonics are converter typical, i.e. they are in a higher order range and non-symmetrical operation is not possible when three phase bridges are used.

3.1 Flicker

When the first DC furnaces started their operation everybody was convinced that one of the advantages of this type of furnaces would be a drastical reduction of the generated flicker. It seemed to be obvious because DC furnaces are controlled in such a way that the current is kept nearly constant even during scrap melting and that means nearly constant apparent power and small reactive power fluctuation. Reactive power fluctuations are causing voltage fluctuations in the supply network which are the reason for flicker. In contrary AC furnaces are operated on constant voltage taps with fluctuating currents and thus highly fluctuating reactive power.

Very brave writers forecasted a reduction of the flicker disturbances to 38% */11* and 50% */8* respectively. They compared AC and DC furnaces in a very theoretical way by taking into account comparable active power input, i.e. same setpoints for the furnace control. This gives indeed a possible ratio of fluctuations of reactive power of AC furnaces versus DC furnaces which seem to prove the above assumptions. *Fig 14* shows such a comparison */11*. However they did not take into account, that not only the absolute value of the reactive power fluctuation but also other factors like the frequency are important for the flicker generation.

Other writers compared high impedance furnaces with DC furnaces. Their conclusion was that due to the additional reactance the arcs of the AC furnace will burn more stable and the flicker of a comparable DC furnace will be only 70% smaller */9*. This estimation was more realistic and was proved later on by measurements */10*.

Fig. 15 shows measured Pst values of a great DC furnace. Only the periods of scrap melting of 100 consecutive heats are shown, separated in first and second baskets. One can see that the flicker caused by DC furnaces is not reproducible and that there is no difference between 1st and 2nd basket melting. This is very similar to AC furnace behaviour.

When free wheeling diodes are used, the reactive power consumption can be reduced and with additional phase shifting control the reactive power fluctuations can be minimised. Phase shifting control with individual firing angles for the half-bridges and highly dynamic control give similar results. Measurements could prove, that this causes a reduction of flicker to about 50% of the flicker caused by a 12-pulse bridge with classic control (taking of course into account the same inductivity of the ripple filter choke) */14*.

DC furnaces with choppers should give similar results.

3.2 Harmonics

Also DC furnaces are - like AC furnaces - generators for harmonics which they emit into the supply network. The generated harmonics of a DC furnace are depending on the type of converter circuit. If the classic Graetz bridge circuit without phase shifting is used for arc furnace supply, the harmonics can be calculated with reasonable results using the well known equations.

Under the precondition of ideal commutation and ideal smoothing the following harmonics will be generated:

$$V = k \cdot p \pm 1 \text{ with } k = 1, 2, 3, \text{ and } p \text{ as number of pulses} \quad (7)$$

The harmonic currents will be:

$$I_v = \frac{I_1}{v} \quad (8)$$

If 12-pulse converter circuits are used the harmonic current will theoretically be of the order 11, 13, 23, 25 etc. If the circuit is going back to 6-puls operation, e.g. in case one bridge is out of order, there will be additional 5, 7, 17 and 19. In real operation, the converter circuits do not commute ideal and the smoothing is not ideal. The firing angles are permanently changing. All this leads to a modulations of the generated harmonic spectrum.

Measurement proved that nearly all harmonics up to the order 25 are present. *Fig. 16* shows measured current harmonics of a great DC furnace. All even and odd harmonics are present. The converter is in 12-pulse operation, therefore number 11 and 13 are dominant. They are smaller than the theoretical calculated harmonics and it can be found that are becoming smaller if the furnace is operating more unsteady. This is a well known reaction of converters under such conditions called the "principle of the air mattress"

Fig. 17 shows a comparison of the harmonics generated by AC furnaces and by DC furnaces with 12-pulse converter circuits. The differences are obvious. The harmonics generated by AC furnaces are in the range of lower orders while the DC furnace has its dominant harmonics above order 10.

If the converter circuits are using free wheeling diodes and/or phase shifting control, they can generate harmonics of lower orders as well. A simple calculation is not possible.

3.3 Limitation of Network Disturbances

The flicker generation can be reduced by increasing the reactance of the DC reactors which are located in the DC circuit. ABB recommends this solution /11/. Because the reactors are in the high current system, there will be an increase of losses.

If there are still problems due to network disturbances, the only way of improvement is the installation of an SVC. The filter circuits have of course to be tuned to the specific converter harmonics. Nearly all important manufacturers have already supplied SVC's for DC furnaces. *Fig. 18* shows an example. The SVC plant was built in the USA and has to compensate two DC furnaces of 130 MVA transformer power each plus two ladle furnaces. Due to the 12-pulse converter circuits, the dominating harmonic is of order 11. Therefore one filter circuit is tuned to this harmonic and it is with 80 MVar the most powerful.

4 Conclusion

There are different possibilities to equip DC furnaces with converters. For the first generation, the classic Graetz bridge circuits with 12-pulse operation have been taken, because the controller could be taken from drive systems. These solution enabled sufficient furnace operation but the expected drastical reduction of flicker could not be realised. Therefore the next generation of furnaces is powered by converter circuits operating with reduced reactive power and minimised reactive power fluctuation. The latest approach is the use of chopper circuits, which have the advantage that the reactive power consumption is minimised. Due to the IGBT's very high switching frequency the reactive power fluctuation in the critical flicker frequency range can be nearly eliminated says the manufacturer.

Even if the flicker problem may be solved in the future the problems caused by harmonics will be still present, because they are generated by the converter circuits itself.

In a few cases DC furnaces which have to be compensated by a powerful SVC problems with the generation of interharmonics had to be solved /13/. The reasons for the presence of interharmonics have been as follows: Because of the great capacitive power of the SVC's there have been parallel resonances with the supply network in the range of the 2nd and 3rd harmonic. The result was an amplification of the interharmonics (e.g. 125 HZ) which are generated by the converter circuit especially if there is unsteady arcing in the furnace. *Fig. 19* shows the interharmonic amplification and *fig. 20* shows the result in the 220 kV supply network. This problem could e.g. be solved by a modification of the controller.

5 References

- /1/ G. Moltgen
Stromrichtertechnik
Siemens AG, Berlin und München 1983
- /2/ S. Salama
Vorlesungs-Script Fachhochschule
Düsseldorf, 1999
- /3/ Grundsätze für die Beurteilung von Netzrückwirkungen
3. überarbeitete Ausgabe 1992, VDEW
- /4/ J. Schnapperelle, W. Horger
A new control strategy for reducing flicker of electric arc furnaces
MPT International, Issue 8/97
- /5/ M. Wursteisen, J. Du Pare, C. Glinski
Converters with low disturbances for the electric power supply of DC furnaces
5th European Electric Steel Congress, June 19-23 (1995), Paris
- /6/ K.H. Stueker
Electric Arcs and Flicker
Robicon Pittsburgh / www.robicon.com/library/index.html
- /7/ B. Bowman
Performance comparison- AC vs DC furnaces: an Update
AISE, 1994 Spring Convention
- /8/ S.-E. Stenquist
The ABB DC Arc Furnace - Past, Present, Future
ABB DC Arc Furnace Conference, 1991, Penang, Malaysia
- /9/ N. Saito, I. Kobashi, M. Musuhi
Investigation and Analysis of Voltage Fluctuation in the DC Arc Furnace
XIIth UIE Congress, Montreal, June 1992
- /10/ A. Robert, M. Couvreur
Recent Experience of connection of big arc furnaces with reference to flicker level
UIEPQ-9430, 1994
- /11/ On the DC learning curve in Turkey
STEEL TIMES INTERNATIONAL November 1995
- /12/ Application note A02-0133E
ABB Support-Mediaservice, Tryckcentra AB, Vasteras 1993.2000+1000
- /13/ L. Tang, D. Mueller, D. Hall, M. Samotyj, J. Randolph
Analysis of DC Arc Furnace Operation and Flicker caused by 187 Hz Voltage Distortion
IEEE Transactions on Power Delivery, Vol. 9, No. 2, April 1994
- /14/ J. J. Schnapperelle, W. Horger, M. Ritz (NUCOR STEEL Berkeley)
DC Electric Arc Furnaces on Weak Power Supply Networks - a Low-flicker Design Yields the
Promised Results, AISE 1997 Annual Convention, Cleveland, Ohio

Figures

$$U_{di} = \frac{3}{\pi} \sqrt{2} V \quad \text{Eq. 1}$$

$$U_{di\alpha} = U_{di} \cos \alpha \quad \text{eq. 2}$$

$$\frac{I}{I_{dN}} = \frac{\sqrt{2}}{\sqrt{3}} = 0.8165 \quad v. 3$$

$$I_1 = \frac{\sqrt{6}}{\pi} \cdot I_{dN} \quad v. 4$$

$$\Lambda = \frac{3}{\pi} \cdot \cos \alpha$$

$$\frac{I}{I_{dN} 2\sqrt{3}} = \frac{1+\sqrt{3}}{2} = 0.7887 \quad v. 6$$

v. 5 = the above eq. show that these type of converters are consuming a lot of reactive power if they are operated with high firing angles. =

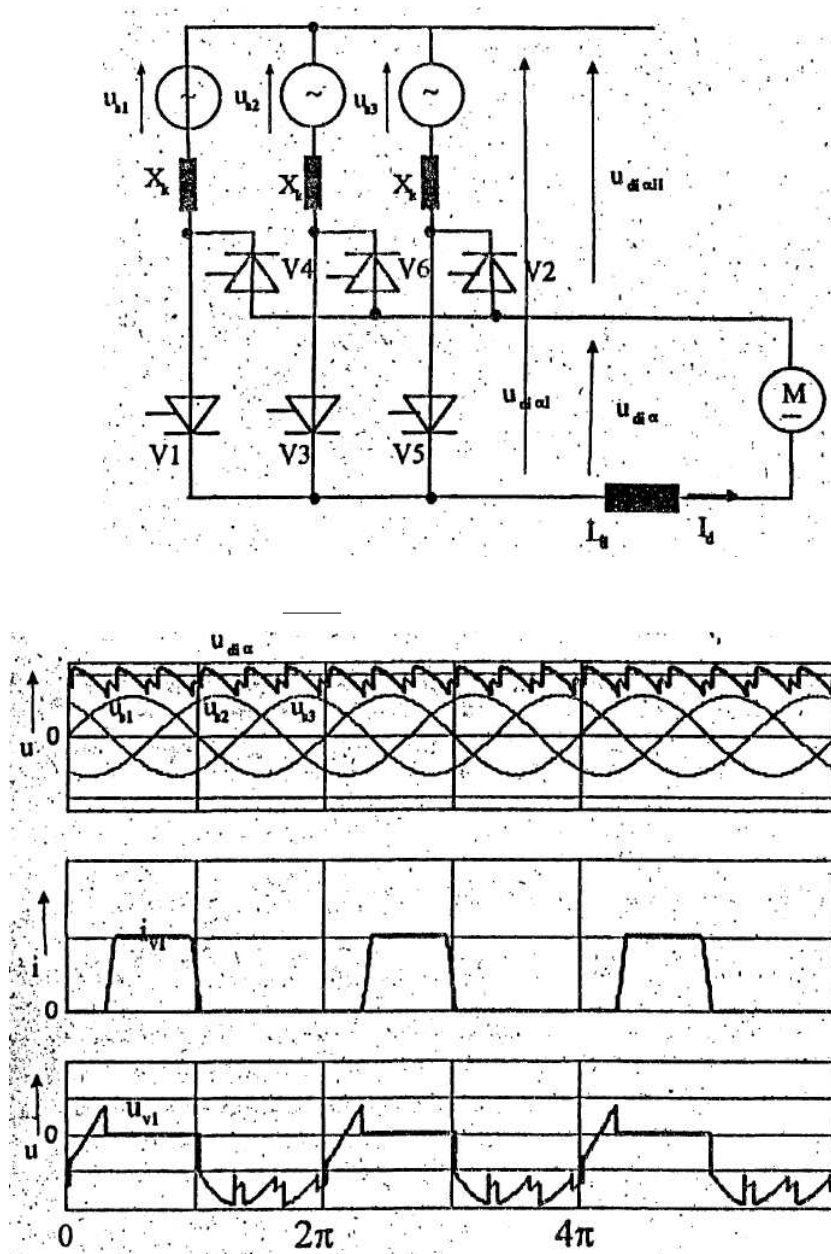


Fig 1: Currents and voltages in a B6 bridge circuit III

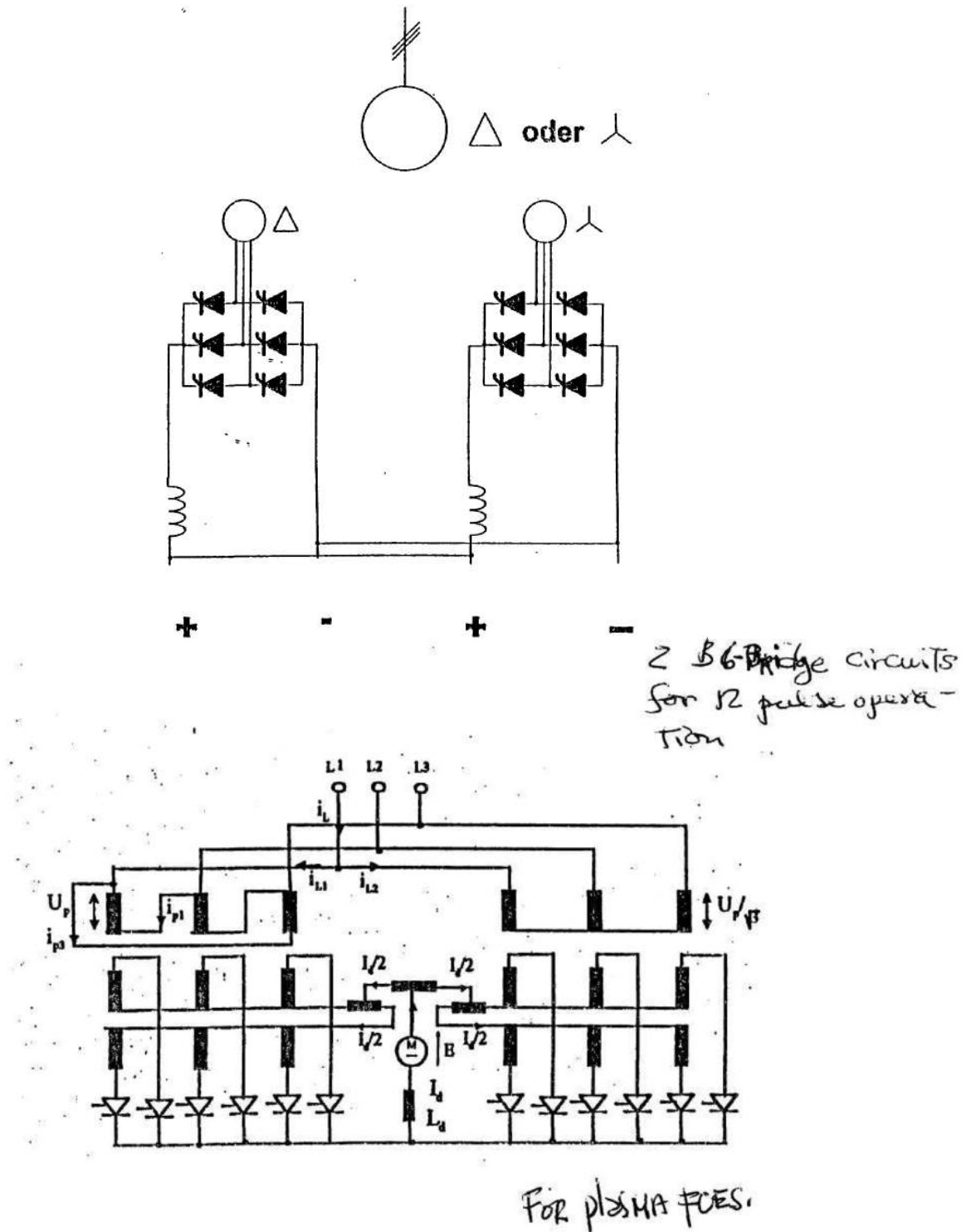


Fig 2: 12-pulse bridge circuit (top) and 12-pulse interphase transformer connection (bottom)

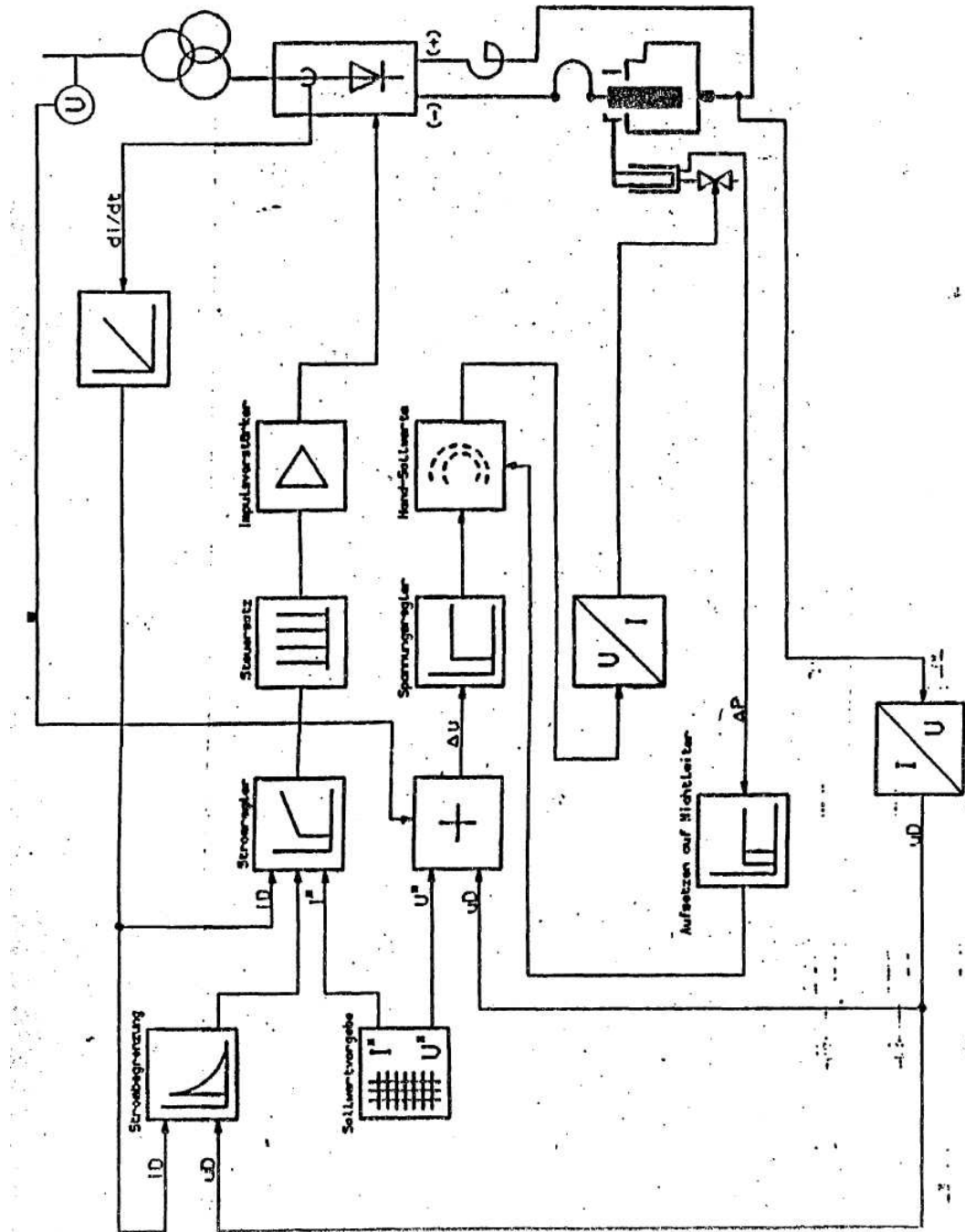


fig 3: Block diagram of a DC furnace controller

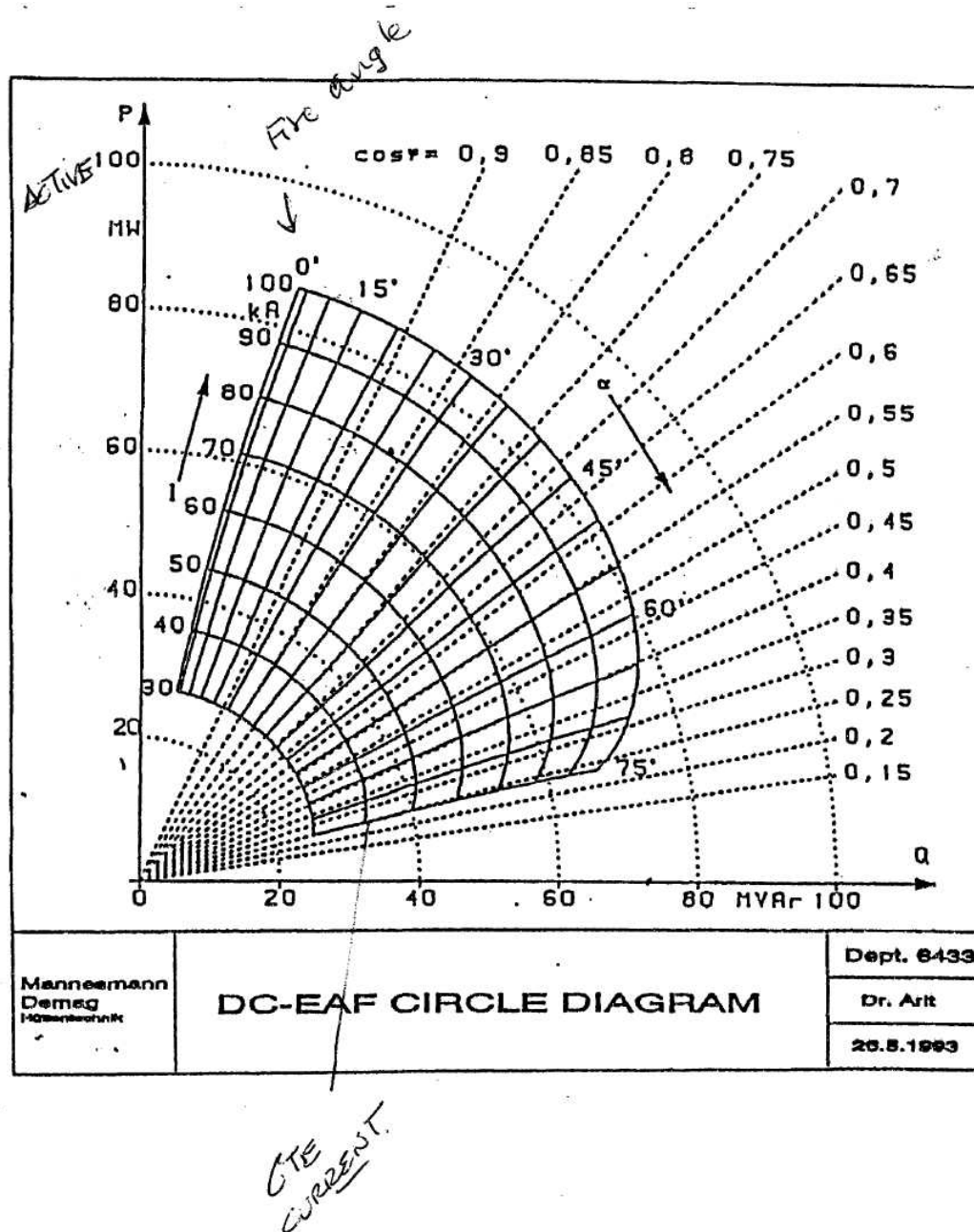


fig 4: Circle diagram of a DC furnace

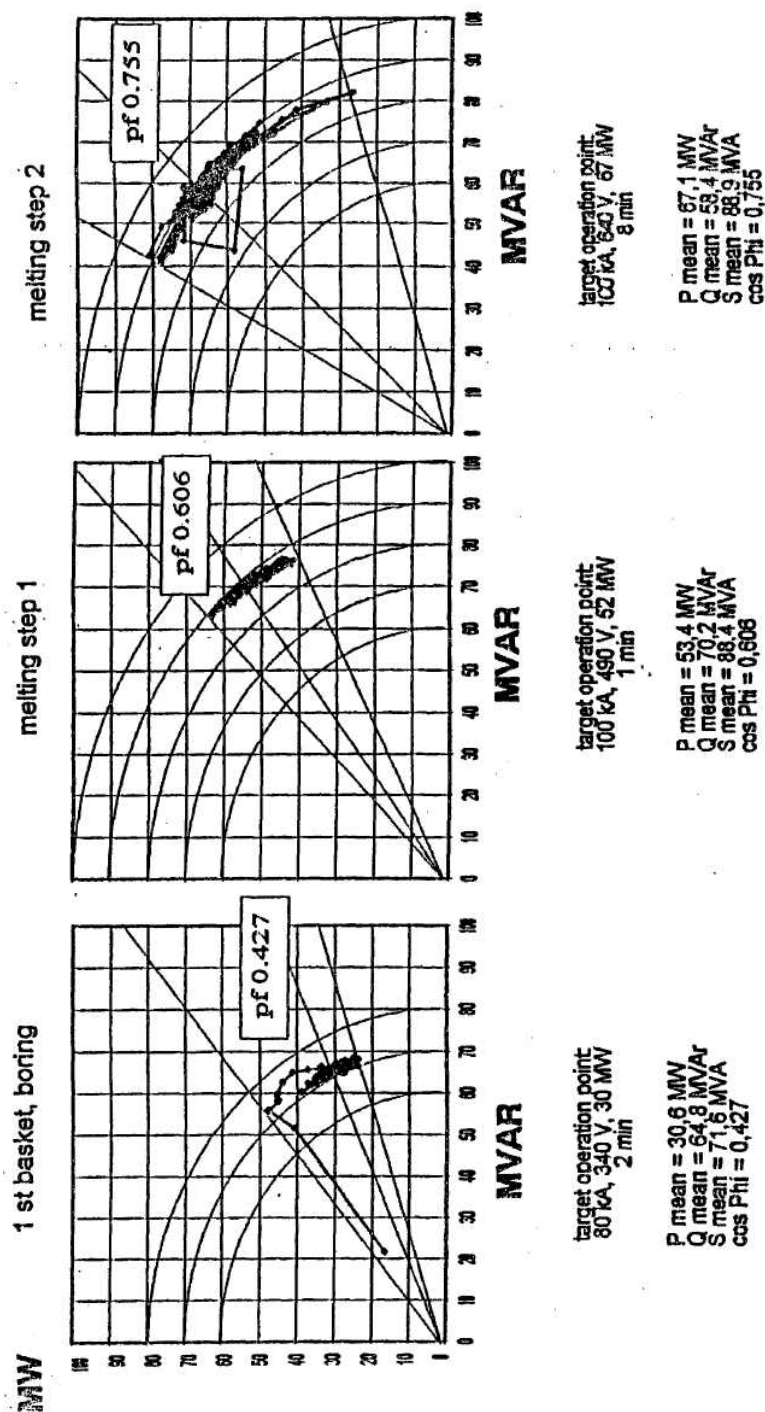


fig5: Power measuiements al a DC furnace

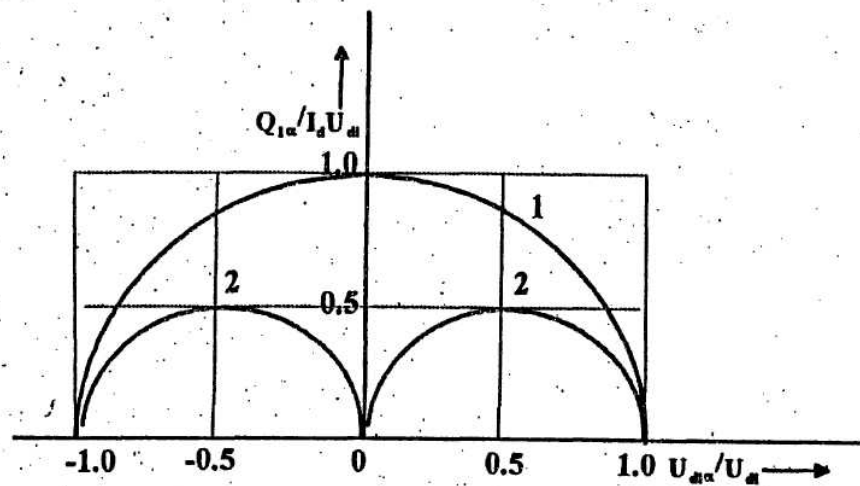
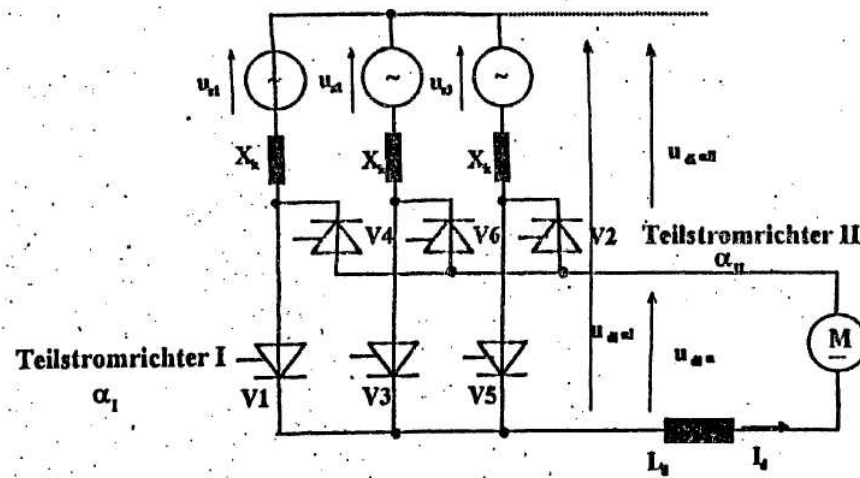


Bild 6: Tlthree phase bridge circuit with phase shifting control (top) and the resulting reactive power function (bottom) *III*

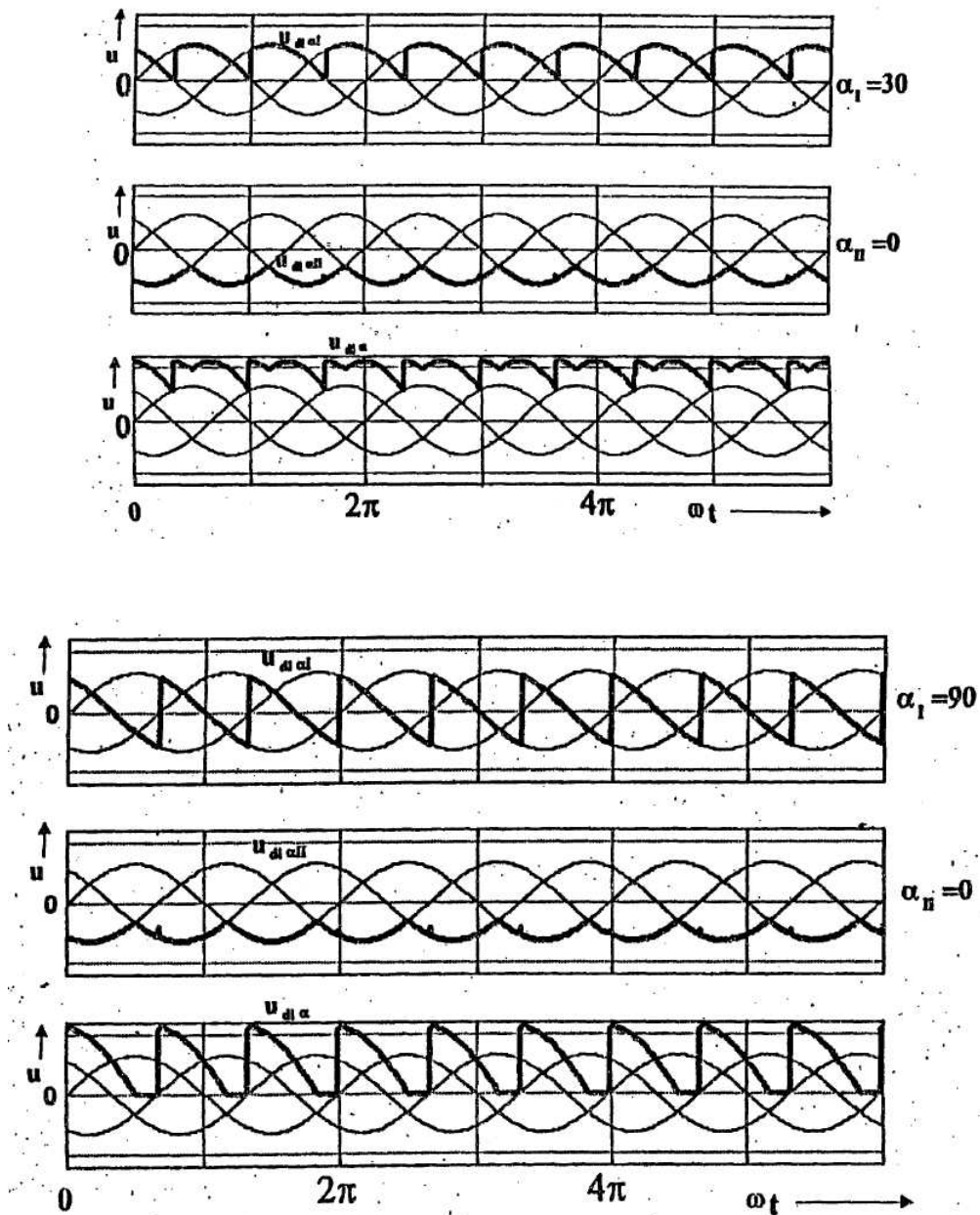


Bild 7: Voltages in a converter according to fig. 6 with phase shifting control

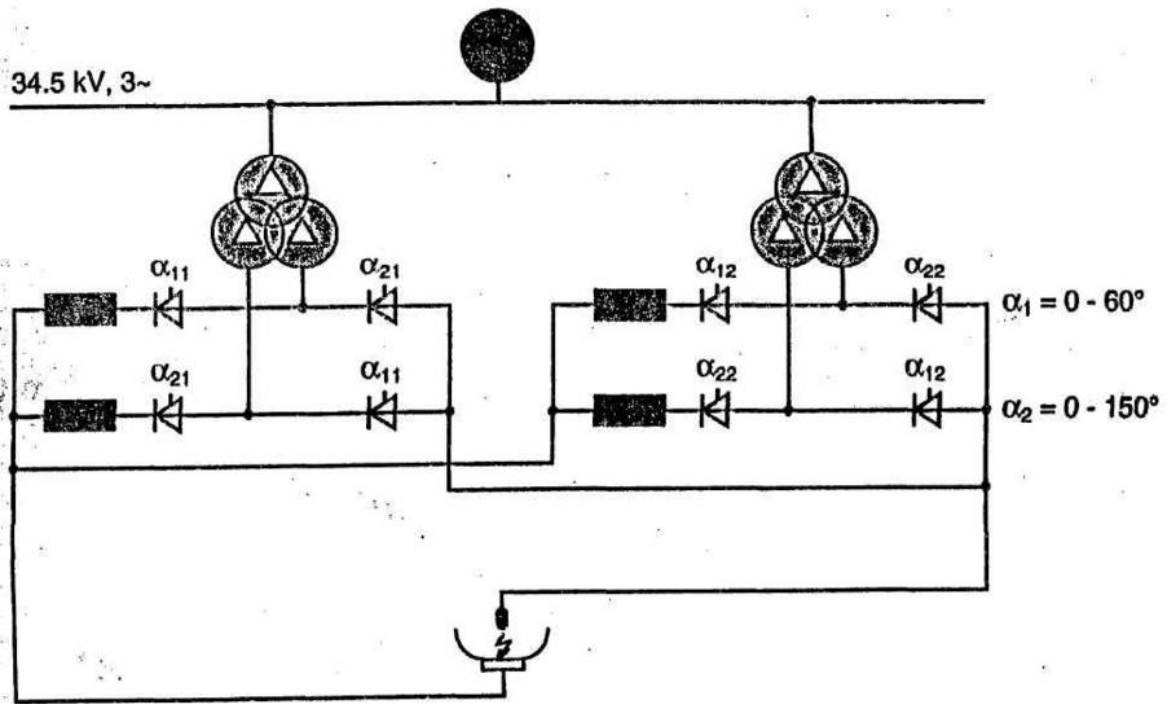


fig 7a Bridges with separate control of the half bridges for constant reactive power

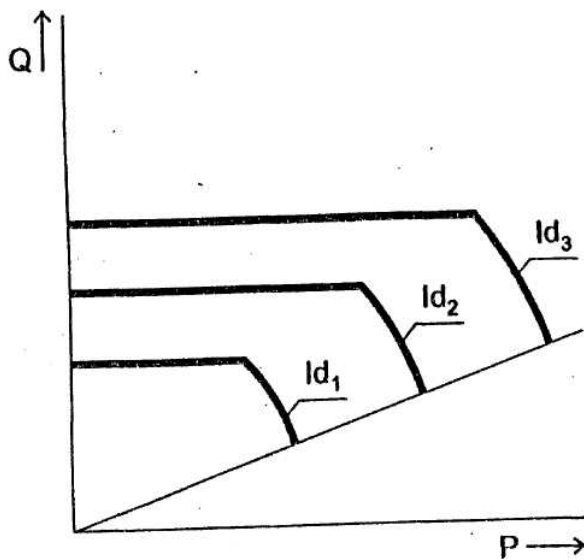


fig 7b Resulting circle diagram

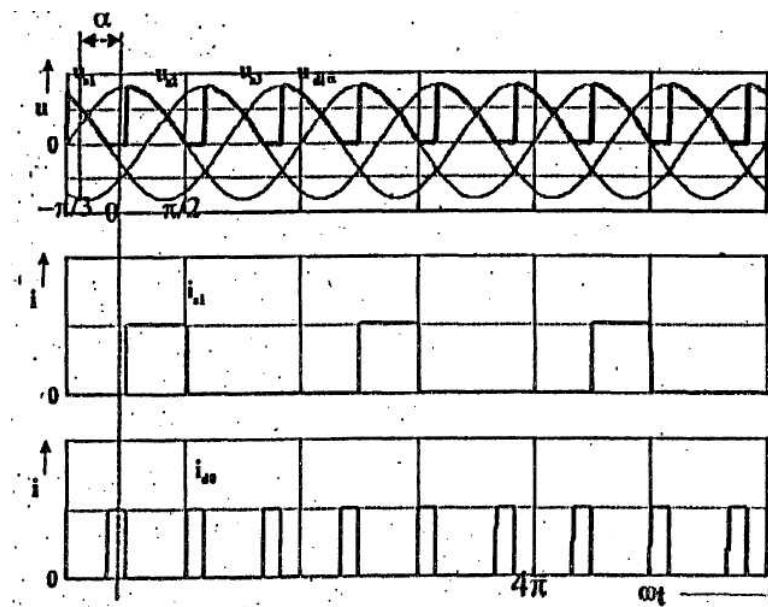
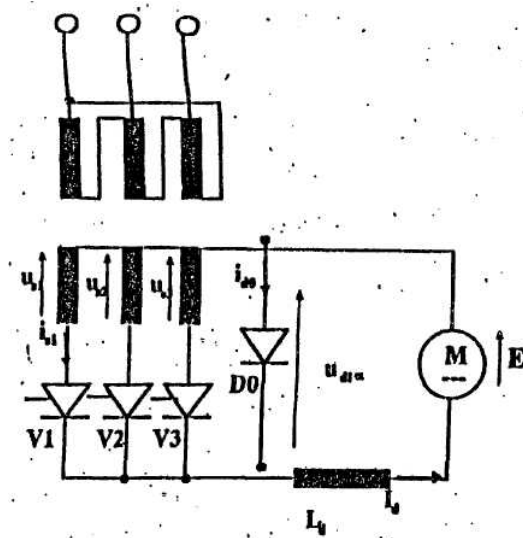


fig 8: M3 circuit with **free** wheeling diode (top) **and** voltage and currents

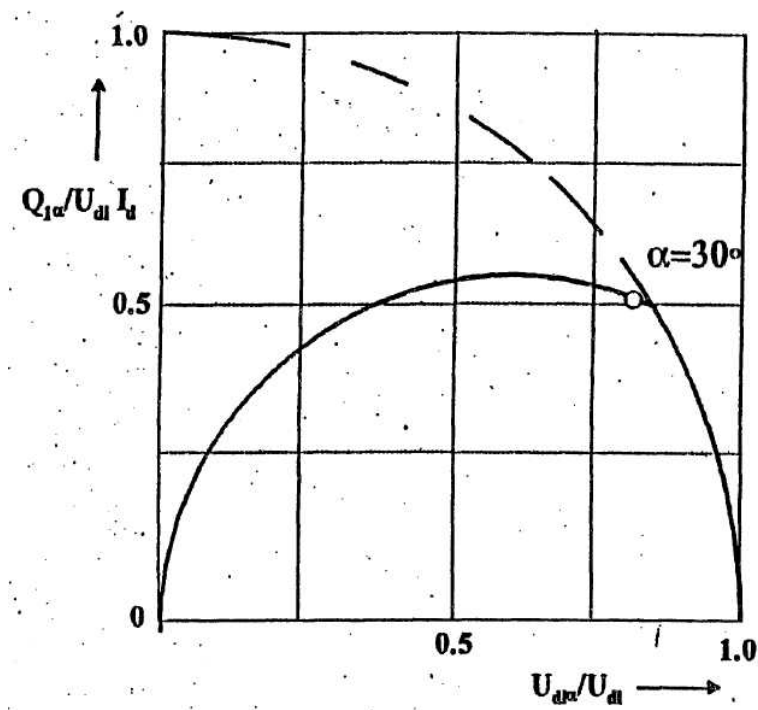


fig 9: Reactive power curve of an M3 converter with free wheeling diode

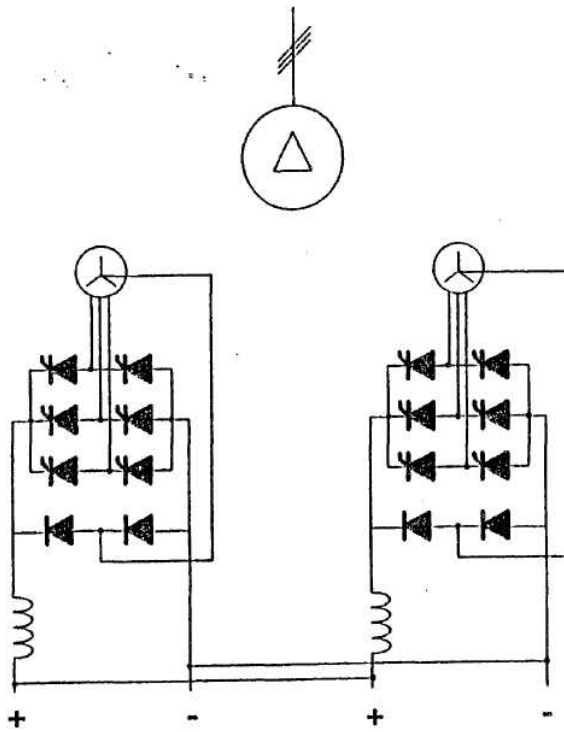


fig 10: Three phase bridge circuit with free wheeling diodes.

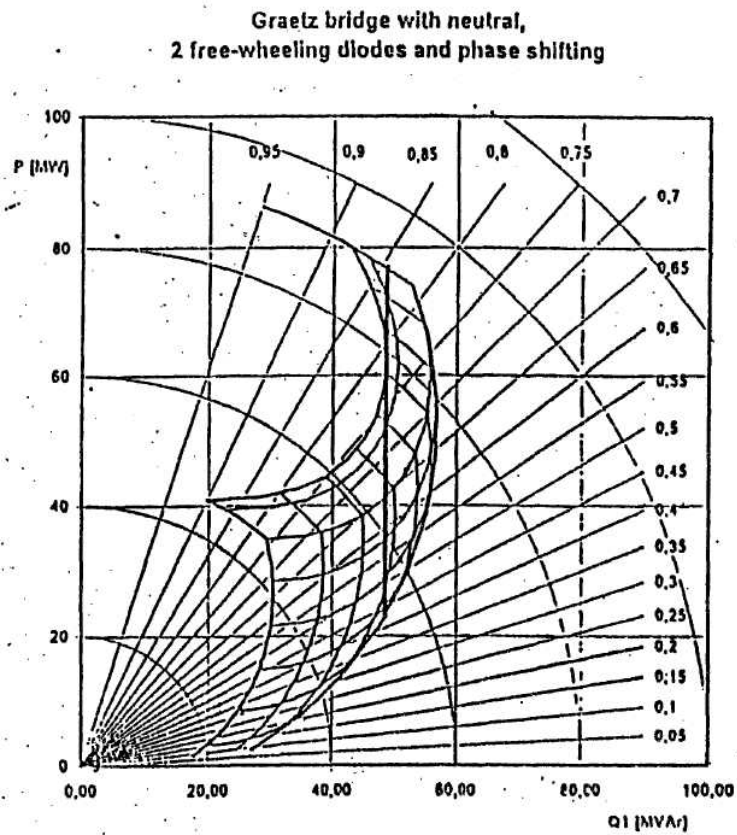


Fig. 11: Circle diagram of a DC furnace with free wheeling diodes and phase shift control

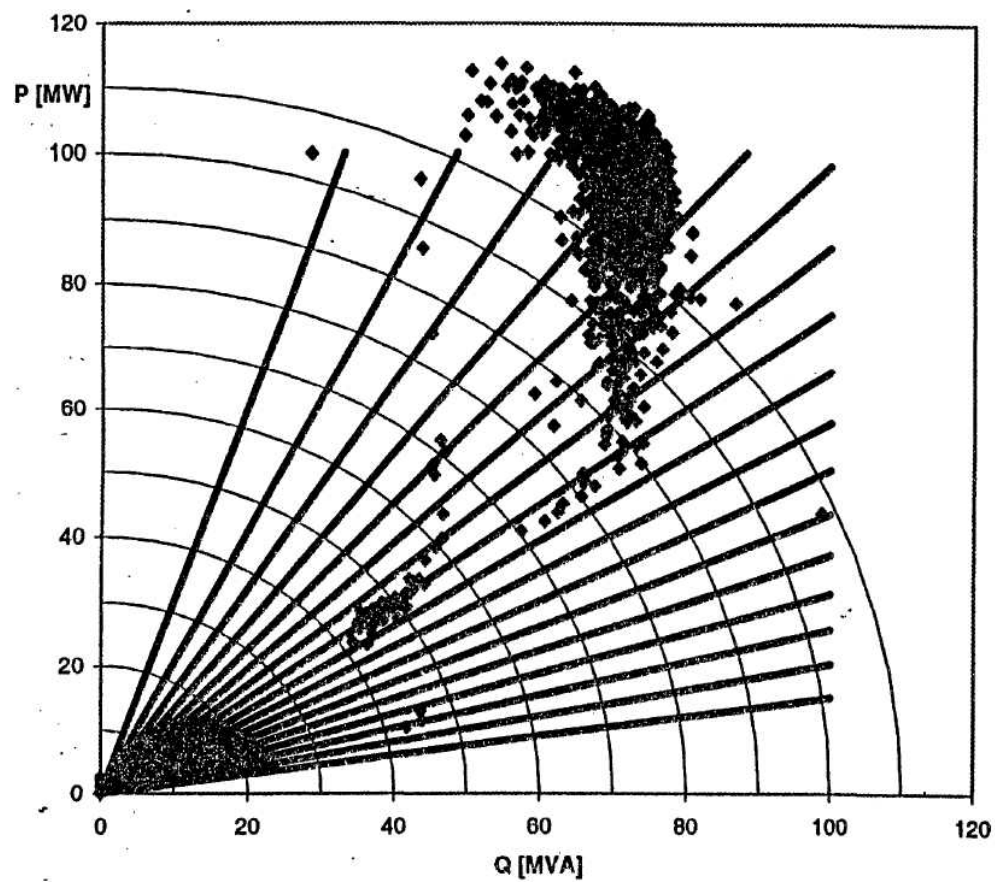


Fig. 12: Measured power of a DC furnace with free wheeling diodes and phase shift control

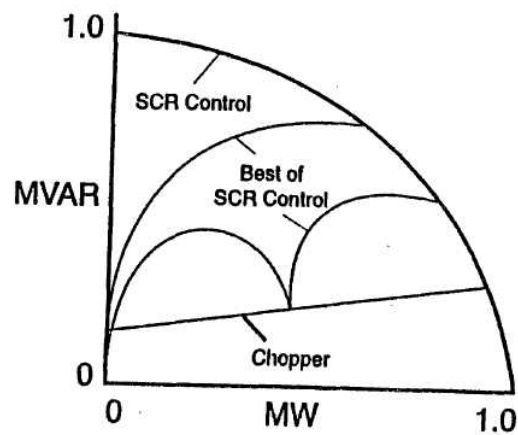
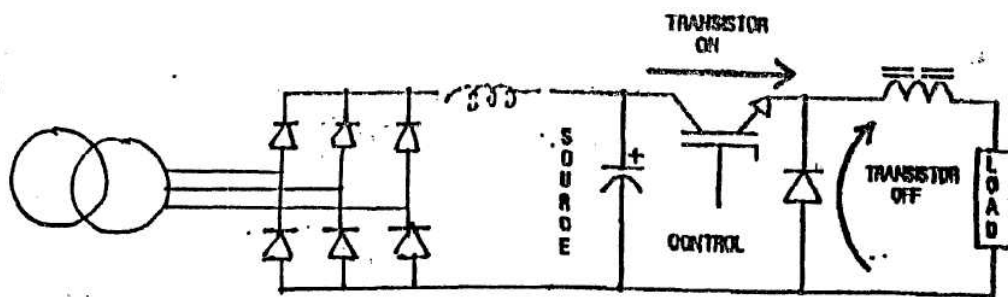
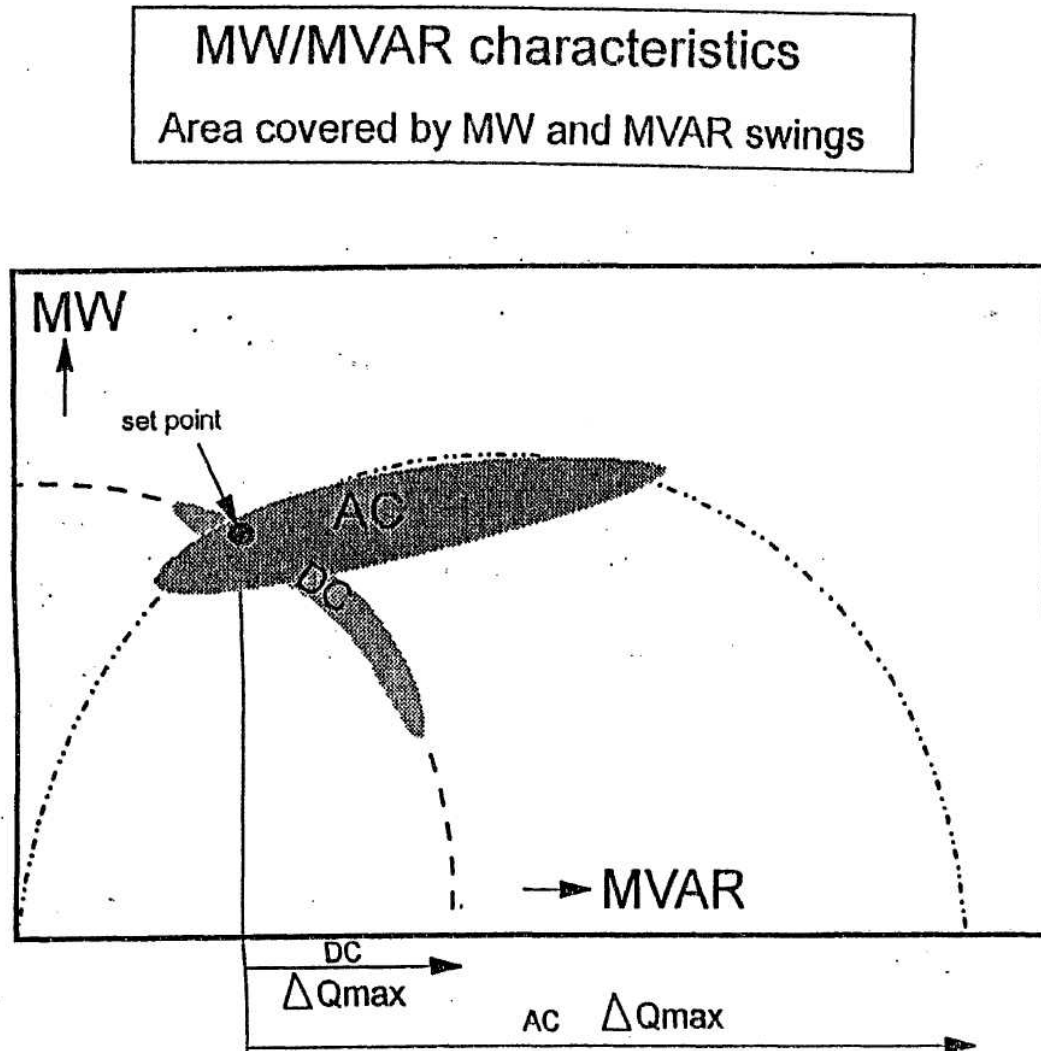


Fig. 13: Elementary Chopper cell and circle diagram of a DC furnace powered by chopper circuits



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C

Fig. 14: (useless) comparison of the reactive power fluctuation of AC and DC furnaces in order to compare the flicker/7/

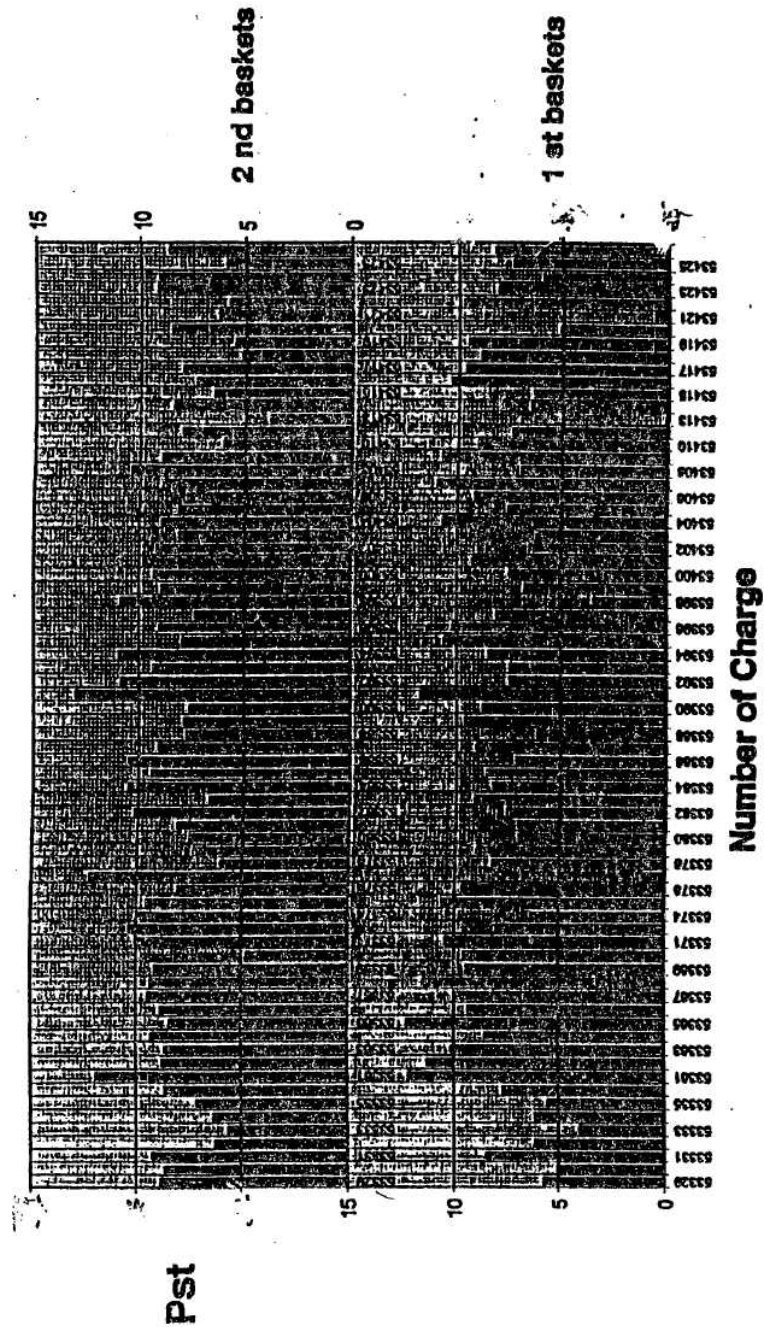
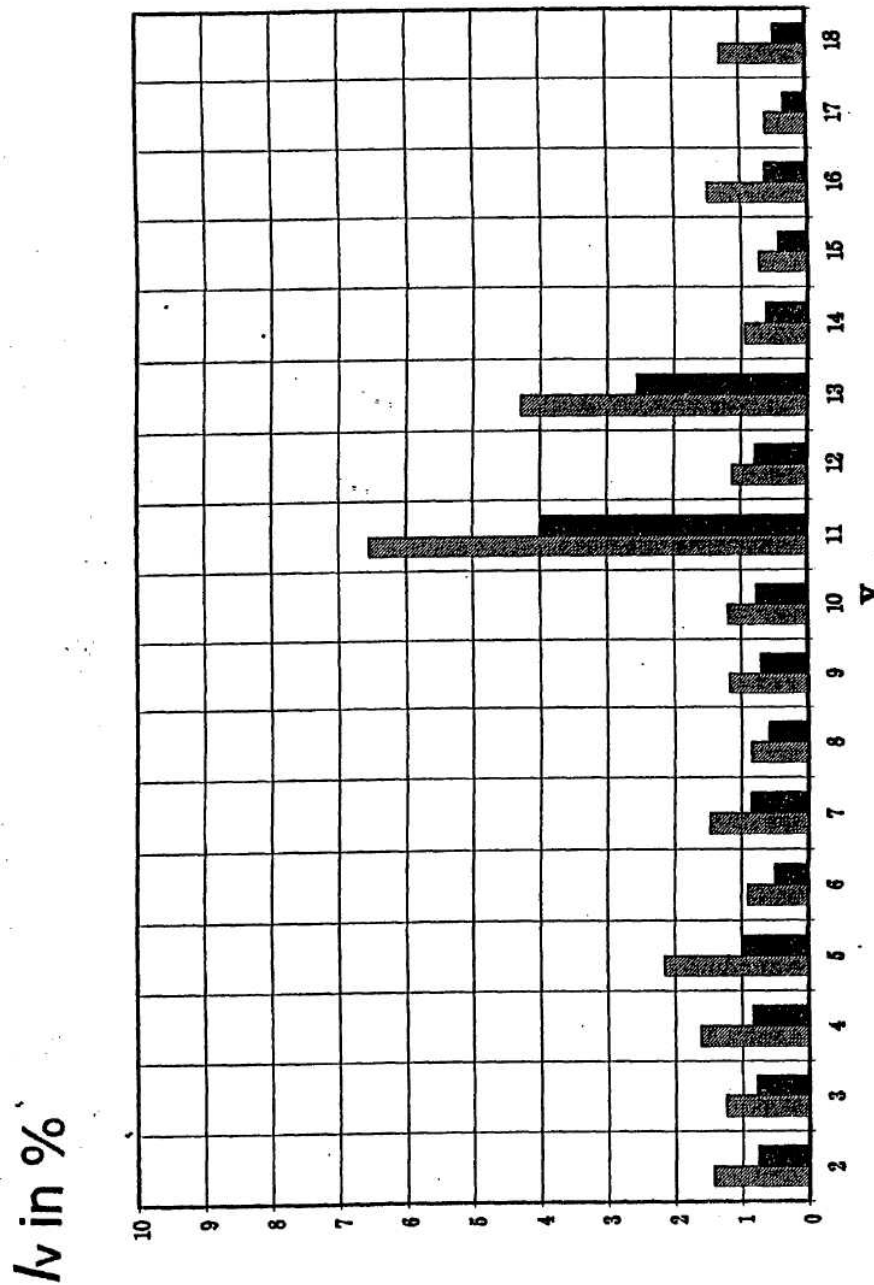


Fig. 15: Flicker of a great DC furnace, 100 consecutive heats, scrap melting periods only, measured at the 30 kV furnaces bus



Fi g. 16: Measured current harmonics (max and mean) of a great DC furnace with 12-pulse converter

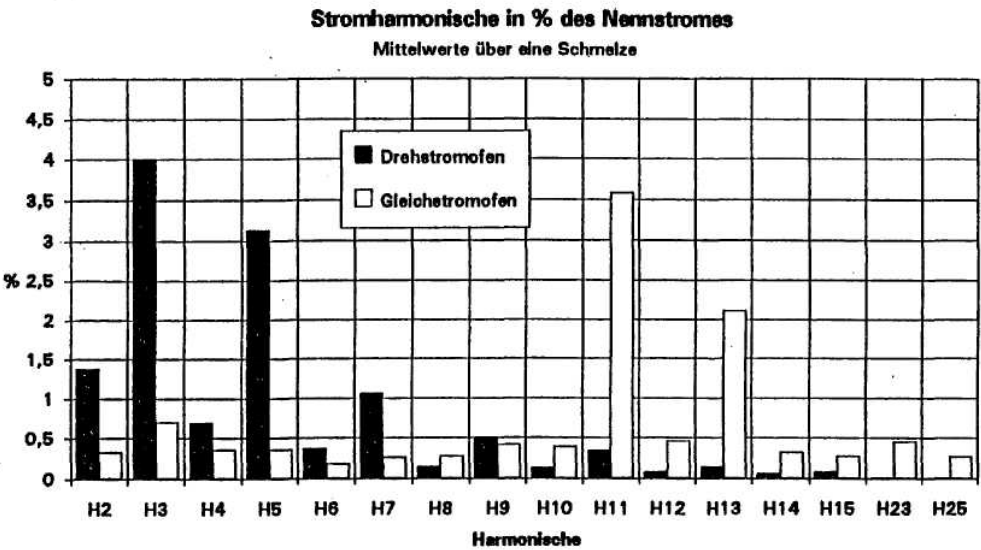


Fig. 17: Comparison of measured current harmonics of a DC (12-pulse) and an AC furnace

ABB Power Systems

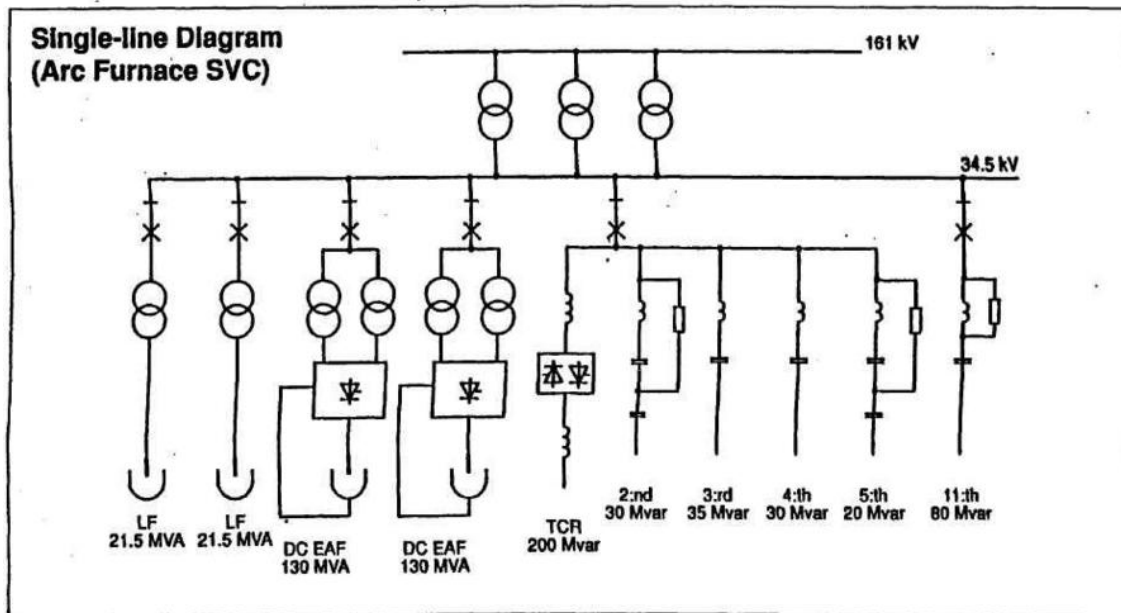


Fig. 18: SVC for DC furnace compensation 712/

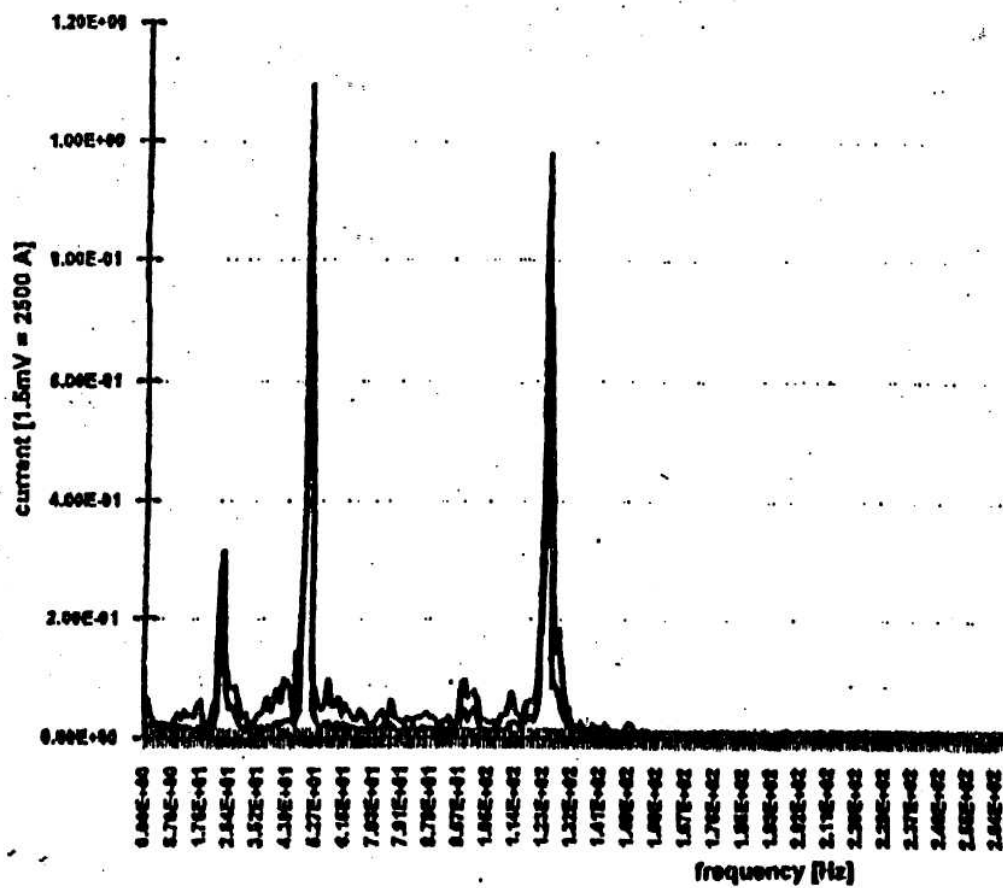


Fig. 19 Interharmonics generated by a DC furnaces and amplified by parallel resonance with the supply network

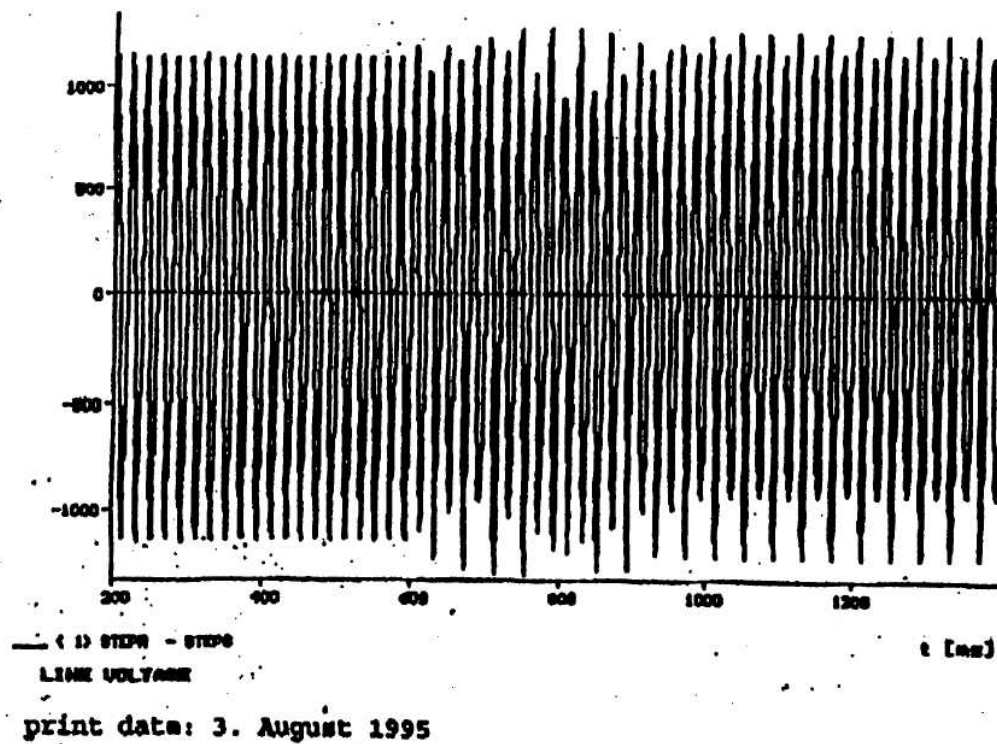
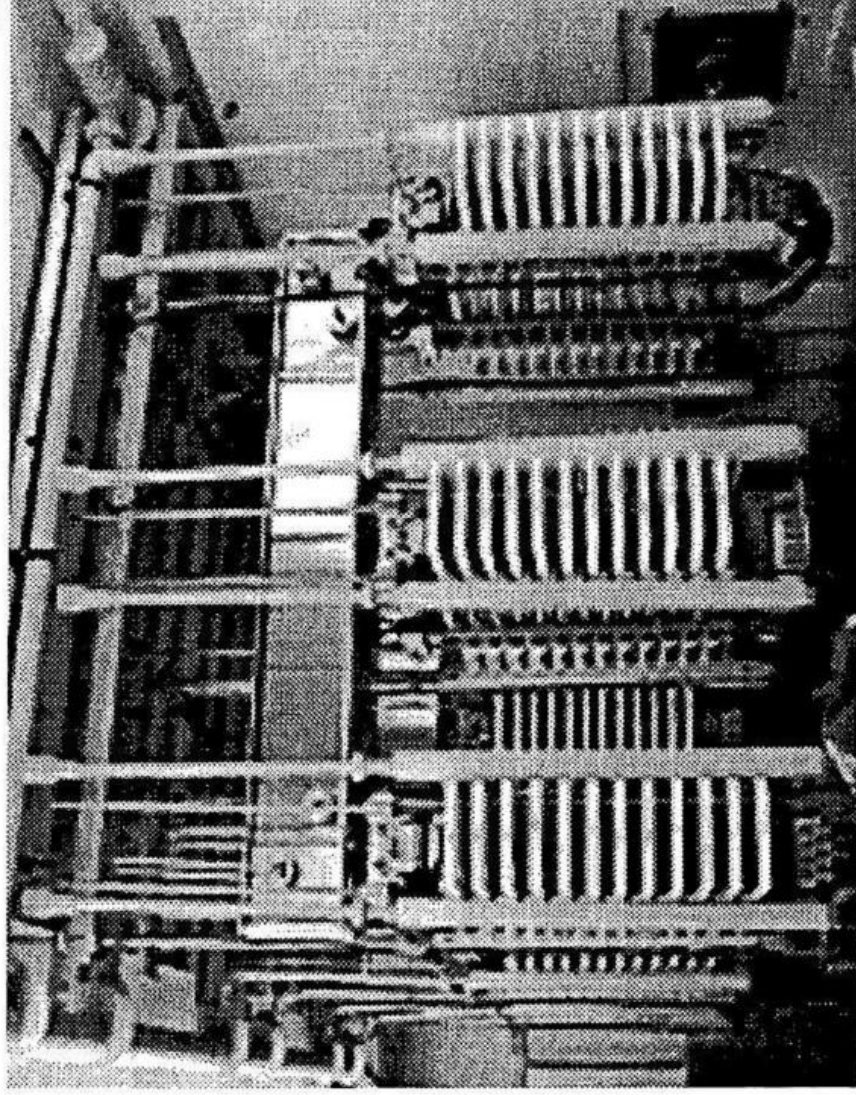


Fig. 20: Beat in a high voltage network due to interharmonics



Arrangement of IGBT`s in a
SVC Light Installation

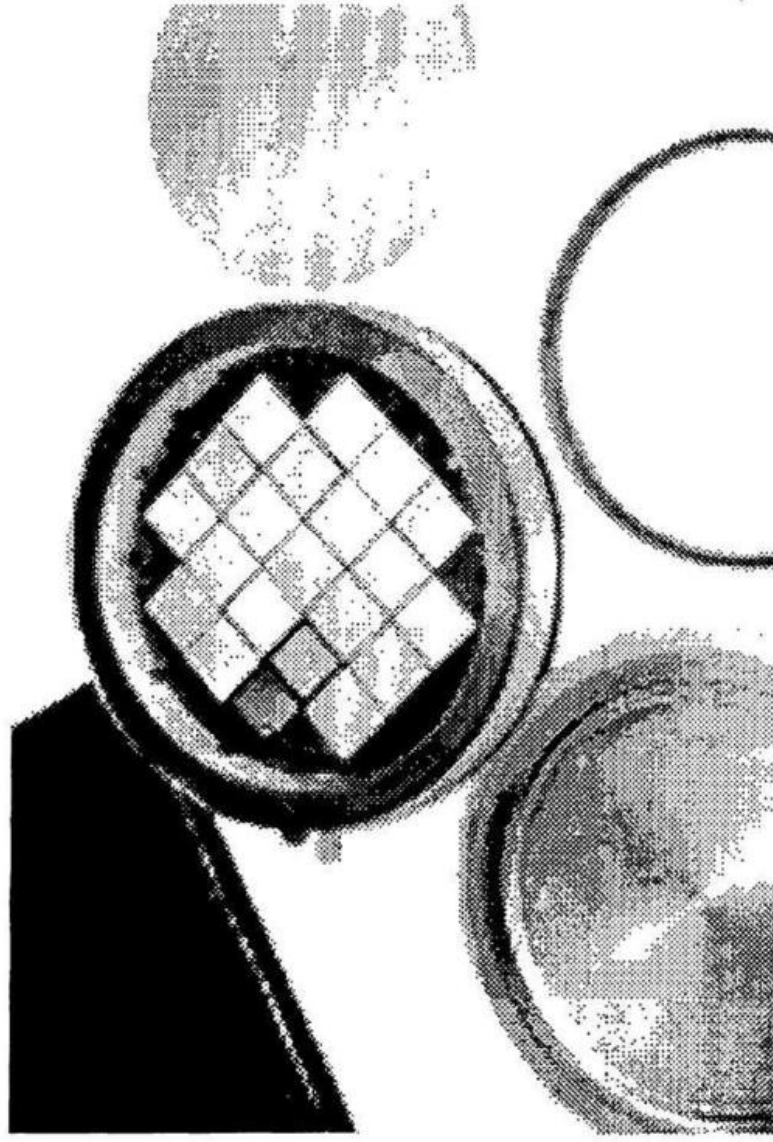
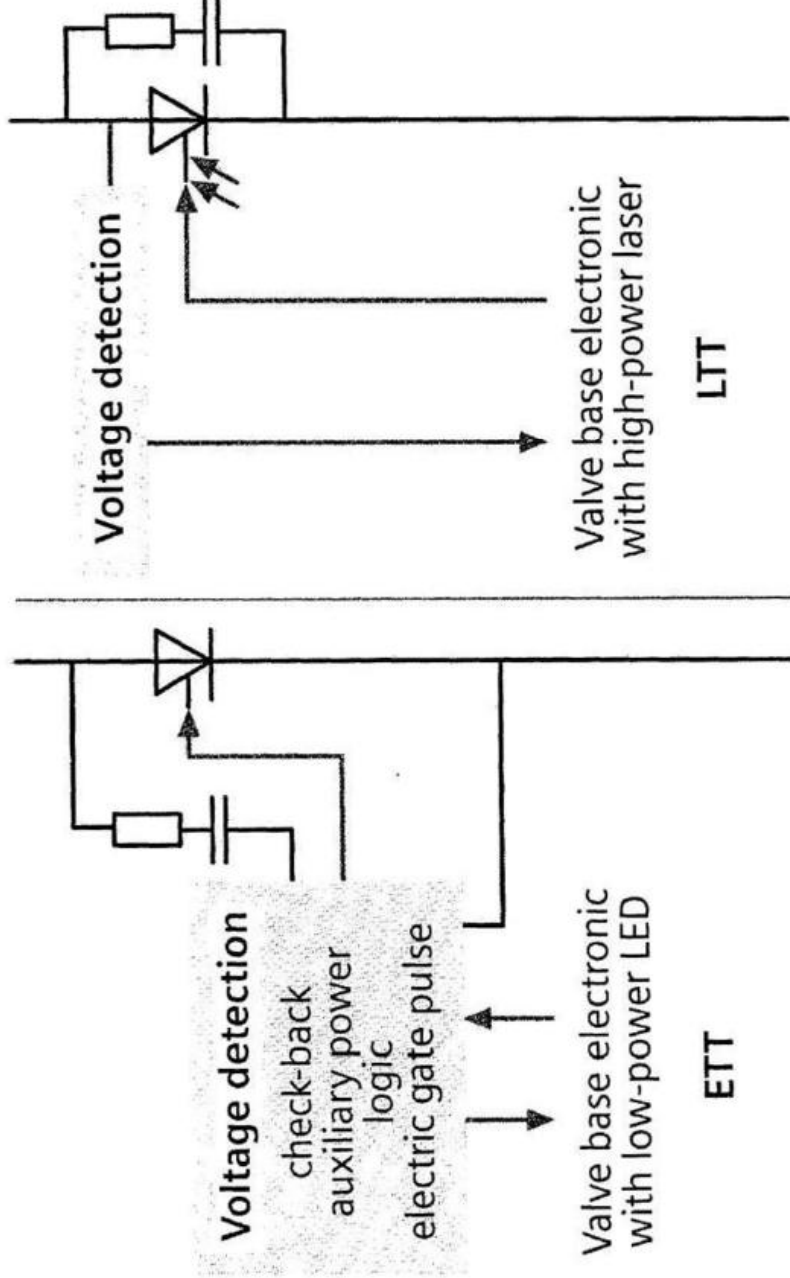


Fig. 4: Presspack IGBTs.



Source: SIEMENS
SVC Systems with Light
Triggered Thyristor
Valves
E10001-P12_A15_V1-
7600

Reduction of electronic parts on high potential due to the use of LTT (Light Triggered Thyristor) with internal forward overvoltage protection firing (BOD) instead of ETT (Electrically Triggered Thyristor) with external BOD

110 kV - Spektrum bei verschiedenen Netzkonfigurationen
 Datum: 08.07.2000 Meßpunkt: U71 DBE Sequenz: 1

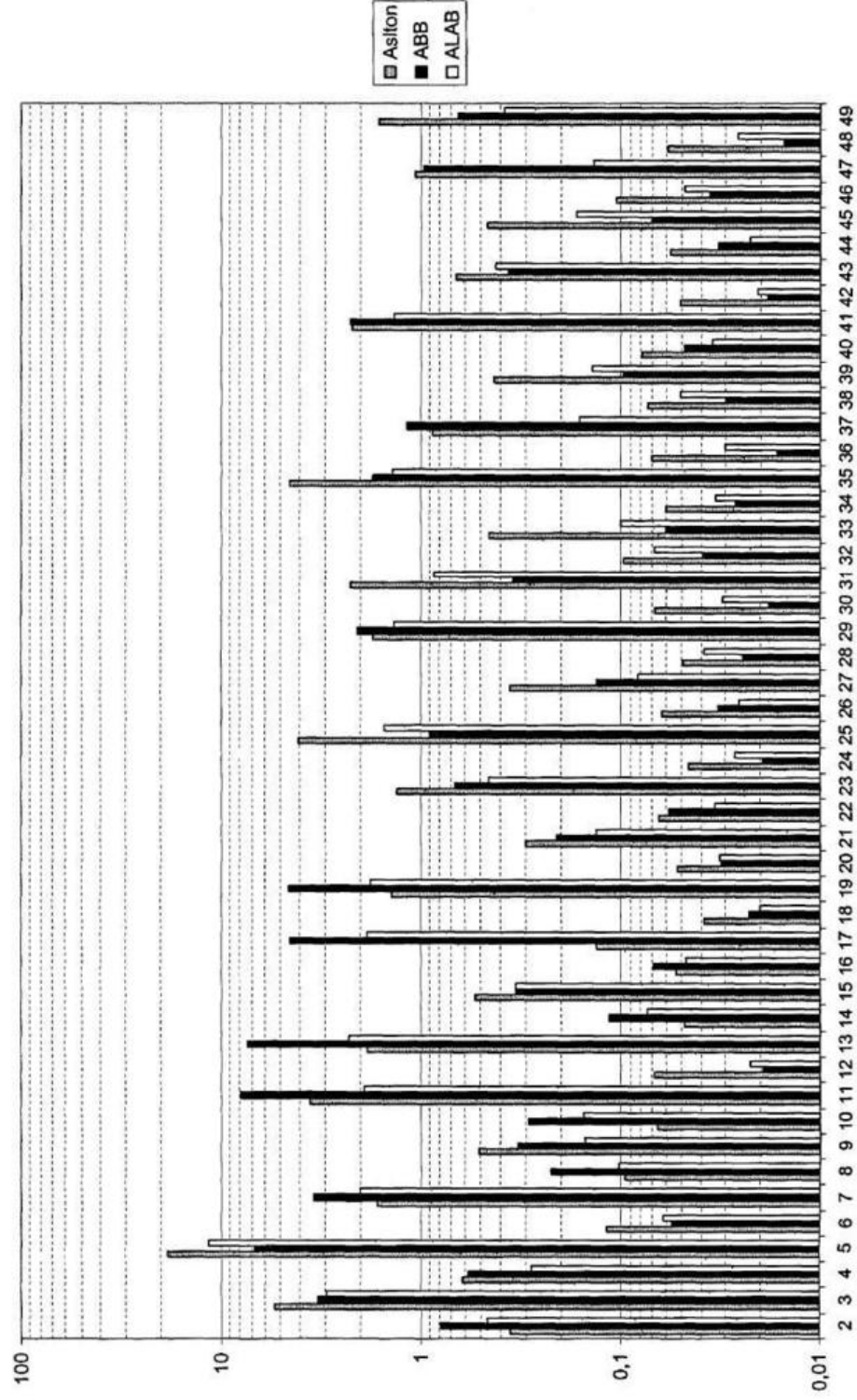


Fig. 17b

Voltage harmonics cause by two chopper converters. One equipped with GTO's and the other equipped with IGBT's

International Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Comparison of AC and DC Arc Furnaces

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Comparison of AC and DC arc furnaces

Electrical parameters of both furnace types

1. Electrical design of AC arc furnaces
2. Design of comparable DC arc furnaces
3. Assessment of performance assumptions
4. Electrical data of investigated furnaces

Evaluation of electrical energy consumption

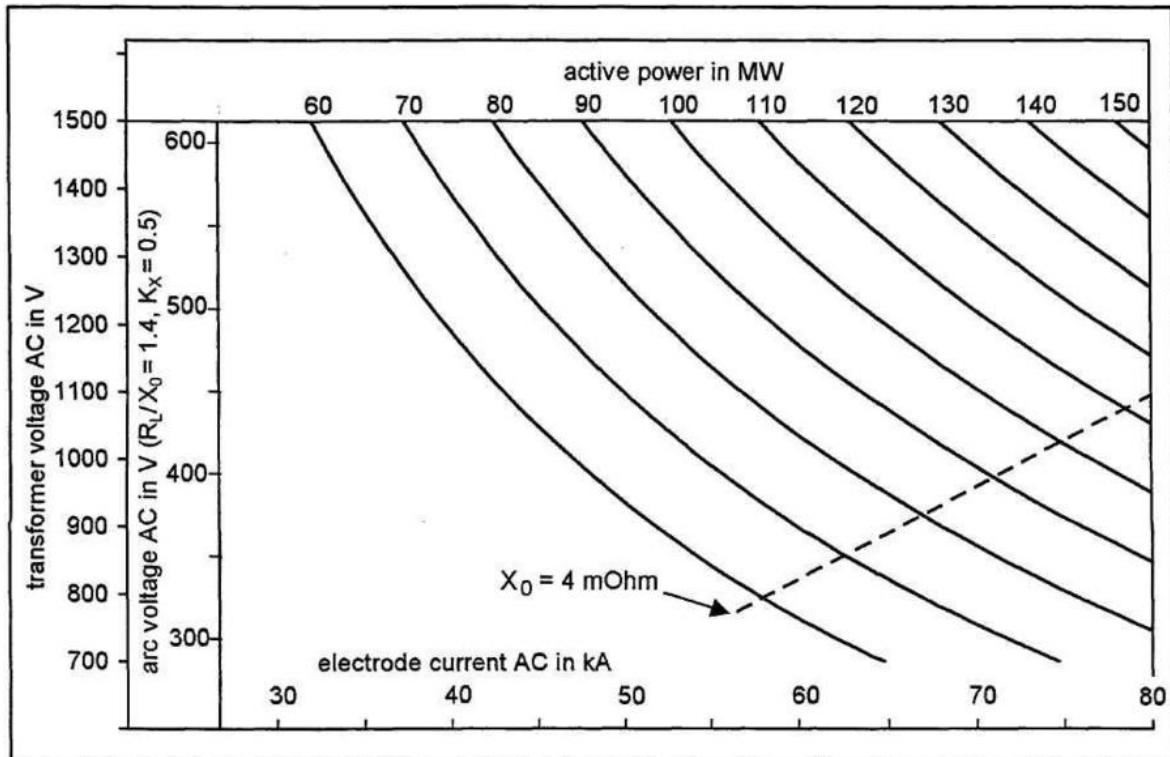
5. Calculation of electrical energy demand
6. Energy consumption of investigated furnaces

Evaluation of electrode graphite consumption

7. Calculation of electrode graphite demand
8. Graphite consumption of investigated furnaces
9. Conclusions

References

1. Electrical design of AC arc furnaces [1]

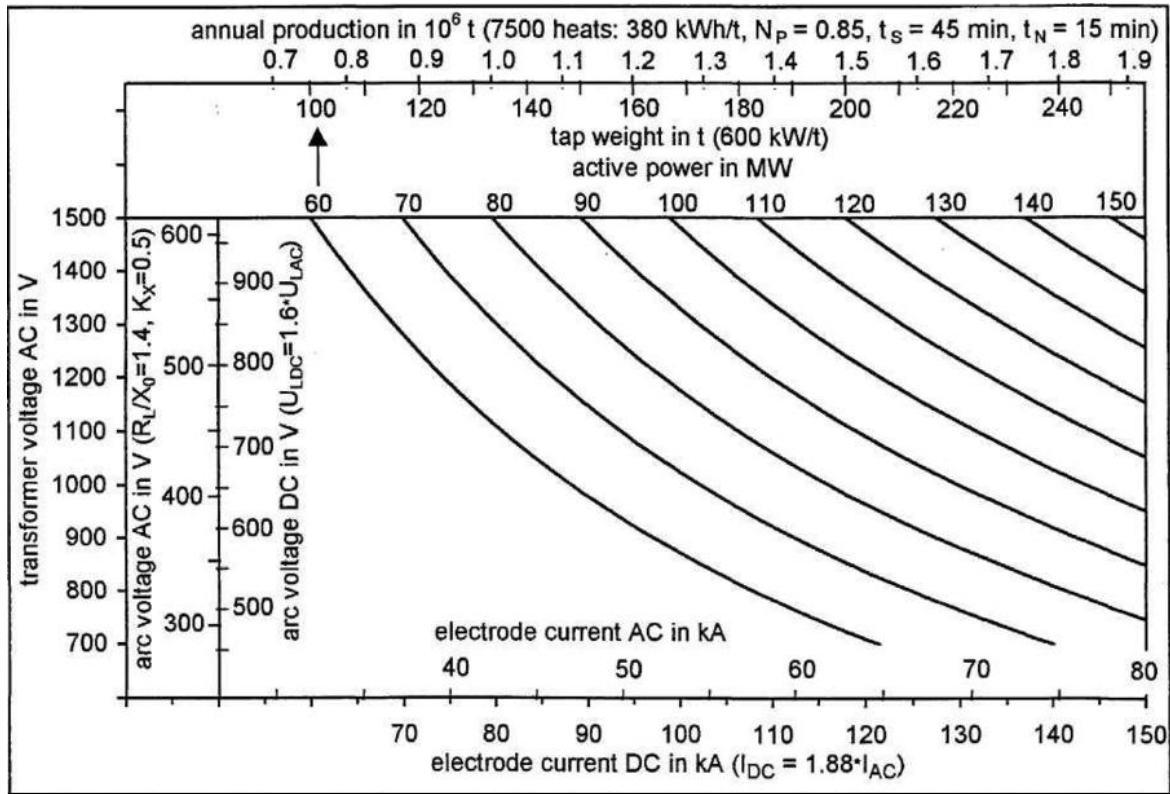


Curves of constant active power (transformer primary side)

Lecture "Model-based control of AC EAF", page 18:

- arc resistancer R_L
 - arc reactance factor $K_x = 0.5$
 - short circuit resistance $R_o = 0.08$
 - short circuit reactance $X_o \ll R_L/X_o = 1.4$ (cos
(add. reactor required above dashed line with X_o)
- transformer voltage U_{so}
- arc voltages $U_{LAC} = U_{so}/2.4$

2. Design of comparable DC arc furnaces [2]



DC furnaces (1 arc) with equal power as for AC (3 arcs):

- arc voltage $U_{DC} = 1.6 \cdot U_{AC}$ assumed
- electrode current $I_{DC} = 3/1.6 \cdot I_{AC} = 1.88$

Assumptions for productivity performance:

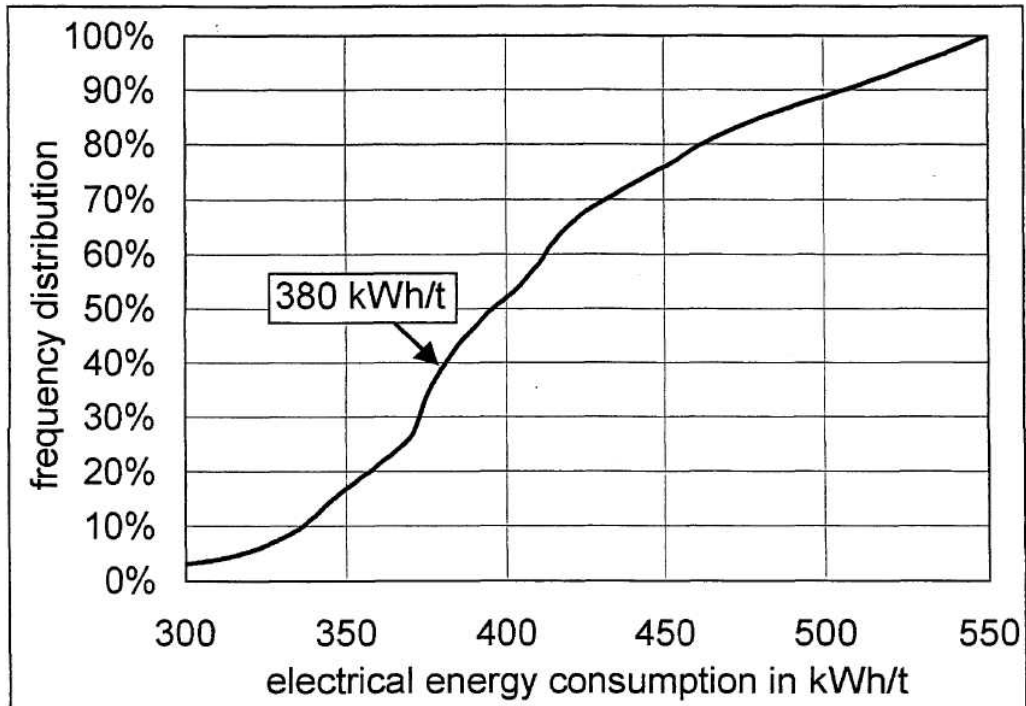
tap weight for specific power of 600 kW/t at main melting

annual production for 7500 heats at 60 min tap-tap time:

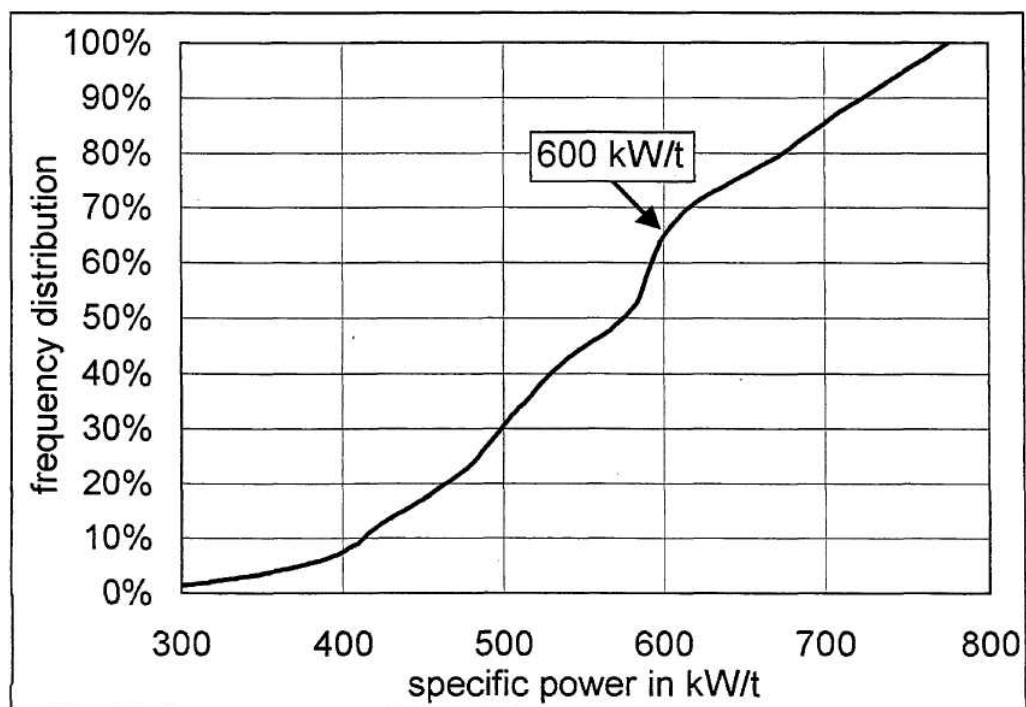
- spec, electrical energy 380 kWh/t
- mean power utilisation 0.85
- power-on time 45 min
- power-off-time 15 min

3. Assessment of performance assumptions [3]

Recent MSI Study with 35 furnaces and some others

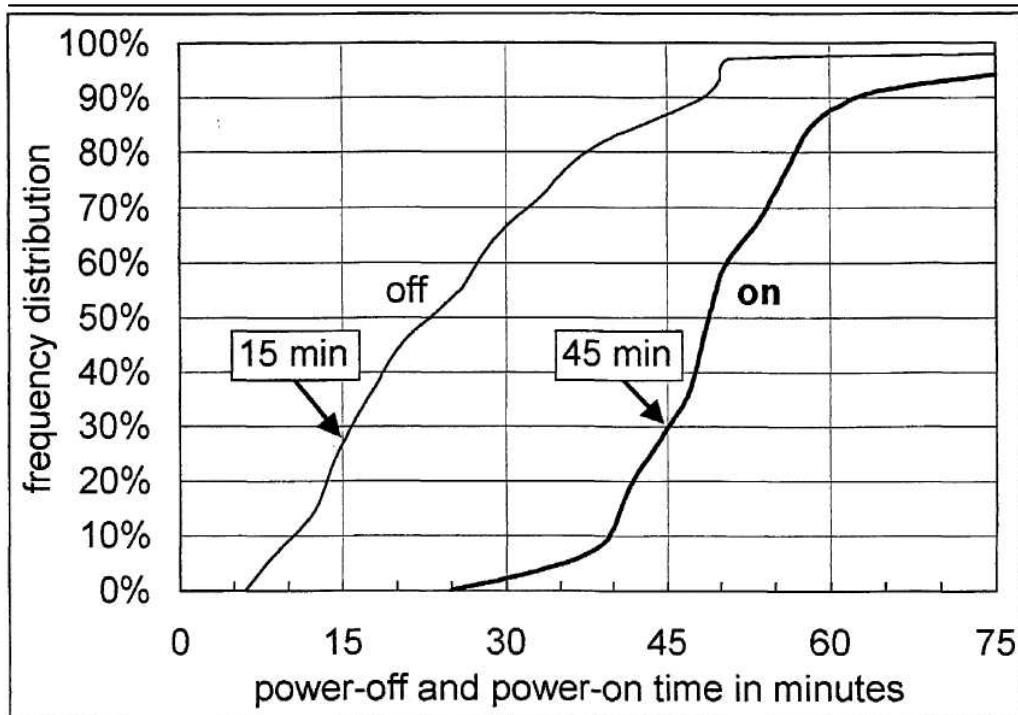


40% of the furnaces with electrical energy <380 kWh/t

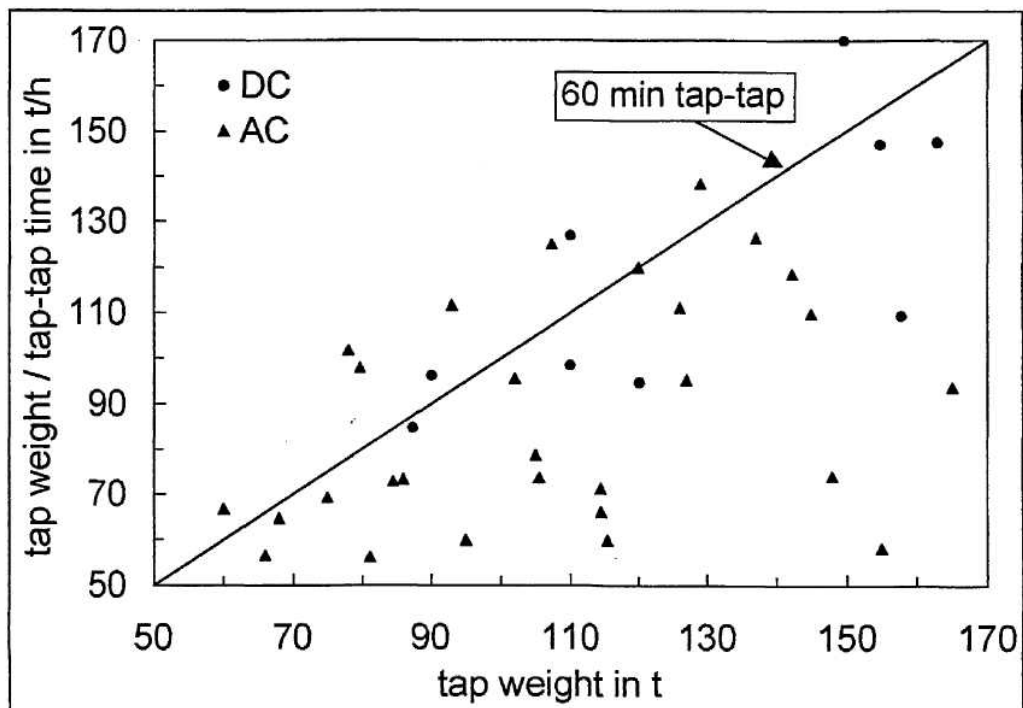


30% of the furnaces with specific power >600 kW/t

3. Assessment continued

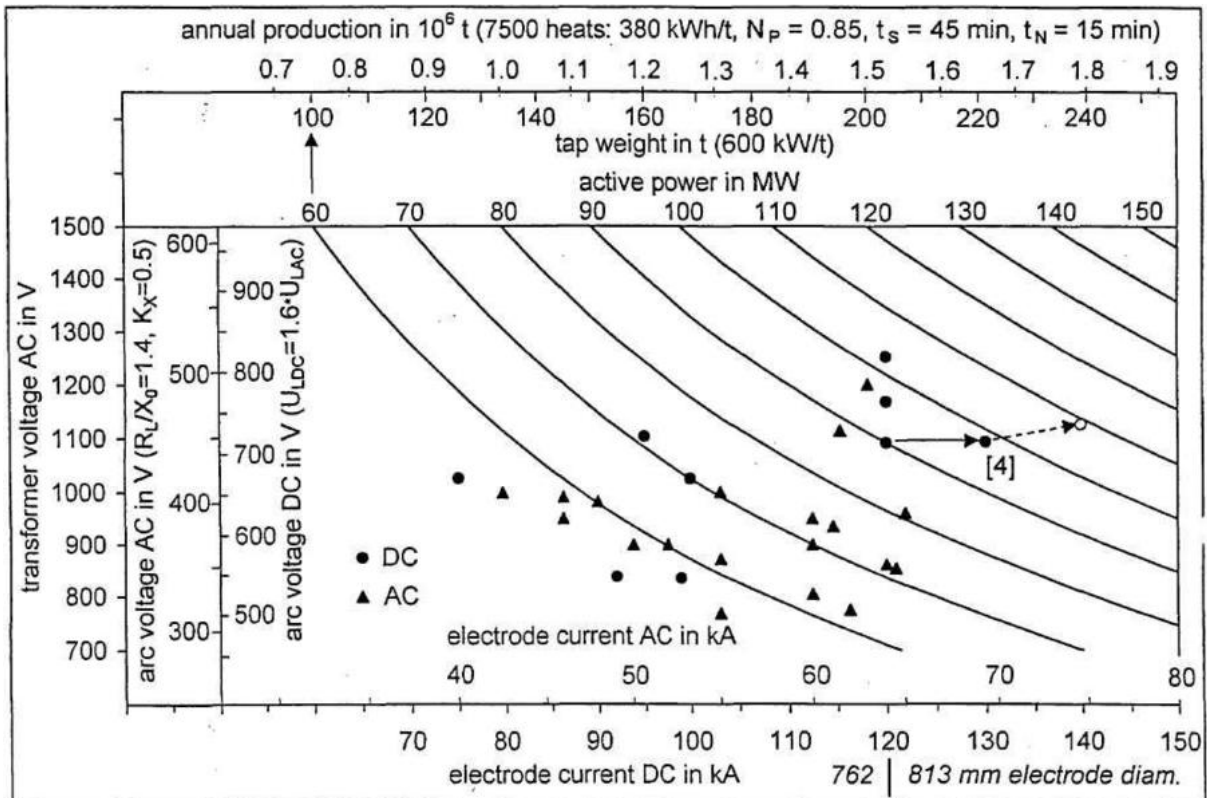


30% of the furnaces with power-on/-off <45/< 15 min



Many furnaces with tap-tap time of «60 min or shorter
→ assumptions for productivity performance are realistic

4. Electrical data of investigated furnaces



Limit values:

- | | AC | DC |
|-----------------------|----------------------------|------------------|
| • highest arc voltage | ≈ 500 V | ≈ 800 V |
| • highest current | ≈ 65 kA | ≈ 120 kA |
| • highest power | ≈ 100 MW | |
| → tap weight | ≈ 160 t | |
| → annual production | $\approx 1.2 \cdot 10^6$ t | |

Restrictions to power increase:

- | | | |
|----------------------|----|----------------------|
| • higher arc voltage | no | yes ← arc deflection |
| • higher current | no | yes ← electrodes |

DC electrode diameter: 711 mm up to ≈ 100 kA

762 mm up to ≈ 120 kA

recently developed [4]: 813 mm up to ≈ 140 kA

5. Calculation of electrical energy demand

Original formula:

$$\frac{W_R}{\text{kWh/t}} = 300 + 900 \cdot \left[\frac{G_E}{G_A} - 1 \right] + 80 \cdot \frac{G_{\text{DRI/HBI}}}{G_A} - 300 \cdot \frac{G_{\text{HM}}}{G_A} + 1600 \cdot \frac{G_Z}{G_A} \\ + 0.7 \cdot \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] + 0.85 \cdot \frac{t_S + t_N}{\text{min}} - 8 \cdot \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \cdot \frac{M_L}{\text{m}^3/\text{t}} - 2.8 \cdot \frac{M_N}{\text{m}^3/\text{t}} - 15 \cdot \text{CON}$$

Modified formula:

$$\frac{W_R}{\text{kWh/t}} = 375 + 400 \cdot \left[\frac{G_E}{G_A} - 1 \right] + 80 \cdot \frac{G_{\text{DRI/HBI}}}{G_A} - 50 \cdot \frac{G_{\text{Shr}}}{G_A} - 350 \cdot \frac{G_{\text{HM}}}{G_A} + 1000 \cdot \frac{G_Z}{G_A} \\ + 0.3 \cdot \left[\frac{T_A}{^\circ\text{C}} - 1600 \right] + 1 \cdot \frac{t_S + t_N}{\text{min}} - 8 \cdot \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \cdot \frac{M_L}{\text{m}^3/\text{t}} - 2.8 \cdot \frac{M_N}{\text{m}^3/\text{t}} + \text{NV} \cdot \frac{W_V - W_{V\text{m}}}{\text{kWh/t}}$$

G_A	furnace tap weight	t_S	power-on time
G_E	weight of all ferrous materials	t_N	power-off time
G_{DRI}	weight of DRI	M_G	specific burner gas
G_{HBI}	weight of HBI	M_L	specific lance oxygen
G_{Shr}	weight of shredder	M_N	specific post-combustion oxygen
G_{HM}	weight of hot metal	W_V	energy losses (if measured)
G_Z	weight of slag formers	$W_{V\text{m}}$	mean value of W_V
T_A	tapping temperature	NV	furnace specific factor (0.2 ... 0.4)
CON	+1 for continuous / -1 for discontinuous operation (eliminated)		

Development of the original formula with furnace average values

1992: 14 furnaces: first version of the formula (5)

1997: 7 furnaces: extension to post-combustion (6)

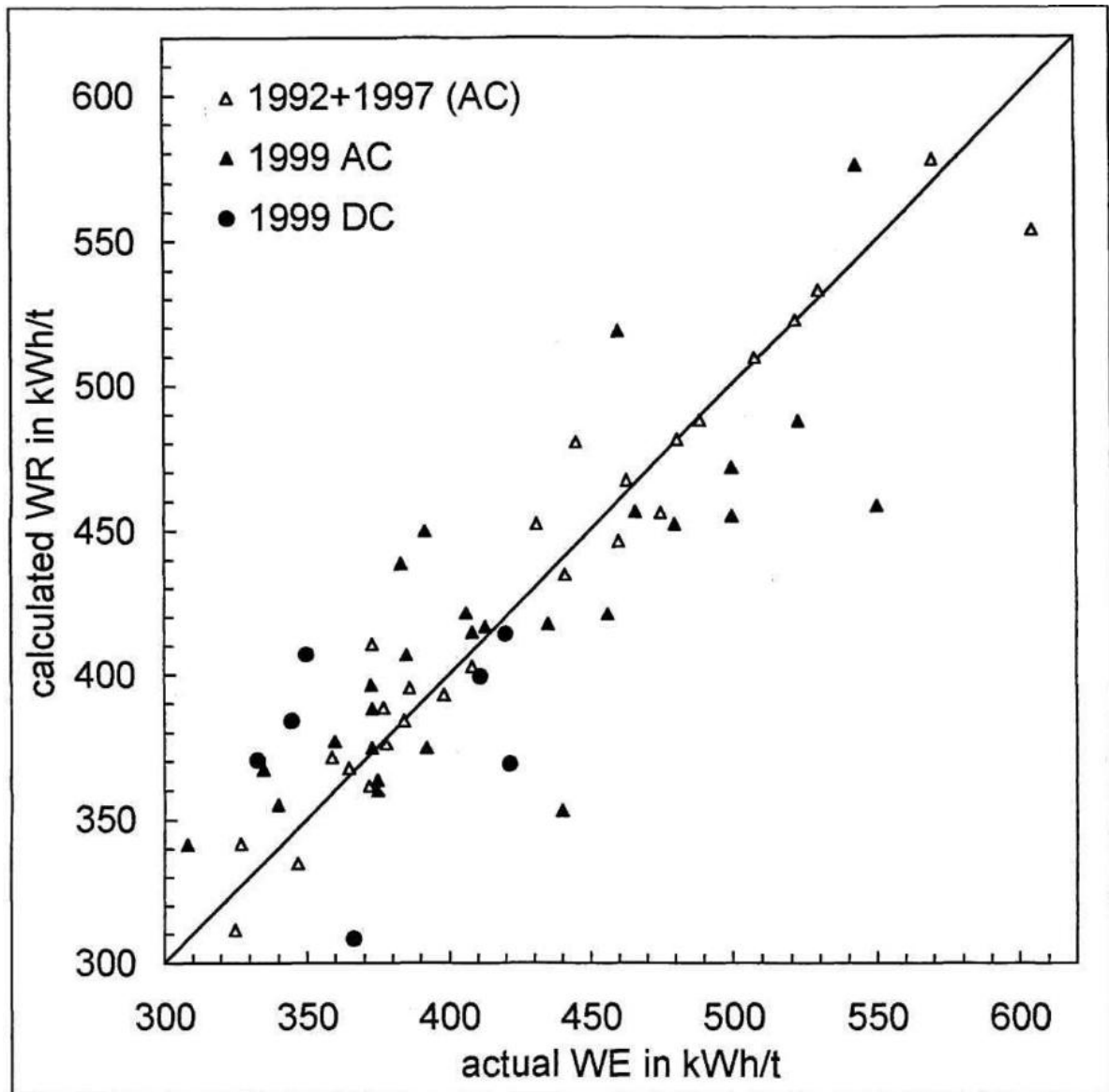
1999: 35 furnaces: extension to DRI, HBI, hot metal, CON (3)

Modification of the formula to fit single heat values from 5 furnaces and monthly average values from 1 furnace [7]

- adaptation of several factors
- extension to shredded scrap
- inclusion of energy losses if measured
- elimination of continuous/discontinuous operation

This modification has no great effect on the average values from the earlier investigated furnaces

6. Energy consumption of investigated furnaces



	actual WE ^K	error dWR = WR - WE	
values in kWh/t	mean value	mean value	standard dev.
1992+1997 AC	432	+1	17
1999 AC	420	-1	38
1999 DC	378	+1	46

Lower WE for DC furnaces with higher power + productivity
 Error dWR → no energetical advantage for DC furnaces

7. Calculation of electrode graphite demand [8, 9]

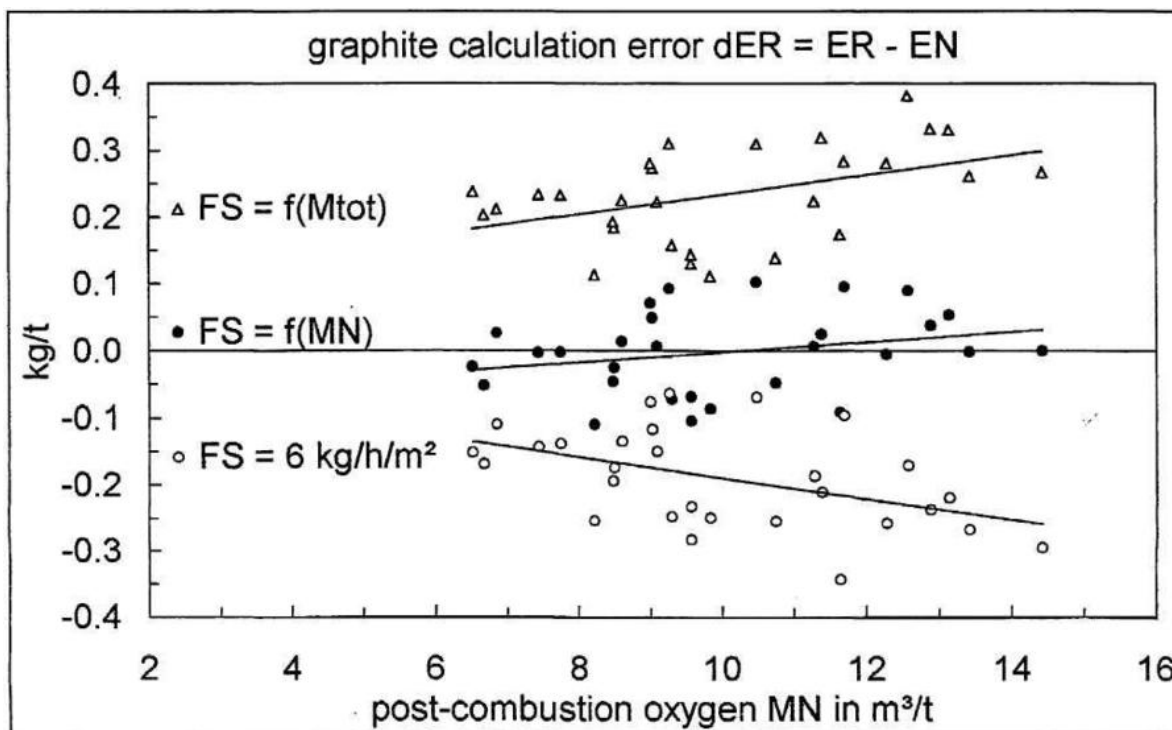
electrode tip consumption:	$E_T = N_E \cdot I_E^2 \cdot F_T \cdot \frac{t_S}{G_A}$
electrode side consumption:	$E_S = \left[N_E \cdot L_S \cdot \pi \cdot \frac{D_E + D_T}{2} \right] \cdot F_S \cdot \frac{t_S + t_N}{G_A}$ oxidising electrode surface
consumption without breakage:	$E_R = E_T + E_S$
N_E number of electrodes	L_S oxidising electrode length (≈ 3 m)
I_E electrode current	D_E electrode nominal diameter
F_T tip factor (0.013 kg/h/kA ²)	D_T electrode tip diameter
t_S power-on time	$D_T / D_E = 0.68$ for AC; 0.82 for DC
t_N power-off time	F_S side factor (6 kg/h/m ² ; see below)
G_A furnace tap weight	

Effect of oxygen on the side oxidation factor.

Total oxygen (10): $F_S = (3.8 + 0.135 \cdot M_{tot}) / (m^3/t)$ kg/h/m²

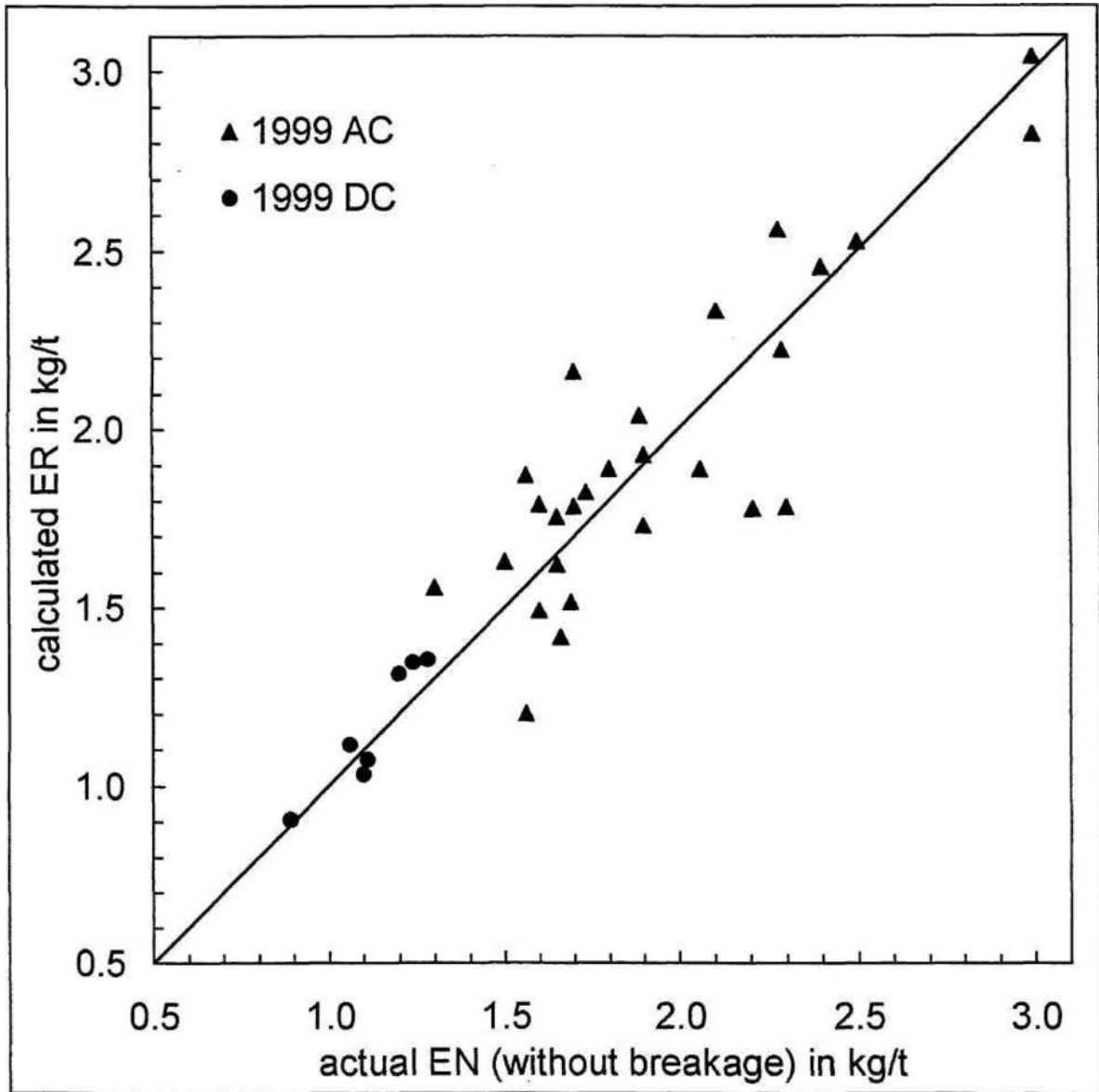
Post-comb.oxygen(11): $F_S = (6 + 0.15 \cdot M_n) / (m^3/t)$ kg/h/m²

Monthly averages of graphite consumption for an AC furnace



8. Graphite consumption of investigated furnaces

Estimation of oxidising electrode length: $L_s = 2.8m \sqrt[3]{G_A/100 t}$



	actual EN	error dER = ER - EN	
values in kg/t	mean value	mean value	standard dev.
1999 AC	1.95	0.00	0.23
1999 DC	1.13	+0.04	0.07

ER $\approx$ 1.5 kg/t for AC furnaces comparable to DC furnaces

9. Conclusions

Many advantages were claimed, mainly by furnace suppliers, for DC furnaces when these came up about 10 years ago [2]

	AC	DC
graphite consumption	100%	40...60% a)
energy consumption	100%	90...96% b)
refractory consumption	100%	70...100%
melting profile	cold spots	symmetric
bath stirring	bottom stirring	inherent
voltage fluctuation (flicker)	c) compensation plant	
	no: 100%	yes: 50 % no: 50 % d)
investment costs	100%	130...150%
bottom electrode	none	required
liquid heel	possible	required
arc voltage	100%	160...190% e)
electrode current	100%	190...160%

- a) Graphite consumption is 70.. .85% of that for comparable AC EAF
Advantage reduced by high graphite price for large DC electrodes
- b) No lower energy consumption under equal operating conditions
- c) AC flicker can be reduced by additional reactor at lower costs
- d) Flicker reduction for high-power DC furnaces lower as expected
- e) High arc voltage (arc deflection, high arc radiation) together with high current (large electrode) restrict electric power to «100 MW

10. References

- [1] Kohle, S.: Model-based control of AC electric arc furnaces.
Lecture within this seminar
- [2] Kohle, S.: Gegenuberstellung von Gleichstrom- und Drehstrom-
Lichtbogenofen (Comparison of DC and AC electric arc furnaces).
Stahl u. Eisen 114 (1994) No. 5, p. 37-41
- [3] Kohle, S.: Improvements in EAF operating practices over the last decade.
57th Electric Furnace Conference, Pittsburgh 1999, p. 3-14
- [4] Fuchs, H.; Schafer, H.; Jager, H.; Krug, K.: The world's first 800 mm diameter
graphite electrode commissioned at Peine, a company of the Salzgitter group.
7th European Electric Steelmaking Conference, Venice 2002, p. 1.75-1.81
- [5] Kohle, S.: Variables influencing electric energy and electrode consumption in
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- [6] Kleimt, B.; Kohle, S.: Power consumption of electric arc furnaces with
post-combustion. MPT International (1997) No. 3, p. 56-57
- [7] Kohle, S.: Recent improvements in modelling energy consumption of electric
arc
furnaces. 7th European Electric Steelmaking Conf.. Venice 2002, p. 1.305-1.314
- [8] Bowman, B.: Performance comparison between AC and DC furnaces.
Steel Times International, May 1993, p. 12-16
- [9] Bowman, B.: Performance comparison update - AC versus DC furnaces.
Iron and Steel Engineer 72 (1995) No. 6, p. 26-29
- [10] Bowman, B.; Lugo, N.; Wells, T.: Influence of tap carbon and arc voltage on
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Newer developments:

DC EAF with 813 mm electrode diam. [4] * 120 MW /140 kA

AC EAF with 1500 V transformer [13, 14] * >150 MW

10. References

- [1] Kohle, S.: Model-based control of AC electric arc furnaces.
Lecture within this seminar
- [2] Kohle, S.: Gegenuberstellung von Gleichstrom- und Drehstrom-Lichtbogenofen (Comparison of DC and AC electric arc furnaces). Stahl u. Eisen 114 (1994) No. 5, p. 37-41
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- [11] Kohle, S.: Improving the productivity of electric arc furnaces. BFI Report 2.32.007, 2003; contribution to ECSC Report EUR 20803, 2003
- [12] Potey, D.; Bowman, B.; Alameddine, S.: Electrode consumption model update 2004. 8th European Electric Steelmaking Conference, Birmingham 2005, Session 3A
- [13] Alameddine, S.; Ignacio, J.; Adams, W.; Bowman, B.: Use and limitations of very long arcs in AC arc furnaces. 8th European Electric Steelmaking Conference, Birmingham 2005, Session 8
- [14] Narholz, T.; Villemin, B.: The VAI Fuchs ULTIMATE - a new generation of electric arc furnaces. 8th European Electric Steelmaking Conference, Birmingham 2005, Session 2

international Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Construction and Operation of DC Electric Arc Furnaces (DC EAF)

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Dipl.- Ing. Andreas Hilbers

CONVERTEAM
THE POWER CONVERSION COMPANY
Essen, October 2006

Electrical Engineering of Arc Furnaces

Technologies leading Into the future

Construction and Operation of DC Electric Arc Furnaces [DC EAF]

**Furnace construction aspects, bottom electrode concepts, new
development of DC EAF technology, power limitation of
DC EAFs**

Design of DC EAF's

Contents

1. Introduction
 - 1.1 Why are DC furnaces used
 - 1.2 Process behaviour
 - 1.3 Comparison of investment costs AC/DC furnace
2. Structural design
 - 2.1 Plant layouts
 - 2.2 Direct-current generation
 - 2.2.1 Main components
 - 2.2.2 Rectifier circuits
3. Electrical design
 - 3.1 Electric arc voltage
 - 3.2 Power control reserve
 - 3.3 Reactor inductivity in direct control circuit
4. Bottom electrodes
 - 4.1 Concepts of bottom electrodes
 - 4.2 Service life of bottom electrodes in the DC furnace
 - 4.3 Electric arc deviation
 - 4.4 Economic aspects
5. Graphite electrode
6. DC EAF in operation
7. Power limit
8. Prospects
9. Sources

1. **Introduction**

The first industrial-scale electric arc furnace was tapped in a meltshop in Remscheid (Germany) in 1906. Since that time, all electric arc furnaces were first designed and built as three-phase AC furnaces, as it was technically and financially impossible to design them as direct-current furnaces. AC furnaces underwent a steady development over the years, resulting in a high-performance smelter which due to its lower investment cost compared to a BOF and its high degree of flexibility has attained a significant share in the world's steel production.

1.1 **Why are DC furnaces used**

The tremendous pressure of costs and the declining steel prices demanded that the electric arc furnaces be optimised and production costs lowered.

At the end of the 70s, the semiconductor industry showed phenomenal progress. It was possible to build high-performance thyristors at a reasonable price and to convert three-phase alternating current into direct current in an economical manner.

MAN GHH was the first to begin with the development of direct-current electric arc furnaces in 1980. The first large-scale technical tests and developments were carried out in the prototype direct-current furnace (121 / 6 MW) installed in the foundry of Schloemann-Siemag AG in Kreuztal-Buschhütten in 1981. Four years later, the first 321 / 11.5 MW direct-current furnace, type: UNARC®, took up operation at NUCOR Corp., Darlington / USA. The expected advantages of the direct-current furnace were proved in this facility in the three-shift operation. The main results were:

- Reduction in electrode consumption
- Reduction in network flicker
- Reduction in energy consumption per ton of liquid steel
- Excellent meltdown behaviour and intimate mixing of the bath
- Reduction in noise level
- High availability
- Uniform thermal load inside the furnace

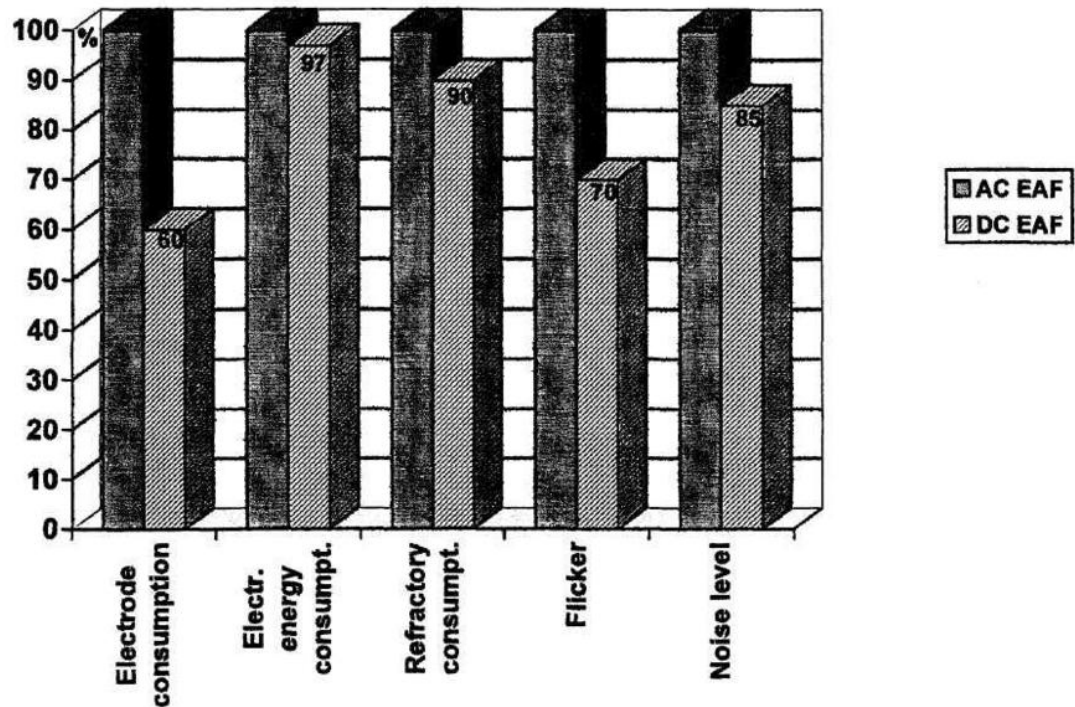


Diagram 1: Advantages of a DC furnace compared with a standard AC furnace(1985)
(average values for medium-range furnace sizes)

These advantages prove that the DC furnace is a good alternative to the three-phase AC furnace.

Around 110-130 DC furnaces are in operation all around the globe today (status: 2006)
with an electrical power output of up to max. 1400 kWt liquid steel.

Performance data of a 1001 DC furnace:

Customer	Peiner Trager GmbH, Salzgitter Group
Manufacturer	MANGHH
Tapping weight	1001
Hot heel	201
Charge material	100 % scrap, cold, charged in two buckets
Shell diameter	7.1/7.3 m
Arc power	85 MW (~ 710 V and 120 kA)
Electrode diameter	750 mm, Start-up (Today 800mm)
Oxygen	0 28Nm ³ /tfl
Charged and injected carbon	0 14kg/tfl
Tap-to-tap time	0 33-35 min.
Power on time	0 23-24 min.
Bottom electrode	Pin-type (large-surface), UNARC
Number of round bar pins	240 (40 with temperature control)
Electr. energy consumption	0 350kW/tfl
Graph, electrode consumption	00,9kg/tfi
Monthly production, max.	100,000 tfi
Heats Der dav. max.	43

Fig. 1: Works photograph of the first German high-performance 1251 / 80 MW direct-current electric arc furnace in the GeorgsmarienhQtte steelworks, Type: UNARC •

Fig. 2: Elementary diagram of an SMS Demag direct-current electric arc furnace Type: UNARC •

1.2 Process behaviour

1.2.1 Bath movement (with "pin- type" bottom electrode)

Due to the central arrangement of the bottom electrode (anode) and the graphite electrode (cathode), the DC furnace shows a considerably better mixing of the bath (see Fig. 3). The reason for this is:

- The magnetic field (tapered current distribution) which is caused by the flow of current from the cathode to the anode in the melt (see computer model for an SMS Demag DC furnace, Fig. 4)

A secondary factor is the displacement of the liquid steel in the middle of the bath as a result of the blowing pressure of the electric arc.

Due to the good mixing of the bath, an additional stirring by means of inert gas or stirring coils can be dispensed with in DC furnaces with centrally positioned bottom electrode.

1.2.2 Meltdown behaviour

Here again, the central arrangement of the anode and cathode in DC furnaces shows an excellent meltdown behaviour for scrap (Fig. 5). The electric arc bores uniformly from the top through the scrap to the bath. The electric arc which then burns on the bath ensures that the scrap melts down uniformly and forms a cavity which looks like a pear. In this melting phase, the scrap protects the wall and roof elements from the extremely high radiation heat of the electric arc. During meltdown, the scrap does not cave in like in the AC furnace (which often leads to electrode rupture), but melts down uniformly.

1.2.3 Foamy slag

Due to the fact that the entire electrical energy in the DC furnace is transmitted by one electrode, the radiation power of the electric arc is very high.

For example: A higher-power DC furnace with an arc power of 80 MW, a direct current of 115 kA, is operated with a direct-current voltage of 695 V. The approximation of 1 V DC = 0.6 to 1.2 mm for the electric arc length results in an electric arc length of 400 to 830 mm during operation, regardless of which process condition is currently prevalent. In comparison, an AC furnace with the same power would have an electric arc length of approx. 210 mm - 350 mm.

	DC furnace	AC furnace
Power	80 MW	80 MW
Theoretical electric arc length	- 400 - 830 mm	-210-350 mm

This clearly shows that when operating a DC furnace special attention must be given to the shielding of the electric arc. During scrap meltdown, the furnace is operated at low power in the initial "bore down" phase. Once the furnace shell is shielded from the electric arc radiation by the scrap, the furnace can be operated at full electrical power. In the liquid phase, directly after the melting of the scrap, the wall and roof elements of the upper furnace shell must be protected by a sufficiently high level of foamy slag from the radiation of the electric arc.

For the production of the foamy slag, the following aspects must be borne in mind in addition to the quality and production conditions:

- sufficiently high carbon content of the bath
- sufficient amount of lime
- sufficient bath temperature

1.3 Comparison of investment costs AC/DC furnace

Compared with the AC furnace, the DC furnace has approx. 25 % to 35 % higher investment costs due to the additional expense involved in the generation of direct current.

On the other hand, this is offset by the savings in the operating costs of the DC furnace. Depending on the local prices for energy, graphite electrodes etc., operating costs worth € 5 /t of steel can be saved.

2. Structural design

For the profitable use of direct-current furnaces, there is one essential prerequisite with regard to the electrical engineering: the hot heel operation

The electrical contact between the bottom electrode (pin-type, fin-type, billet-type) and the meltdown material (scrap, DRI etc.) is established by means of the liquid hot heel in a uniform manner. This ensures that in the case of max. direct current, none of the contacts (conductors) of the bottom electrodes is overloaded and possibly melts.

2.1 Plant layouts

The layout of a DC furnace is similar to that of an AC furnace. The two deviating features are the current supply to the bottom electrode and the arrangement of the direct-current generation system. The following elementary diagrams show the various solutions presented by the individual furnace builders:

Fig. 6 Danieli (billet-type)

Fig. 7: SMS Demag (pin-type)

Fig. 8: SMS Demag (pin-type), New design

Fig. 9: SMS Demag - Concast(ABB) (carbon bricks)

Fig. 10: SMS Demag (billet type)

Fig. 11 :Siemens VAI (fin-type)

2.2 Direct-current generation

The direct current technology allows the continuous input of power into the DC furnace.

In the case of the DC furnace, the rectifier transformer/s and the power converter/s can be installed on the mill floor (favourable civil-work costs).

A special advantage of the DC furnace is the possibility of not installing the power supply unit directly near the furnace shell and not on the furnace centre line. In the case of very large DC furnaces, twin-shell DC furnaces and the installation in existing steelworks bays, this can be decisive.

Fig. 12 shows a possible, practical design.

2.2.1 Main components

Rectifier transformer

Fig. 13

Rectifier transformers are three-phase transformers which transform high voltage into low voltage. The secondary-side circuitry is matched with the type of rectifier circuit (6 pulse, 12 pulse etc.).

Rectifier transformers can be operated without a tap changer since the rectifier technology enables infinitely variable setting of power. In practice, some furnace builders install a tap changer (no load) on the high-voltage end of the rectifier transformers. The reason for this is to optimise the cos phi with changing meltdown materials.

Rectifier

Fig. 14

Thyristor

Fig. 15

Cooling

Fig. 16

Control

The control system for the DC furnaces consist of two control circuits which can be set independently of each other. The first control circuit is the voltage control which, by activating the electrode positioning control circuit (regulating cylinder), influences the electric arc length and indirectly the direct-current voltage. The second control circuit is the current control which determines the direct current via activation of the thyristors.

Smoothing reactor

Fig. 17

- Function of the reactors

Fig. 18

High-current system

Here, electrical losses have to be taken into account when selecting the conductor material (copper or aluminium).

2.2.2 Rectifier circuits

- 6-pulse circuit
- 12-pulse circuit

3. Electrical design

3.1 Electric arc voltage

Theoretical examinations of [1] and operating experience with high-performance DC furnaces show, depending on the direct current amperage, that at approx. 750 - 800 V the value for the maximum direct current voltage is attained at a direct current inductivity of 75 uH.

Practical figures show that the ratio between direct current voltage and direct current should be approx. 7:1000 for a stable electric arc.

Higher direct current voltage can be attained with higher direct current inductivities and/or correspondingly higher direct current in the DC furnace.

3.2 **Power control reserve**

The electric arc of the DC furnace has to be re-struck in case of interruption. This process takes up precious production time. In order to avoid this, the electric arc can in the case of an impending electric arc interruption be extended within the period of 20 to 40 msec (12-pulse circuit, $L_{\text{total}} = 75 \text{ uH}$) by bringing forward the firing angle (Fig. 19 and 20) of the thyristors.

The risk of electric arc interruption can, for instance, occur if the electric arc burns between the graphite electrode and a long, thin steel piece. The steel piece melts down faster than the graphite electrode (mass inertia) can be reset by the electrode regulation circuit.

SMS Demag has a fixed power control reserve here of 20 % ($L_{\text{total}} = 75 \text{ uH}$). This means that in the case of an impending electric arc interruption, the rectifier control intervenes and the electric arc voltage is increased by 20 % and the electric arc is consequently extended by 20 %.

3.4 Reactor inductivity in direct current circuit

The main function of the reactor in the direct current circuit is to protect the thyristors in case of a short circuit (see 2.2.1). This defines the minimum reactor inductivity.

Another function is the stabilising of the electric arc current. The decisive factor here is the amount of the total inductivity (Fig. 21). The measurements (Fig. 22) of DC furnaces with varying total inductivities clearly show the influence of a more constant electric arc current on the disturbing flicker.

Typical reactor inductivities for DC furnaces:

Furnace builder:	Reactor inductivity	Total inductivity
Danieli	?	?
SMS Demag (without Concast)	First generation: 2 * 75 jxH Actual: 2* 500 jxH	First generation: 37.5 jxH Actual: 250 jiH
Siemens VAI	Actual: 4*100 p.H Future: 4* 150 iLiH	Actual: 25 juH Future: 37,5 viH

4. Bottom electrodes

4.1 Concepts of bottom electrodes 4.1.1

Uncooled bottom electrodes

- **Bottom electrode Siemens VAI (fin-type) [3]**

Fig. 23

Conductor material:	Steel plate 1.5-2 mm
Cooling:	None
Monitoring:	Temperature measurement
Min. change time	8 hours
Wear rate, average	0,3 - 0,5 mm/heat

4.1.2 Air-cooled bottom electrode

Bottom electrode SMS Demag (pin-type)

Fig. 24

Conductor material:	Round bar 0 42-45 mm
Cooling:	Air
Monitoring:	Temperature measurement
Min. change time	10-12 hours

- Change of bottom electrode

Fig. 25

- Bottom electrode

Fig. 26

- Hearth without bottom electrode

Fig. 27

- **Bottom electrode Concast (former ABB)**

Conductor material:

Cooling :

Monitoring :

Min. change time

Fig. 28

Large-surface, conductive
shell bottom of magnesite % and
graphite bricks(C>15)

Air

?

The hearth is relined here.

4.1.3 Water-cooled bottom electrodes

- **Bottom electrode SMS Demag (billet-type)**

Conductor material

Cooling:

Monitoring:

Min. change time

Fig. 29

Steel/copper billets

Water, outside the shell

Temperature measurement

Normally a furnace shell
change is carried out.

- **Bottom electrode Danieli (billet-type)**

Conductor material

Cooling:

Monitoring:

Min. change time

Fig. 30

Steel/copper billets

Water, within the shell

Temperature measurement

Normally a furnace shell change
is carried out?

4.2 Service life of bottom electrodes in the DC furnace

When designing the first DC furnaces, one of the crucial questions raised by the furnace builders was: How long will the bottom electrode last compared with the refractory material of the furnace bottom?

For all furnace builders the service life of the bottom electrodes has distinctly increased from the first bottom electrodes to the ones used today.

	Carbon bricks	Billet-type	Pin-type	Fin-type
Service life	Up to 3000 melts	Up to 1500-3000 melts	Up to 1500 melts	Up to 2000 melts
Refractory material	Carbon bricks	Ramming mass/bricks	Ramming mass	Ramming mass
Intermediate repairs	Yes (Carbon bricks)	Yes (refractory material)	No	No

The bottom electrodes with metallic conductors (billet-type, fin-type, pin-type) are changed after the conductors have been consumed and reassembled outside the furnace, i.e. the consumed conductors are replaced. To ensure short idle periods of the DC furnace, replacement bottom electrodes are recommended.

4.3 Electric arc deviation

The electric arc should burn centrally inside the furnace to ensure uniform meltdown behaviour and thermal loads.

The following decisive factors must be borne in mind when designing a DC furnace:

- Thermodynamics inside the furnace
- Arrangement of the direct current system
- Arrangement of lances and burners
- Feeding and type of melting stock
- Feeding positions of addition agents

4.4 Economic aspects

The most important points for the steel maker are reliability in operation/availability and the costs per ton of liquid steel.

When looking at the operating costs, the following points must be taken into account:

- Costs of the bottom electrode incl. the refractory material
- Service life of the bottom electrode in the DC furnace
- In-between repairs on the bottom electrode

Idle period of the DC furnace when changing the bottom electrode

In a sample calculation for a 1351 SMS Demag UNARC DC furnace with a tap-to-tap-time of 60 minutes, the operating costs for the bottom electrode per ton of liquid steel range from approx. 0.9 to 0.11 €.

5. Graphite electrode

The graphite electrode is centrally positioned in the furnace shell. Like in the AC furnace, the conductive material used here is also graphite. Since the entire electrical power in the DC furnace is supplied to the furnace only via one electrode (three-phase alternating current: 3 electrodes), this electrode is expected to meet special requirements.

The high-performance DC furnaces used in steelworks today (e.g. the Salzgitter AG steelworks in Peine: 1001 SMS Demag DC furnace with an electrical effective power of 85 MW) demand that electrode manufacturers develop graphite electrodes for direct currents in the range of 110 kA to 140 kA.

A special problem here is the thermal conductivity from the electrode core (~ 2400 - 2700 °C) to the electrode surface (~ 1650 - 1700 °C). This occurs in particular with the swung-out electrode (~ 20 - 50 °C outside temperature) during charging (Fig. 31).

Today a Ø 750 mm graphite electrode is offered on the market by electrode manufacturers for an amperage of 120 to 130 kA. The costs (€/kg) of the Ø 750 mm graphite electrode compared with the standard sizes (of the Ø 500, 600 mm) of the AC furnace are approx. 15 % higher.

Diameter in mm / inch	600/24	700/28	750/30	800/32
Max. current acc. to manufacturer in kA (for standard consumption)	100	120	130	140-160
Price*	100%	110%	115%	120%?

*) Depending on manufacturer

6. DC-EAF in operation (example)

Nucor Berkeley / USA Main data Fig. 32

Power input Fig. 33

7. Power limit

The power limit for DC furnaces (with one graphite electrode) is nowadays clearly determined by the graphite electrode. The max. electric arc power of a modern DC furnace with a 750 mm Ø graphite electrode falls within the range of 90 MW to 105 MW today (Fig. 34).

With the newly designed 800 mm Ø graphite electrode, a range of 125 to 135 MW could be attained.

If even larger electrical power systems are to be installed in the future, this will imply new tasks for

- the furnace builders
- the manufacturers of graphite electrodes

By limiting the max. current for the graphite electrode, a larger electrical power will automatically result in a higher direct-current voltage. The ensuing longer electric arc and the related higher radiation as well as the additional increase in the use of chemical energy (e.g. oxygen, natural gas, post-combustion) requires an accurate observation of the inside of the furnace with regard to the thermal load that then occurs.

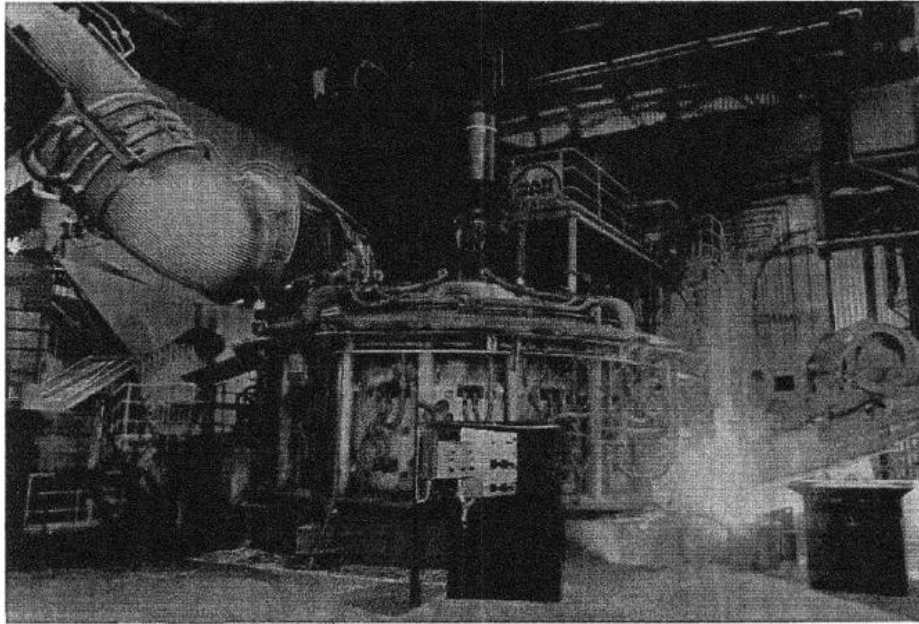
8. Prospects

- Two graphite electrode direct-current furnaces Fig. 35
- Replacement of bottom electrodes in existing DC-EAFs (first generation)

9. Sources

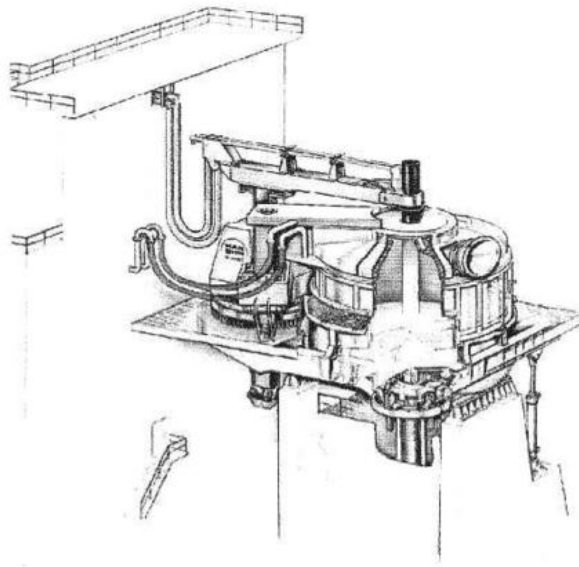
- [1] Bendzak, G.J.; MQller, E.G.: Effect of electromagnetic forces on arc and steel bath circulation in high powered electric arc furnaces**
- [2] Klein, R.-D.; Wimmer, Karl: Gleichstromelektroden-Schlusselfaktor des Fortschritts in der Elektrostahlerzeugung Stahl und Eisen 115 (1995)**
- [3] The world of VAI/Fuchs / EAF and LF Technology, May 1998**

125 t DC- Furnace in Germany



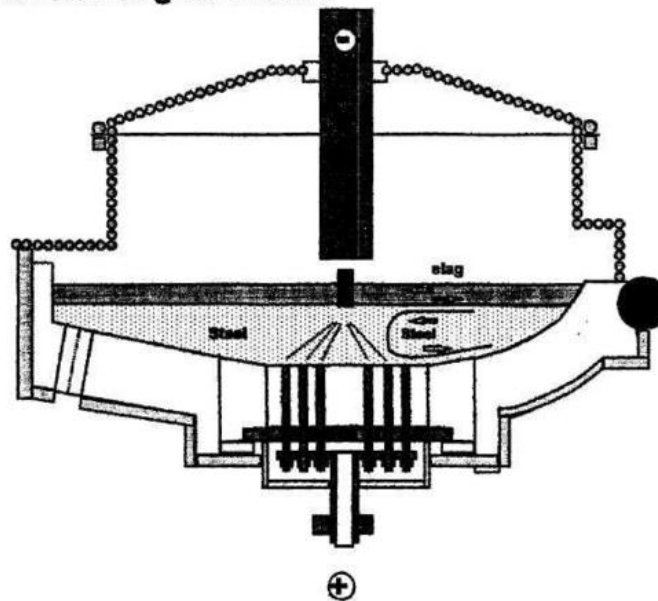
1

Elementary diagram of an SMS Demag DC-Furnace



2

**DC- Furnace
Steel bath and slag movement**



**Computer model
Bath movement in a DC Furnace**

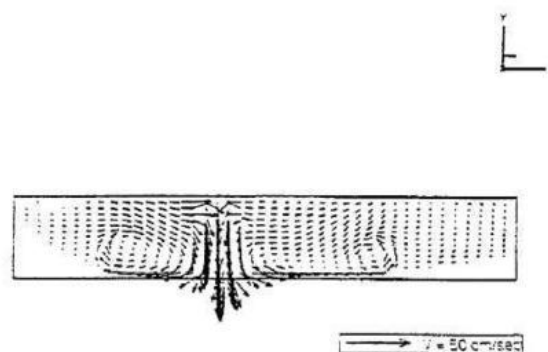
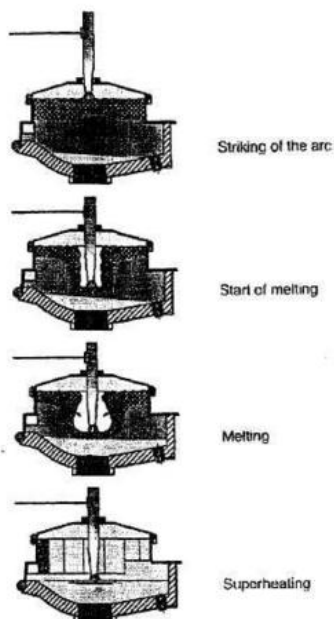


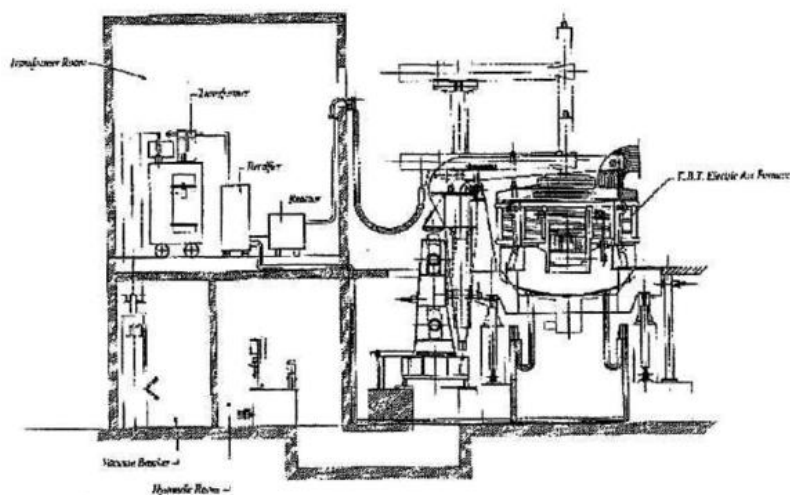
FIG. 14 Furnace Circulation Along Line 1 of Figure No. 13

Meltdown behaviour

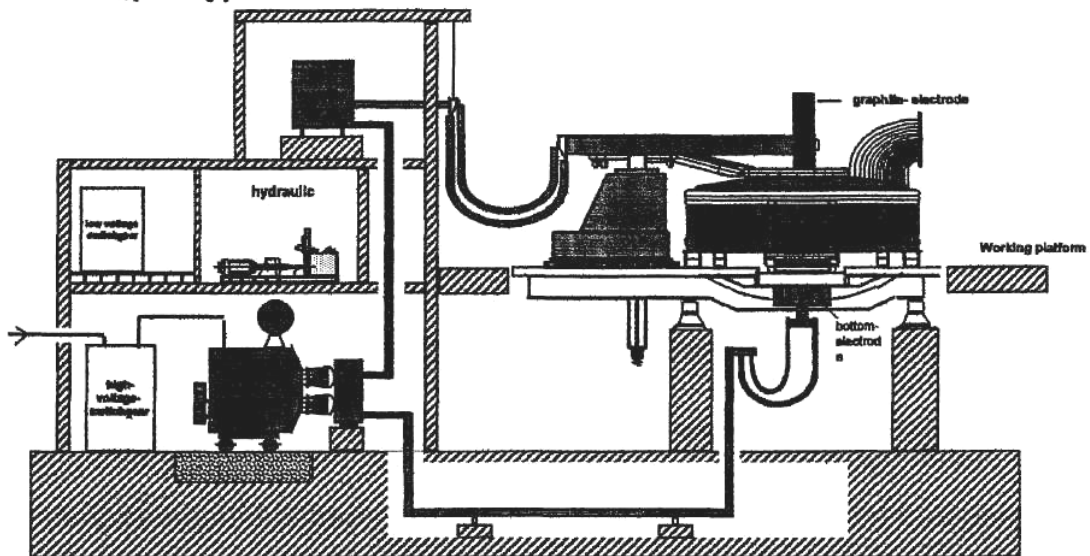


Layout of a Danielli- DC-Furnace „billet type“

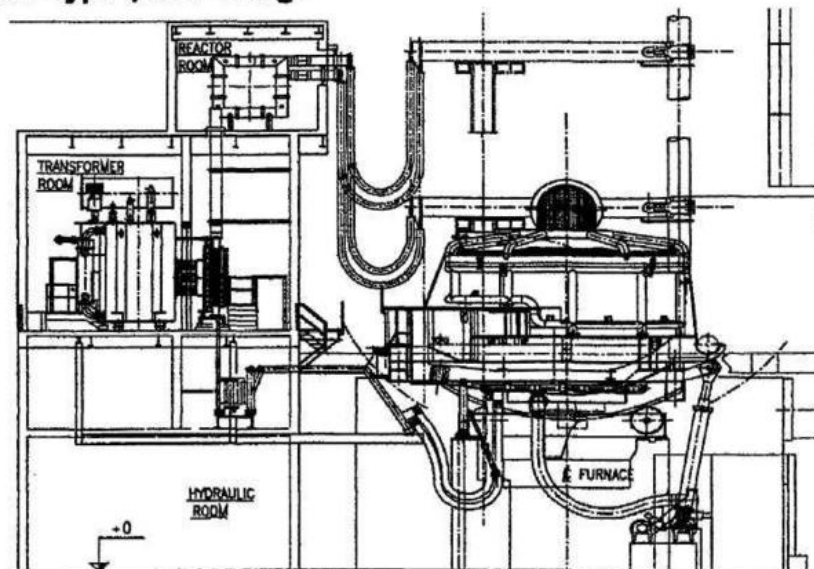
DC furnace assembly



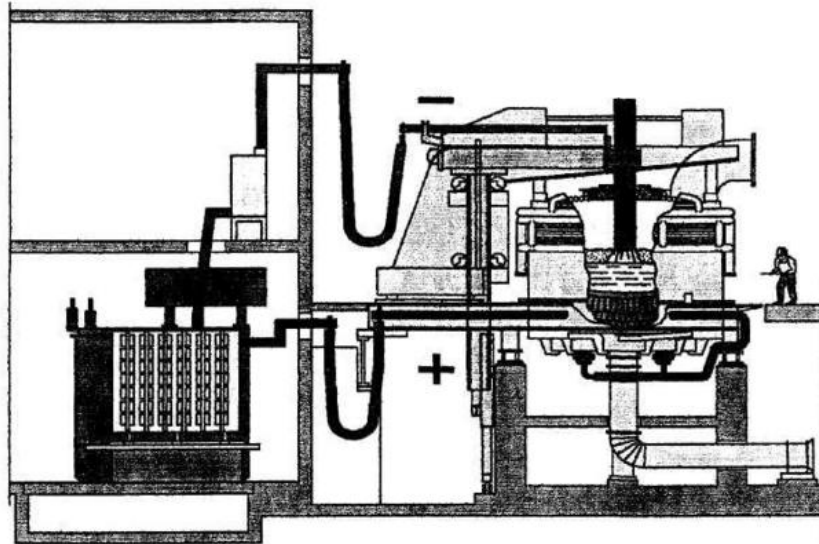
Layout of a SMS Demag- DC- Furnace „pin- type“



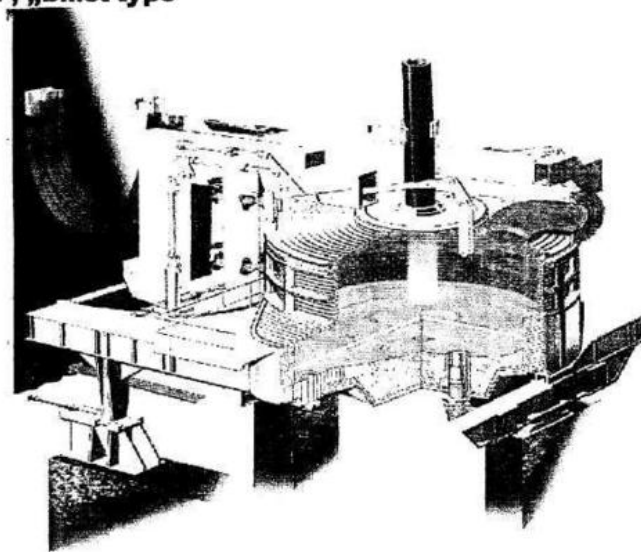
Layout of a SMS Demag- DC- Furnace „pin- type“, new design



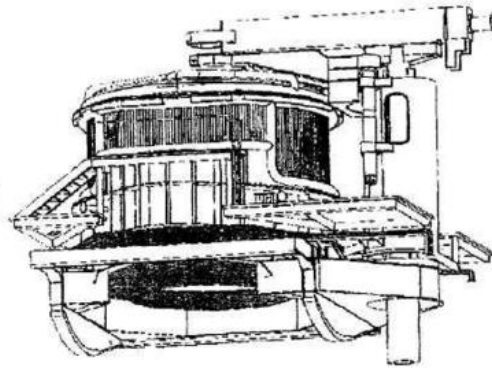
**Layout of a Concast- DC -Furnace
„Carbon- bricks“**



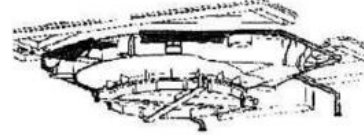
**Layout of a SMS Demag
DC EAF, „billet type“**



Layout of a Siemens VAI - DC Furnace „fin-type“

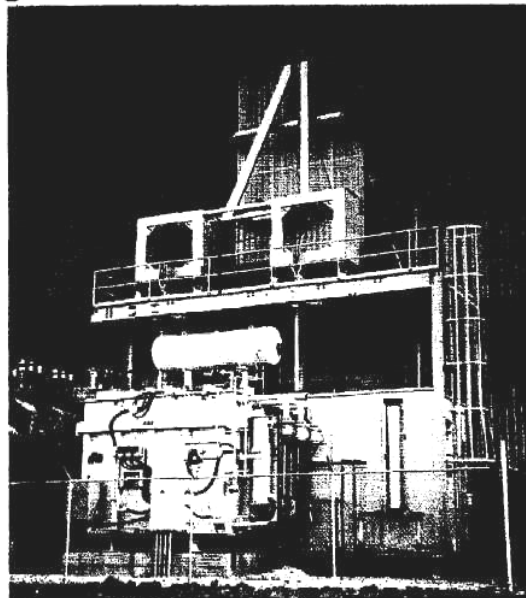


GENERAL ARRANGEMENT
(ANODE REMOVED)

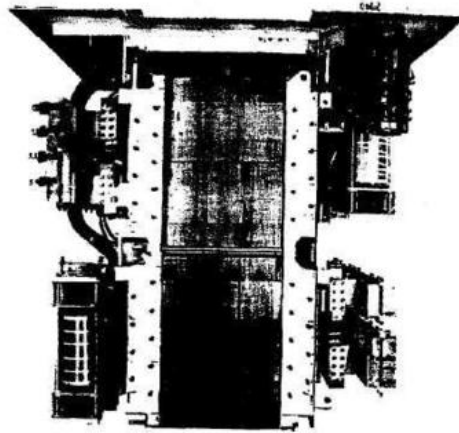


CONNECTION OF HIGH CURRENT PIPES

Works photograph ABB Practical design



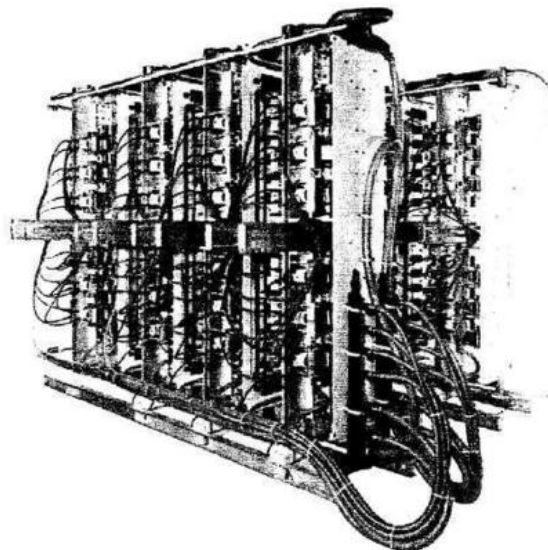
**Works photograph ABB
Rectifier transformer**



109 MVA - 120 kA for 12 pulse
thyristor rectifier

13

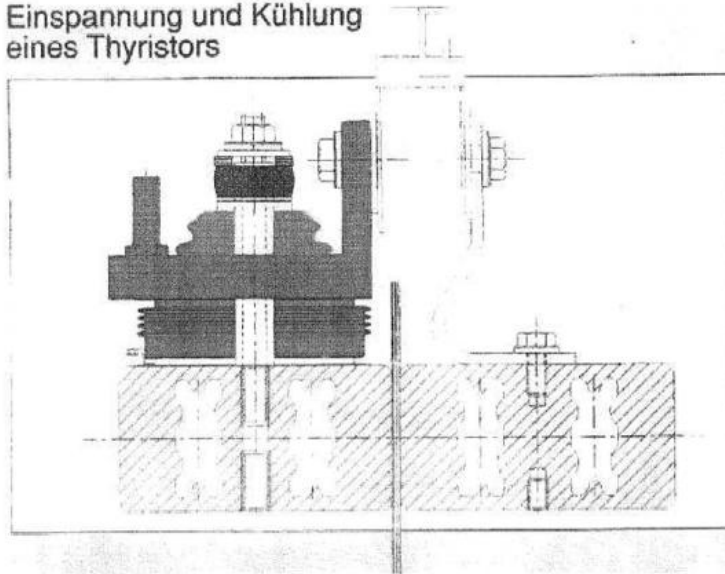
**CONVERTEAM:
Water cooled rectifier**



14

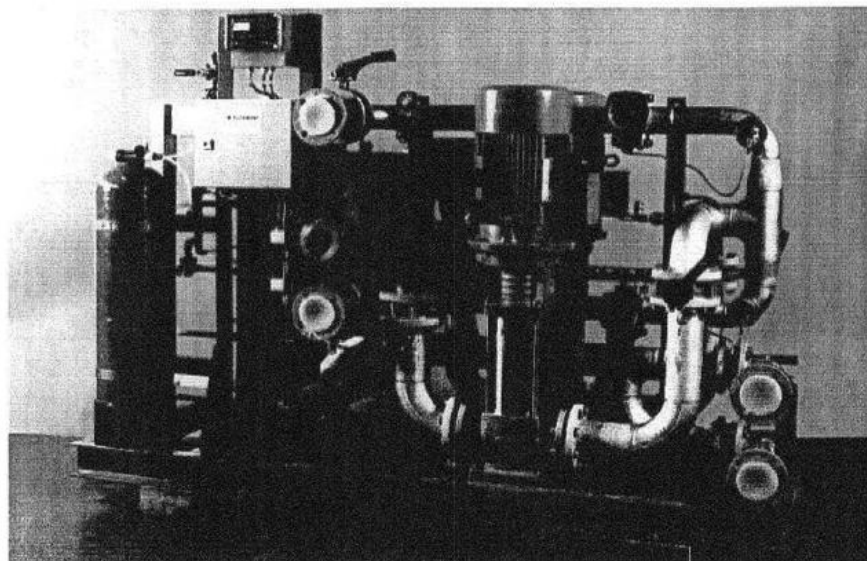
**Siemens VAI:
Thyristor**

Einspannung und Kühlung
eines Thyristors



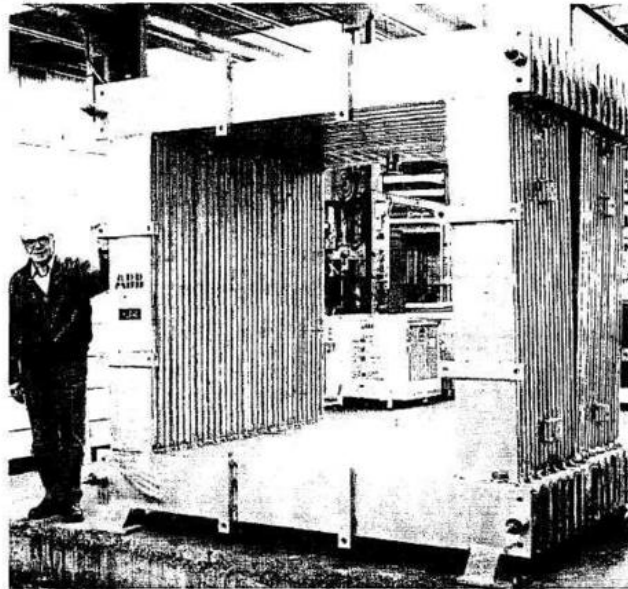
15

**Works photograph ABB
Cooling modul**

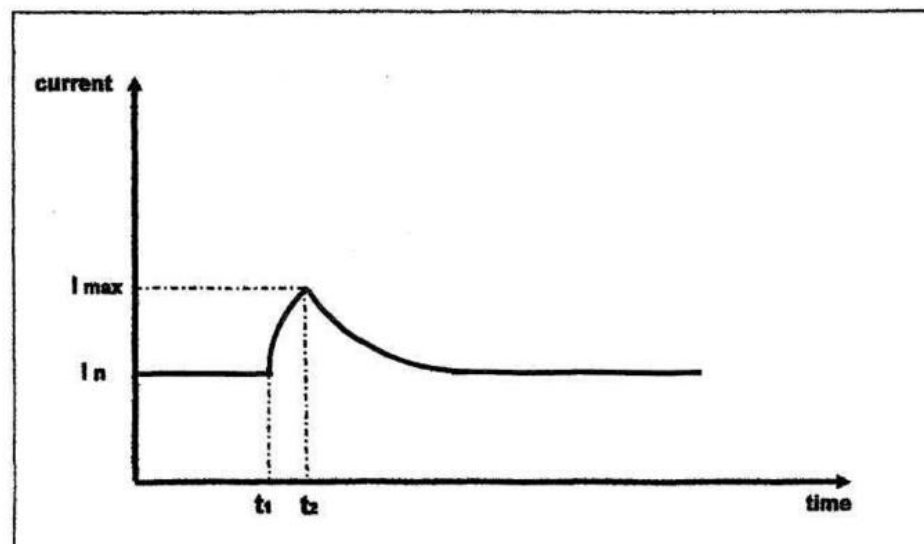


16

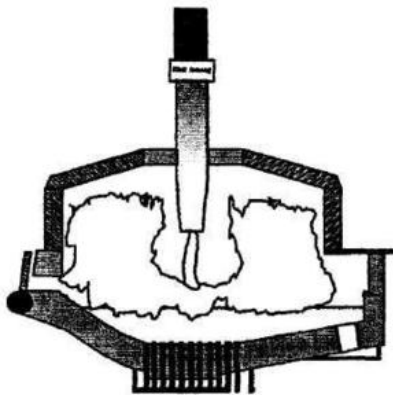
**Works photograph ABB
Smoothing reactor**



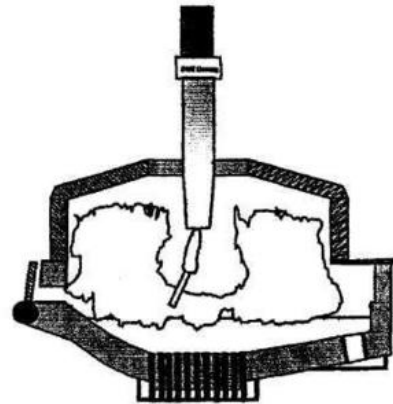
Function of the reactor



Electric arc interruption



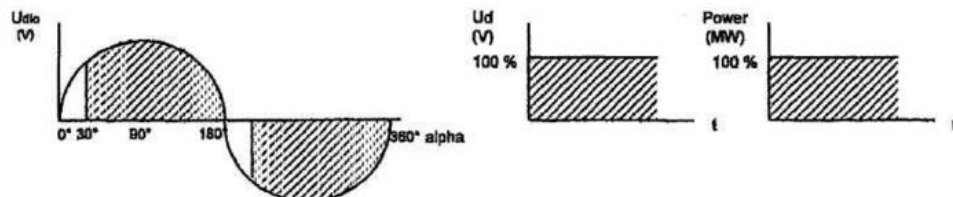
Case A) Normal operation



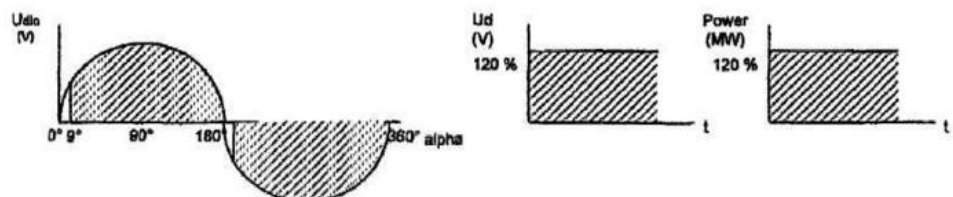
Case B) Interruption

Firing angle / voltage reserve of the rectifier

Case A) Normal operation



Case B) Interruption



DC-current stability in dependence on the total inductivity of the DC- Furnace

Total inductivity
[$\mu\text{H}/\text{DC-furnace}$]

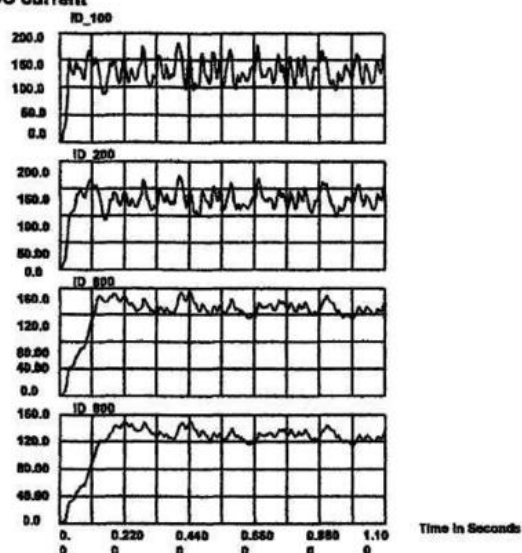
50 μH

100 μH

200 μH

300 μH

DC current

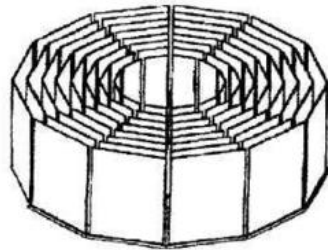


Flicker- Level

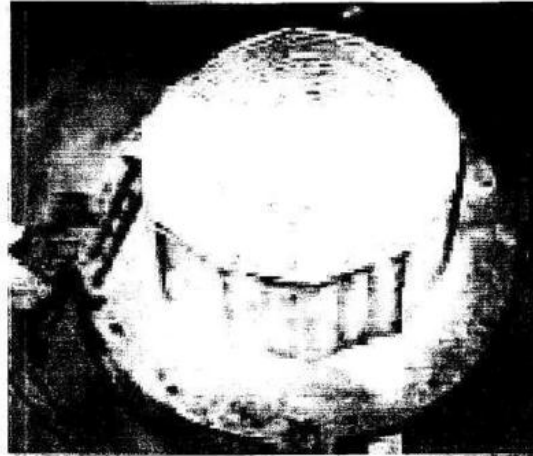
DC- Furnaces	A	B	C	D
Short circuit capacity at Pcc [MVA]	2750	3136	5160	2600-3000
Ratio: Short circuit capacity at Pcc / DC Furnace short circuit capacity	40	42	42	31-36
DC-furnace total indutivity	41 μH	40 μH	100 μH	550 μH
Pst Flicker (10 min)	2.2	2.0	1.0	0.84

(Flicker value without compensation equipment)

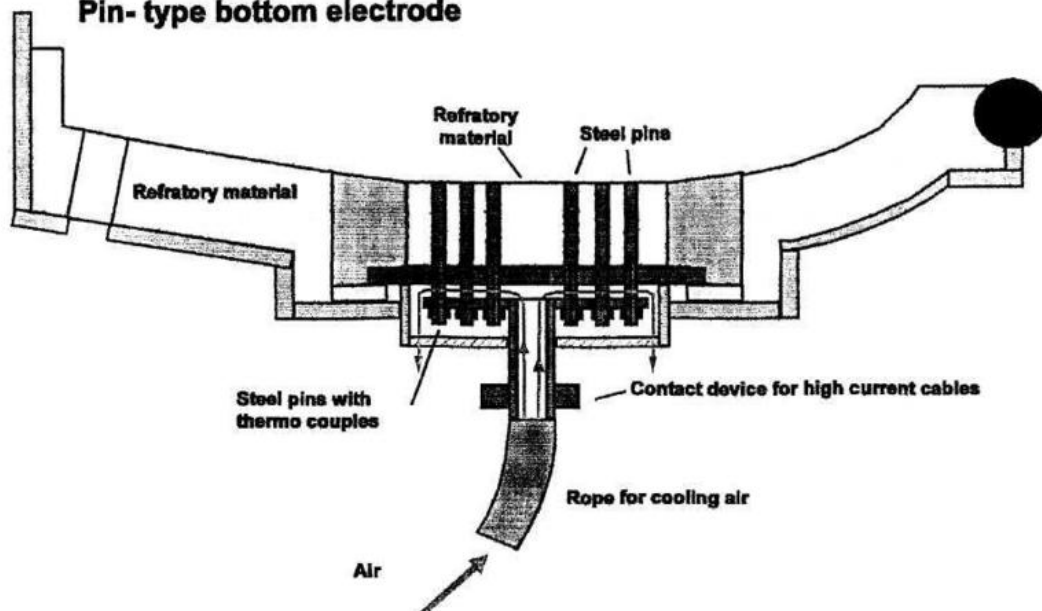
**Siemens VAI
Fin- type bottom electrode**



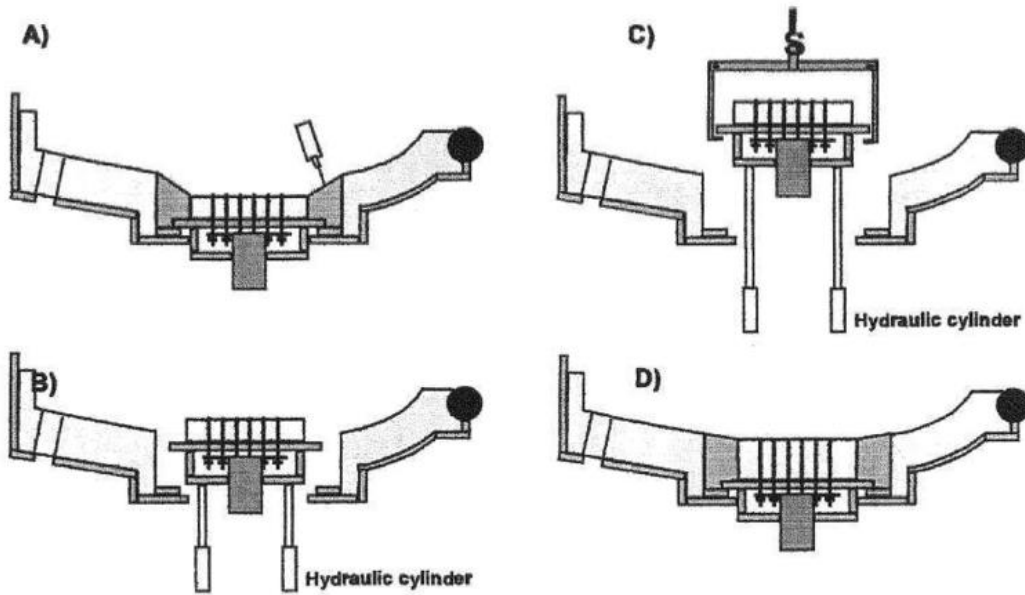
FINS ARRANGEMENT



**SMS Demag
Pin- type bottom electrode**

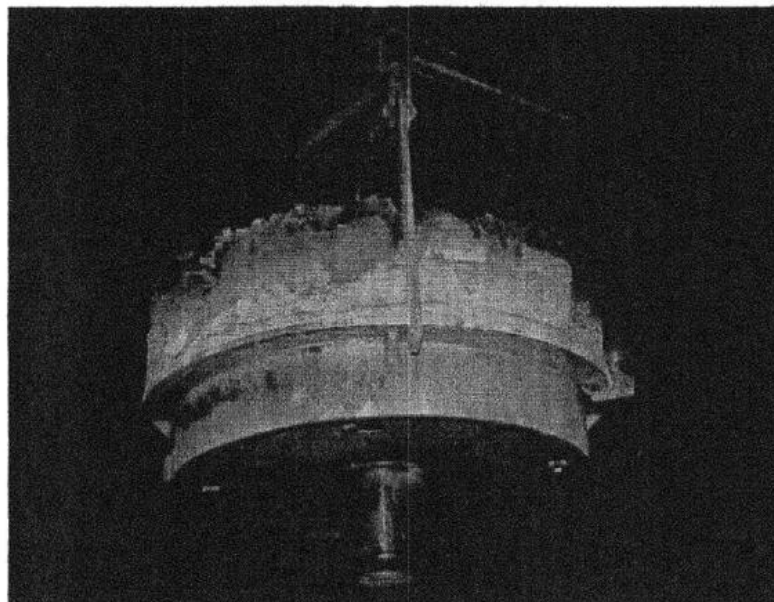


Change of pin- type bottom electrode



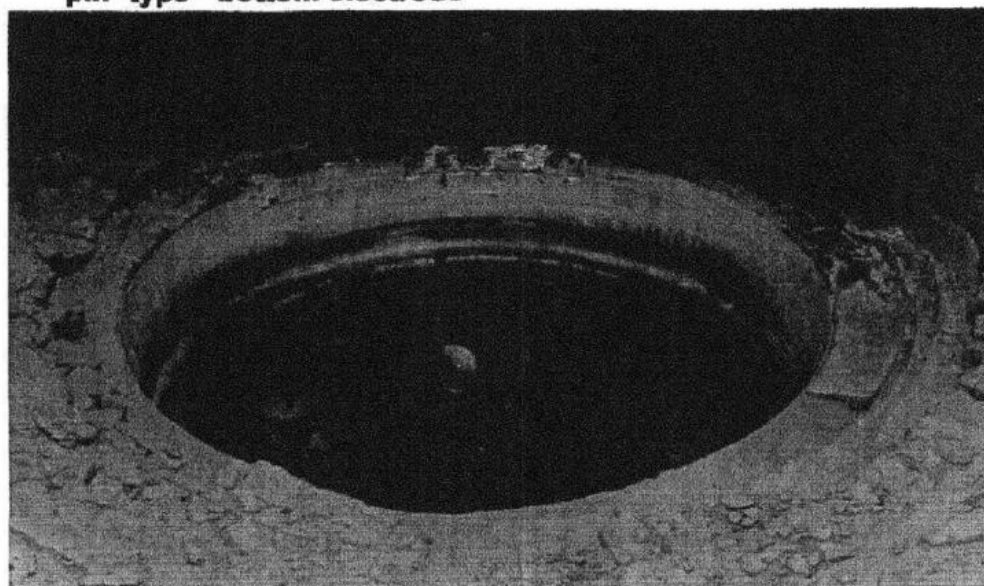
25

Pin- type - bottom electrode



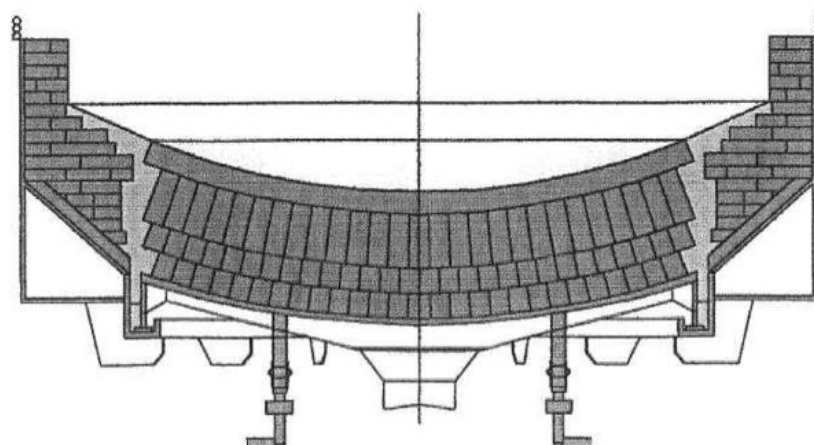
26

**Furnace shell without
pin -type - bottom electrode**



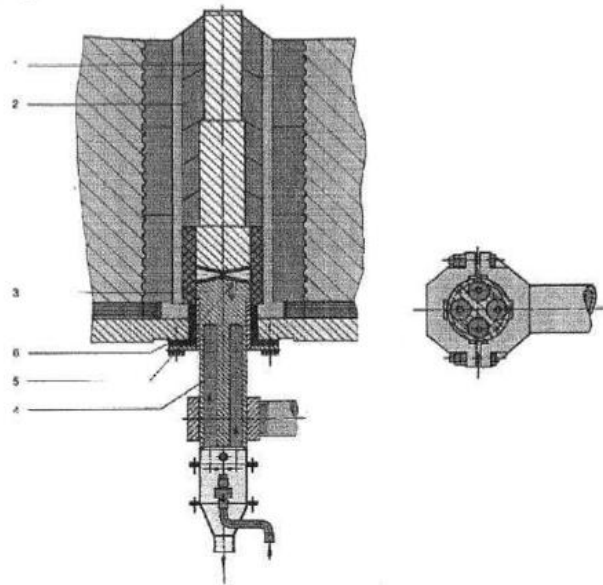
27

**Principle: Bottom electrode
Concast (Former ABB)**



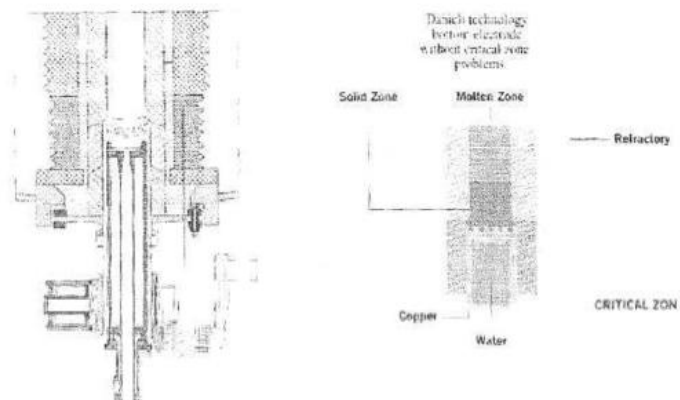
28

**Principle: Billet- type bottom electrode
SMS Demag**



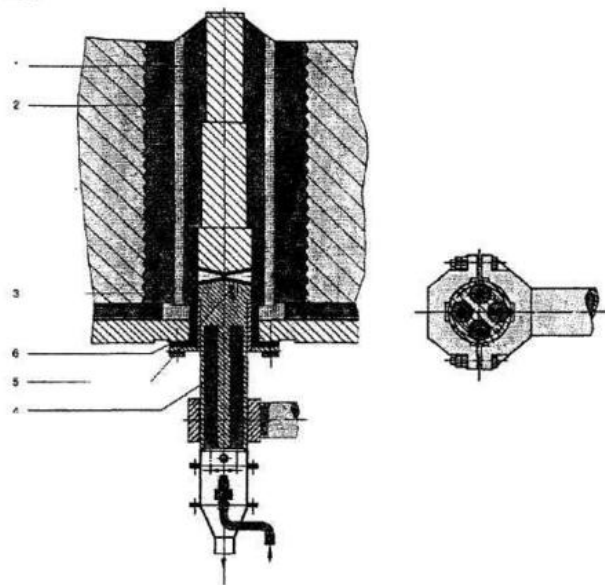
29

**Principle: Billet- type bottom electrode
Daniele**

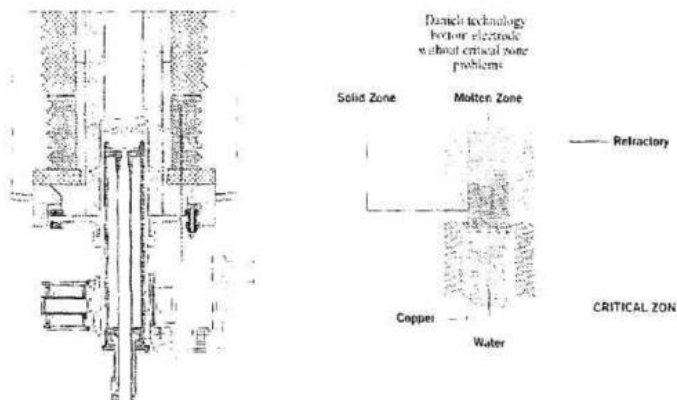


30

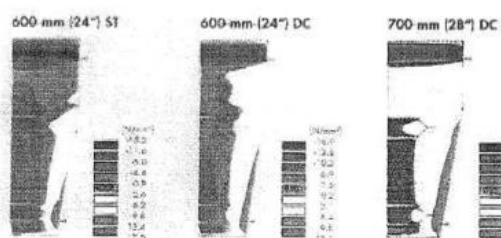
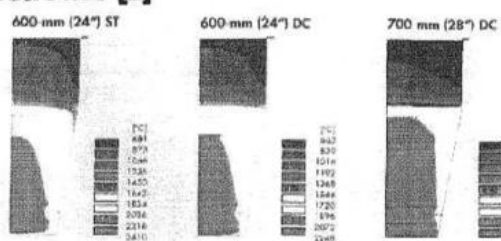
**Principle: Billet- type bottom electrode
SMS Demag**



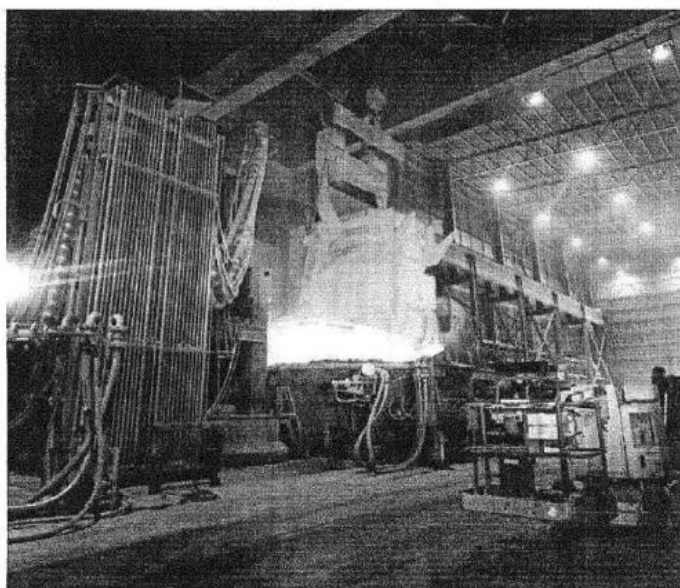
**Principle: Billet- type bottom electrode
Danieli**



Temperature und tension in graphite electrodes [2]

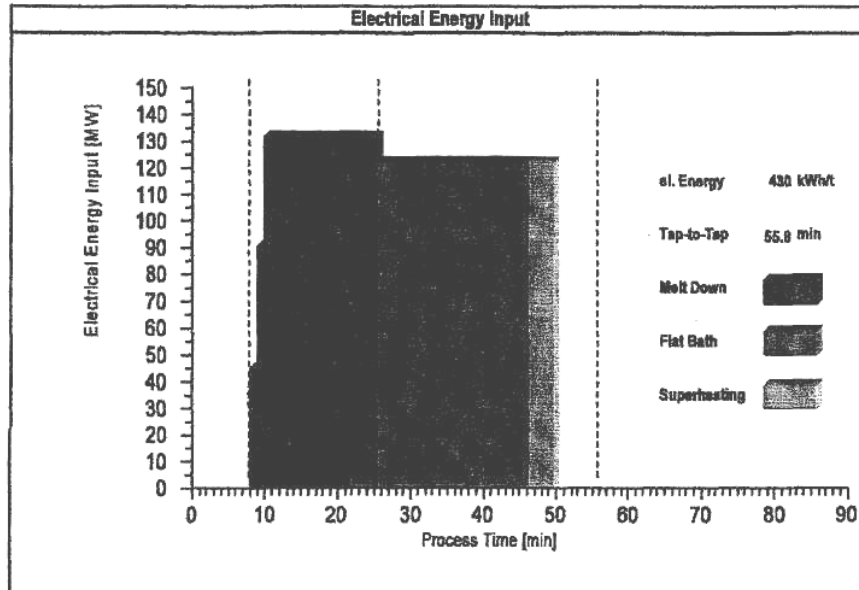


Nucor Berkeley/USA EAF Charging – single bucket charge

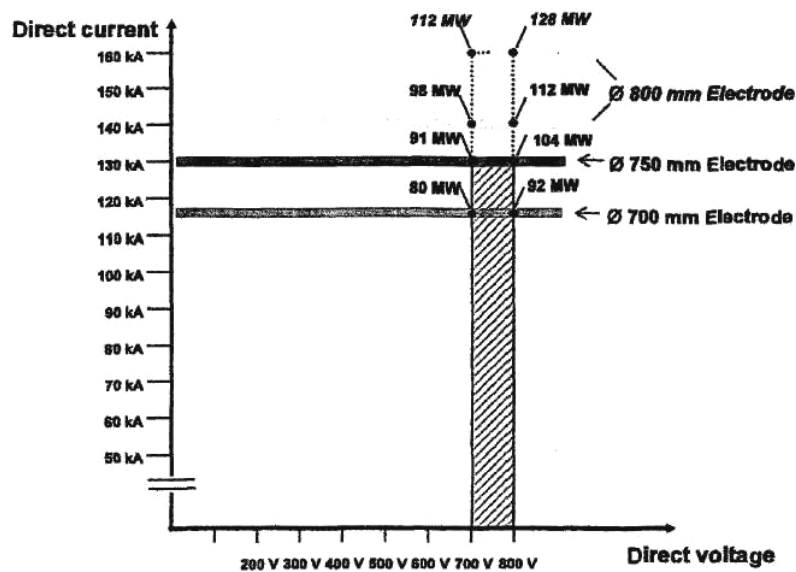


Manufacturer	SMS Demag
Start up	1996
Heat size	150 t
Upper shell dia	7.6 m
Sell top above floor	3.7 m
Bottom electrode	Pin type
Single Charge	
Tap-to-tap	55.8 min
Production (2004)	1.7 Mio. t
Transformer(2)	80/90 MVA
OP voltage	915 V
DC current	140 kA
Power	129 MW

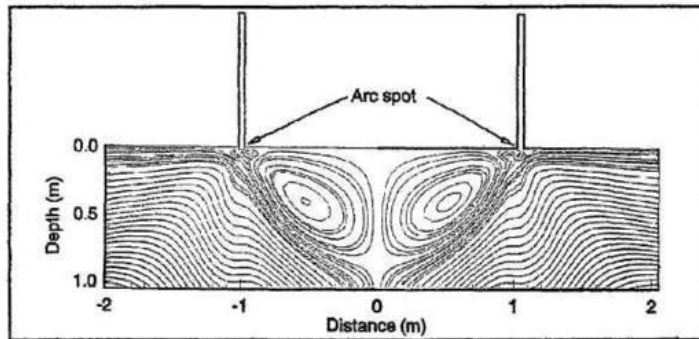
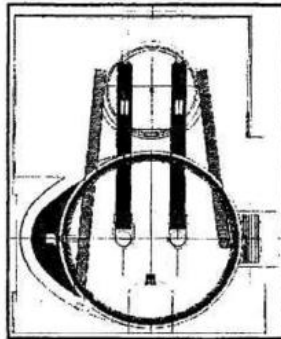
Nucor Berkeley/USA EAF Power Input



Power limit for DC EAFs (with one graphite electrode)



Twin cathode DC EAF



International Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

AC Furnace Development

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Situation of AC Furnace Design

Abstracts:

In the following report a short review will be given about the history of the first high impedance furnace operating with secondary voltages up to 1200 V and the latest high impedance furnaces with secondary voltages between 1350 up to 1500 V /1600 V !.

Comparison between low and high impedance design will show the advantage of both designs , but to day practically all new furnaces are high impedance design .

Even AC-EAF's for stainless steel production are using additional reactors to optimize The electrical parameters .

The influence of high impedance design on the flicker level will be shown in one example .

Finally in part 1 a new trend is explained , the EAF with one single basket charge . (ULTEVIATE-EAF, ARCsess-EAF)

And finally in part 2 a short review about integrated scrap preheating including off gas treatment will show the economic features of this latest development.

Part 1 : High Impedance AC Furnace

In the last years practically all new furnaces were designed as High Impedance AC furnaces . The enthusiastic DC-phase seems to be finished since High Impedance AC furnaces have achieved electrode consumption below 1,4 kg/t, even 1,1 kg/t have been reached . The reason for this might be the fact, that DC furnaces were built by former BOF shops , looking for the Latest technology . Since several years AC operating melt shops are modernizing their plant and decided to go modern designed AC-furnaces , **High Impedance Design** .

The first paper about high impedance design was published approx. 23 years ago , when everybody -including me- pushed still hard for low impedance design .

At this time the aim was to use the existing transformers to its maximum capacity to achieve more arc power . A lot of existing furnaces had not sufficient secondary voltage and with the reduction of resistance and reactance with current conducting arms it was possible to get more arc power .The small pitch circle did help to overcome the hot spot problem and the copper clad cc-arms are nearly maintenance free.

In the paper of Mr.Ben Bowman the effect of a reactor with a switch was explained allowing longer arc with stable operation and with reduced electrode consumption .

The first installations of reactors with offload switch , a 35 t EAF and a 54 t EAF , showed the expected reduction of electrode consumption in combination with improved foamy slag practice.

Ispat-HSW had a design with an On-Load switch for the reactor, resulting in maximum flexibility for the operators of the furnace

The real success of a high impedance furnace came with the DC furnaces .

The reduction of electrode consumption of a DC-EAF is counterbalanced by extremely long arcs , especially during the meltdown phase without foamy slag , But even with foamy slag the arc length of a DC-EAF is much longer than an AC-EAF .

But indeed , the High Impedance EAF is also working with longer arcs -not as long as DC - but the direction is the same .

Picture 1.01 :Comparison of arc length DC versus AC

Because an AC-EAF has three electrodes the arc length is shorter and the new target was to find an economic design for a high impedance EAF with high power input, low secondary currents with high voltages , but stable arc conditions .

At that time the rules in Germany did not allow to use more than 1000 V and all high impedance EAF's used secondary voltages below 1000 V .

Finally a British customer agreed with a design of a 170 t EAF with 120 MVA TRF , maximum 1200 V , $\eta_k=21\%$.

The installed reactance had a fixed value and therefore the electrical design had to be made in a safe manner . This is the most economical solution , but the flexibility to modify the arc length is partially lost. This design was selected to show a large cost difference between the DC-design , favourite of the board of directors , and the AC - design , engineers favourite .

Picture 1.02: Single line diagram

It is important to note , that the power factor is mainly interesting at the power source , or at the point, where the primary voltage is more or less constant.

The power source can be either the power station or the SVC-system or even the capacitor bank

To explain the electrical design to the customer the following formulas were used . These formulas allow a power input calculation starting from an existing or proposed Single line situation . Yesterday you learned a method starting from an arc power target.

Picture 1.03 , Picture 1.04 ,...1.07

Picture 1.08 :Operating reactance under various arcing conditions

The factor $F = \text{Operating Reactance} / \text{Short Circuit Reactance}$ is varying during the melting process , so any calculation can only be an average calculation .

Table 1.09:Linecalc

The above mentioned formulas were used in this Excel Sheet:

As you see from Table Linecalc the calculated power factor at the EAF is approx. 0,8 , at the power source it was calculated only 0,74

Indeed the power factor at the beginning of operating with 1200 V was much lower .

The explanation is , that the Factor F (ratio operating impedance versus short circuit impedance) is very high at the beginning of meltdown .

Of course the 1200 V tap was not used right at the beginning of meltdown , but even when the electrode is far enough away from the roof and the 1200 V tap was possible , the Factor $F = \text{Operating Reactance} / \text{Short Circuit Reactance}$ - is still high.

Our calculation are using an approximation of the Bowman curves . meanwhile you have learned another calculation method of Prof.Kohle .

A few minutes later the "melting"line is reached and the power input was comparable with the calculation .

During the hole melting process no arc instability could be seen and the electrodes were extremely stable without any side movements . This stable operation has from my experience several reasons :

- electrical design and operating points
- mechanical design -metallurgical process influence

Electrical design and operating points

Picture 1.10 :Circle diagram high and low impedance

As you see from this picture the same MW-input can be achieved with complete different operating points . For the mechanical stress into the electrodes , the electrode arm , column and roller guiding the "Lorenz Forces " are responsible and they are related on current squared .

Table 1.11 : Technical data of low and high impedance design

The ratio of operating current versus short circuit current is an important factor for the side movement of the electrode . The "Lorenz Forces " of a low impedance design versus high impedance can be up to 2,4 times higher !

This low short circuit current is also helping to reduce electrode tip consumption .

In any case the foamy slag practice is extremely evident.

A good balanced reactance of the three phases and the use of reactors is helping to minimise the harmonic distortion .

Picture , 1.13 and 1.14

The disadvantage of fixed reactor set point is, that the transformer should have a slightly larger capacity . This disadvantage can be avoided if an **on load** switch for the reactor design is selected .

Picture 1.15a , Secondary Voltage 1350 V , current up to **56 KA** possible with the proposed reactor . arc power 84 MW during melt down phase . 87 MW during foamy slag , arc length up to 462 mm .

1.15b ,Secondary Voltage only 1000 V , currents can not be increased above **56 KA** , arc power only 64 MW, arc length 344 mm ,

1.15c ,Secondary Voltage 1000V , Reactor 0% , current now up to 72 KA possible, arc power up to 81 MW , arc length 336 mm .

Mechanical design

Picture 1.16 :Current Carrying Capacity of Electrodes AC versus DC

A large electrode diameter is helping to reduce the deflection of the electrode caused by bending stresses from the " Lorenz Forces" , Any side movement is starting at the electrode tip and the electrode has a limited bending capacity and the joints are the weak point of the electrode , Since spray cooling is standard there is no need to look for small electrode , just opposite is better , because the tip consumption is related to the tip surface divided by current squared.

To avoid to much side movement the mechanical design of electrode arms , columns, guiding and so on must be stiff enough .

Further on it is possible to counter balance the electromagnetic forces by a proper Electrode arm /column design.

Picture 1.17 : Electrode Consumption versus Current Load DC-EAF

This picture is just for information to avoid a wrong selection of electrode diameter for DC-EAF. Our experience is , that there is a similar behave in AC furnaces .

Picture 1.18: Ratio between front part versus tail end of an EAF

The long tail end is helping to counterbalance some of the electromagnetic and mechanical forces .

One advantage of the "loop symetration" of the electrode arms is , that there is no need for a triangulated high current cable configuration, thus the counterbalancing is easy .

In the first high impedance EAF with 1200 V all of this features were used to get maximum stability of the electrode guiding system , which was indeed achieved.

Metallurgical Process Influence

The usage of oxygen- fuel burners or preheating of scrap or both is a well known possibility to stabilise the arc early .

Picture 1.19 : Power Input into a FS-EAF without and with Scrap Preheating

As can be seen from this picture the improvement of power input is in the range of 10 % . and meanwhile most of the fast operating "Standard EAF's" are using burners . **Picture 1.20 and 1.21**

These two Pictures are showing Japanese surveys about the influence of oxygen and scrap density to yield and power consumption . It is obvious , that the to days power consumption numbers are much lower, but it is also clear, that the influence of the scrap density is high , especially when using scrap preheating with burners and lances in the furnace . If the scrap is too dense , the off gas of the burners can not penetrate the scrap sufficiently .

Practical Results of the 1200 V operation

With only 52 to 58 kA operating currents the power input showed approx. 80 MW .

The arc length is in this case approx,470 mm .

Of course it is clear , that the duration to operate such arc length is depending strictly on the availability of perfect foamy slag .

Any interruption of oxygen blowing , for instance by elongation of the pipes of the Lance manipulator , or an empty carbon bin is causing a loss of foamy slag and immediate overheating of water cooled panels .

Finally the customer changed to copper panels with fins , where the slag is caught much better than on steel panels.

Picture 1.22 Panel Comparison Steel vs, Copper

Very helpful could be electrode control systems with the possibility to detect foamy slag .

In case of missing foamy slag carbon blowing starts automatically .

(For instance ARCOS , SPIE TRENDDEL etc)

The only problem occurred during start up of this furnace was arcing of the rubber hoses of the high current cables . The hoses had to be exchanged against better insulated one .

In the performance tests an electrode consumption of < 1,7 kg/t was achieved . Meanwhile high impedance furnaces with electrode consumption below 1,4 kg/t are existing. The power level of high impedance furnaces have reached values above 130 MW , electrode consumption < 1,12 have been confirmed (Shaft Furnaces).

Effect of high impedance on flicker

A modification of a furnace from low impedance to high impedance has shown (in this example !), that the so called Kst-factor did drop from 85 to 70 .

$$P_{st} = S_{sh.c.eaf} / S_{sh.c.line} * K_{st}$$

This furnace was equipped with a 64 MVA transformer without reactor and only 680 V . The furnace was causing flicker and the power supply company pushed the customer towards a SVC System .

After changing to a transformer of 100 MVA, max. 1200 V , with reactor the flicker level was acceptable and the calculation showed a Kst-factor of 70 .

In an other example we found a Kst-factor of even 65 , transformer was 120 MVA , max. 1350 V .

But I have to point out, that in this case , the scrap was preheated with burners (double shell Design) and the scrap had small sizes with high density , approx, 0,78 t/m³ .

Picture 1.23 Different Operating Points of High Impedance Furnaces

Pictures 1.24-1.39

Some practical furnace picture showing the specific design of this first high impedance furnace with max. voltage of 1200 V . The single point roof lift system is allowing a fast exchange of the refractory delta or the complete roof itself.

The last three pictures are showing an extremely high powered SS-EAF , 8 m shell dia And 3,2 m upper shell height, which would allow a single basket charge , if a scrap density of 0,8 is available . Power On-time for melting 150t liquid stainless steel is only 40 min , In spite of the large shell diameter and height.

The latest stage of AC-High Impedance Furnaces is a **250 t EOBT-Furnace equipped with a 240 MVA** transformer and using the **Single Point Roof Lift** . The transformer is equipped with an **On-Load Tap-Changer for the reactor** allowing a perfect adjusting of the system reactance during the melting and overheating process . Shell diameter approx. 9,1 / 9,3 m , shell height 3,2 m , electrode diameter 711 mm , but also 762 mm diameter is possible .

Due to the extremely high transformer capacity a large SVC-System is necessary to stabilize the primary voltage .

The On-Load Tap Changer for the reactor allows a smooth adoption of the total reactance controlled by the electrode control system . The power input level and the arc length can be adjusted to the process requirements . The maximum power input is approx 180 MW using a voltage below 1500 V . If a secondary voltage of 1600 V is allowed to be used a maximum power of 200 MW might be possible in future ,

Finally I got two reports about a new trend in electric steel making : The Single Basket Charge .

ULTIMATE EAF and ARCsess .

Picture 1.39 and 1.40

Without knowing all details it is not explainable , why furnace A has such high energy Consumption . The reason might be poor scrap and different burner / lance design , reactor not on-load switchable , off gas suction to high and so on . But the productivity of these type of furnaces is extremely high .

As you see from this picture there is a lot of burner - lance -post combustion nozzles needed to Get the high productivity .

But never the less the total oxygen consumption with approx. $32 \text{ m}^3/\text{t}$ is in an reasonable range.

Due to the very short tap-to-tap-time a special ladle furnace design is used .

Conclusion

Today practically all new furnaces are high impedance design , even in stainless steel furnaces reactors are used to reduce the mechanical loads to the system and to stabilise the arc .

With an **on load** switch of the reactor the transformer can be used to its maximum capacity and it is more easy to find an optimum operating point during melt down (scrap influence!) and to adopt the arc length to the foamy slag practice during flat bath operation ,

The new trend with Single Basket Charge will bring another step in EAF productivity .

Part 2 : Integrated Scrap Preheating

The definition of a furnace with integrated preheating is :

-Closed loop of the preheated scrap . No open movement or open charging of preheated scrap . The off gas coming from preheated scrap must be kept in a closed loop to allow A perfect treatment of the off gas .

In the report of "Prof.Pfeiffer " a complete overview of scrap preheating process routes is given , so this report is limited to the latest information of the "Finger Shaft Furnaces " .

The principle of a Finger Shaft Furnace is well known

Picture 2.01

The preheated scrap on the fingers is charged after finished tapping , tap hole filling and burner shell ignition by opening the fingers and immediately the second basket is charged with the charging crane .

The melting process with the electrodes begins now . After melting down the scrap for the actual heat and the fingers can be closed , the basket for the next heat is charged on the closed fingers .

Picture 2.02

Safety fans are blowing air at the entry of the PC-Chamber to take care of the CO cloud , which occurs during scrap collapsing .

The normal combustion oxygen for the melting process is either coming from oxygen nozzles, Suction air into the furnace from the dedusting fans or from additional air fans in the finger housing.

Scrap with impurities from plastic , rubber, colour and so on is creating smell and poisonous Gases during melting , but especially during slow preheating . But even with the fast melting pattern of a Finger Shaft Furnace this problem exists . The creating of these smelling and poisonous gases starts at 250 to 300 °C and some of them are extremely stable .

Picture 2.03 Shaft Emission Control

Even for the destroy of the VOC's an off gas temperature of above 700 in the PC-Chamber is required .

Picture 2.04 Temperature in the Combustion Chamber

As seen from the picture 2.04 it is not economical to reheat the off gas to a temperature of 900 or 1000 ° C to destroy the PCDD's ..

The complete system to control the off gas of a finger shaft is shown in

Picture 2.05

The temperature in the PC-Chamber is hold in a range of >700 to 750 °C by a burner system . The off gas is cooled down to a range of approx.550 °C in the following water cooled duct followed by a quench . After the quench a temperature level below 250 °C is achieved , consequently only a small recombination of Dioxines does occur .

To flail fill the latest requirements for Dioxin a Carbon Injection System is installed before the bag house.

Such a System was installed several years ago in Swiss Steel Gerlafingen and a second one is installed in Spain .

The results of Gerlafingen are shown in

Picture 2.06

The economic effect of integrated scrap preheating is shown in

Picture 2.07

As you see , an important cost saving factor is the improvement of scrap yield and the reduced Amount of dust in the bag house .

Also a reduced flicker level was observed , which might help sometimes to avoid a SVC System.

The Thermo Shaft is the next step to minimise the burner energy in the PC-Chamber .

Some examples for integrated scrap preheating are shown in the following pictures :

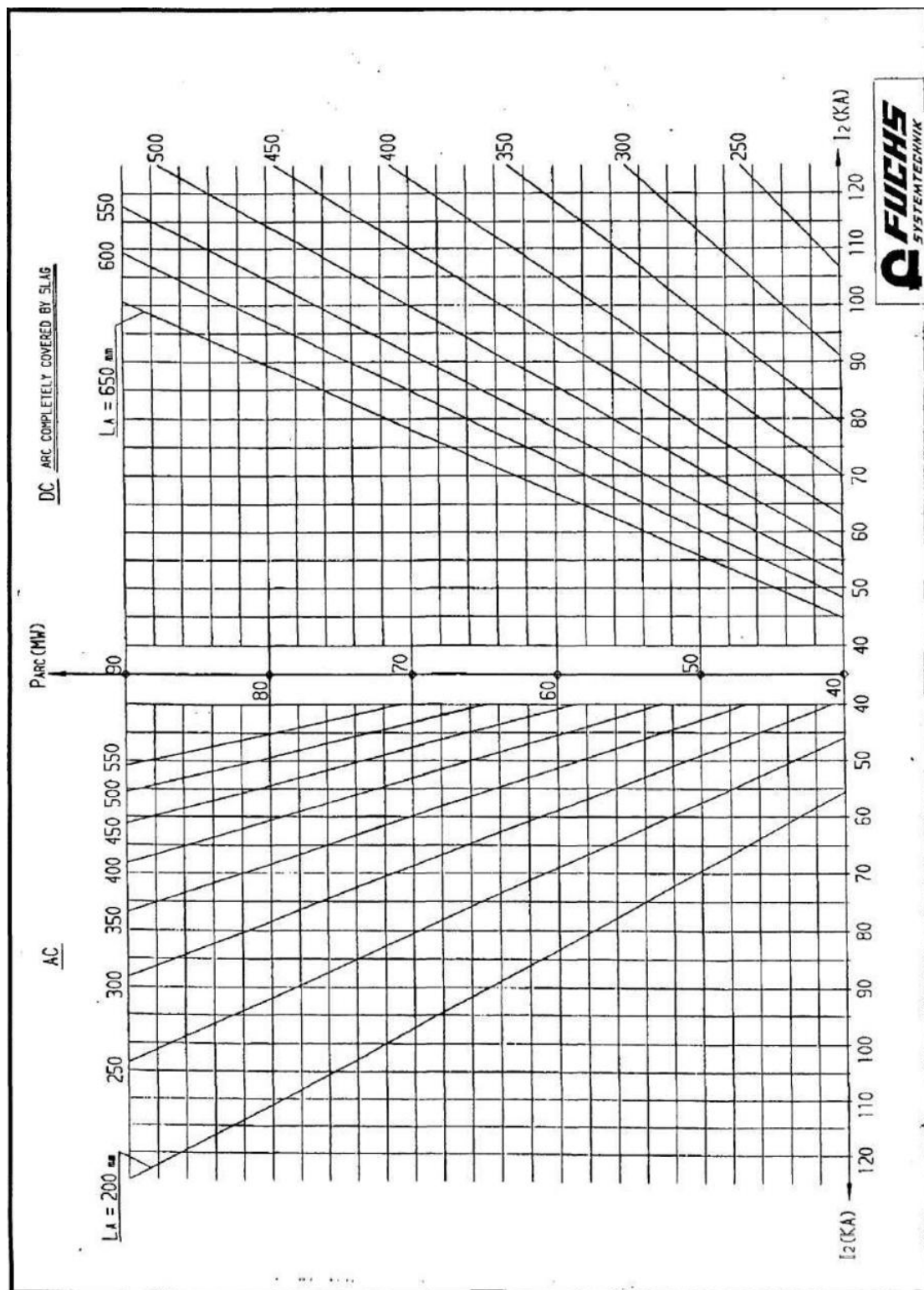
Finally I show some actual shaft furnace pictures of different designs . **Conclusion**

With the to days technology it is shown , that integrated scrap preheating is proven to full fill Even the strongest off gas requirements still showing an economic effect on the conversion cost of the EAF-Process .

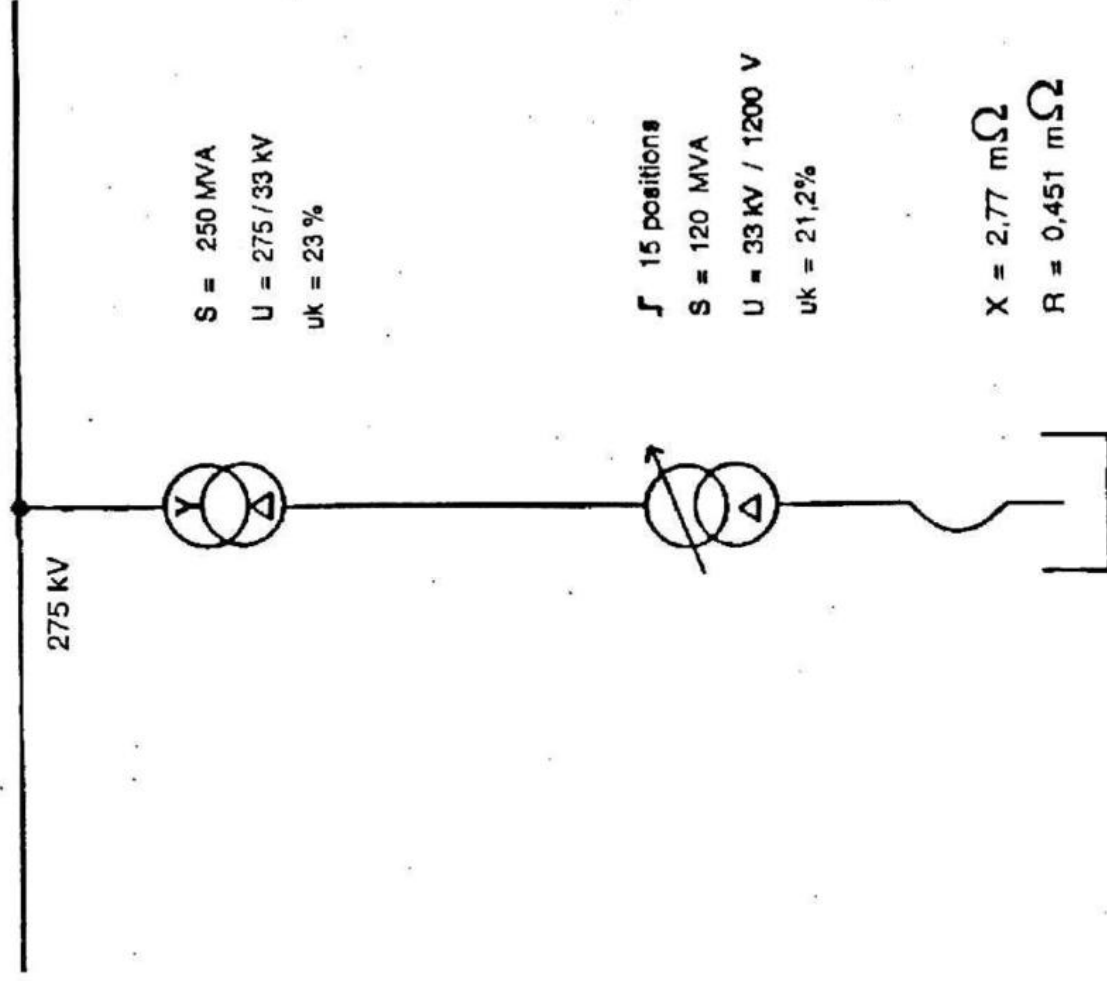
World wide more than 30 shaft furnaces of different designs are operating with AC -power level up to 110 MW , DC-Single Electrode up to 90 MW , DC-Double Electrode up to 130 MW.

The Technology is not easy , so one customer in an industrial country is dismantling the shaft after two years , the other customer did just start up the third Finger Shaft within six years . Couple of years ago a melt shop superintendent told me : Success of a Technology is depending only 30% on equipment but 70 % on the operating team .

But it is also easy to understand , that the new technology with Single Basket Charge is more easy to handle , but also not easy to design .



Power supply for EAF (N-Fumace) of Rotherham Eng. Steel, GB



The influence of the line capacity to the system reactance is :

Simulation of the line impedance	Jance = line reactance:	$Z_n = 1,1 \cdot L T^2 / S_k = X_n$				
	Example					
Primary Voltage	$U_0(KV) =$	275				
Line Short Circuit Capacity!	$S_k (IVN/A) =$	15000				
	$Z_n = X_n =$	5,5458333 Ohm				
	.					
Related to the secondary side of the EAF-Transformer:						
	$x_n = X_{ri} \cdot (U_2/U_0)^2 \cdot 1 / 1000 \text{ mOhm}$					
	or $x_n = 1 \cdot L C^2 S_k^2 / 1000 \text{ mOhm}$					
	Example:	1200				
	$U_2(V) =$		$x_n =$	0,1056	mOhm	
			$x_n =$	0,1056	mOhm	
The influence of the line cables can be considered , if the impedance (reactance) is known:						
Example : line cable Resistance = approx. Reactance X_l			0,8	Ohm		
Secondary side of EAF-Transformer: $x_l = (U_E/U_0)^2 \cdot 1 / 1000 = x_l$				0,0152	mOhm	

	Step Down Transformer						
Primary Voltage Uo =		Uo =		275	KV		
Appearant Power of Step Down Transformer	S1			200	MVA		
Sec.Voltage TRFstd = Primary Voltage of Reactor				34,5	KV		
Impedance of TRFstd (%) =		ukstd		22,00%			
Losses of TRFstd		Pk =		600	KW		
The total Impedance Z related to the secondary side of the EAF-TRF is :							
		$Z_{stdtrf} = ukstd \cdot U_2^2 / S1 / 1000 =$		1,5840	mOhm		
		$R_{stdtrf} = Pk \cdot (S2 / U_2)^2 \cdot 1 / 1000 =$		0,0167	mOhm		
		$X_{stdtrf} = (Z^2 - X^2_{yKJ.S} =$		1,5839	mOhm		

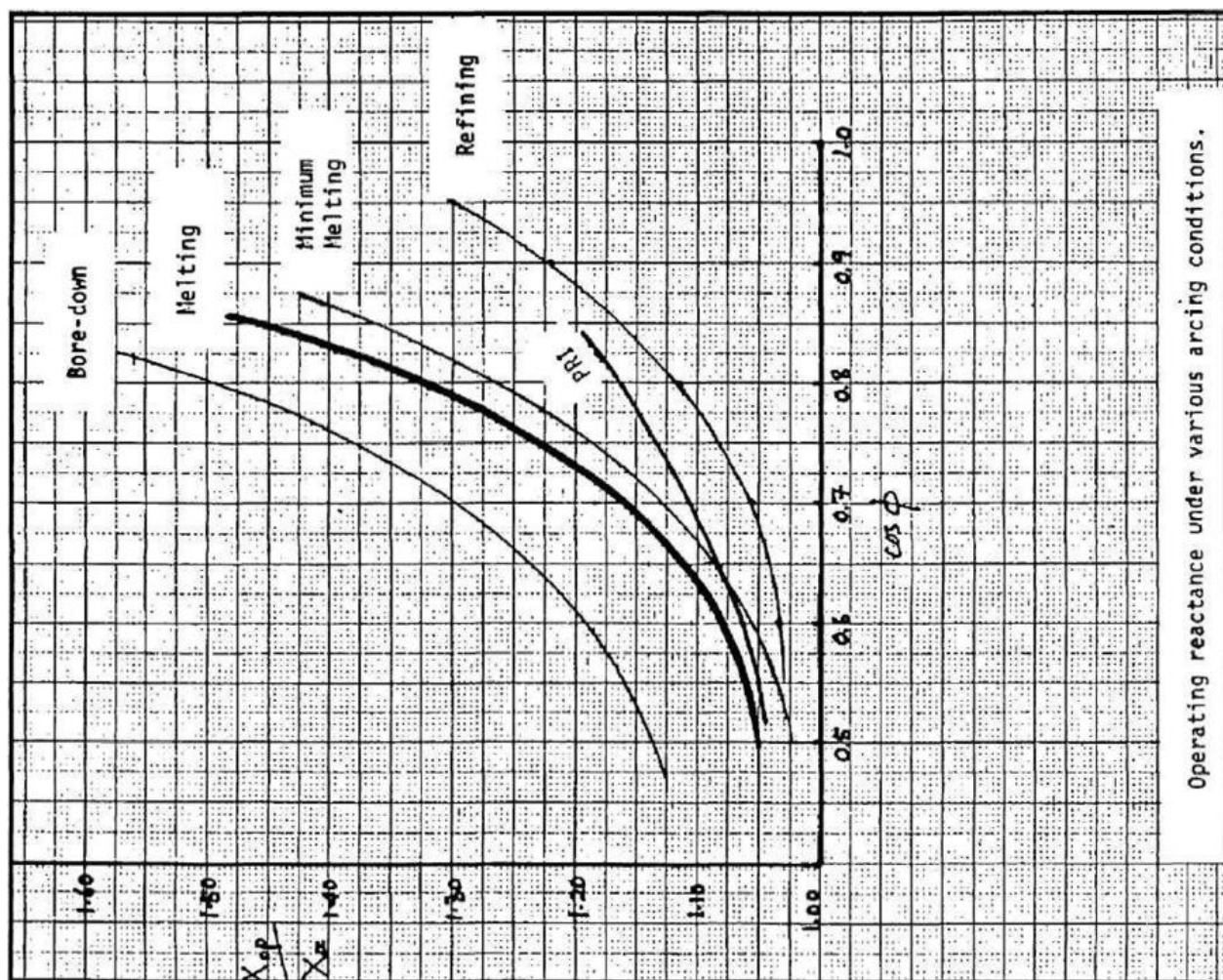
1.04

A Reactor is normally at the primary side of the EAF-transformer, it might be inbuilt into the EAF-transformer							
The effect of the Reactor is a voltage drop at the primary side of the EAF-TRF , when operated at							
nominal current. This is causing a damping effect, the system gets softer.							
Seaf = Appearant Power of EAF-Trf =			120	MVA =Qb of Reactor = Through going Powe			
U1 (kV) = Primary Reactor Voltage =			34,5	KV = Sec.side of Step Down Trf			
Usec (V) = Used secondary voltage of EAF-trf =			1200	V			
Xd1 = Primary Reactor Impedance =			1,4	Ohm			
Pk (KW) = Reactor losses =			200	KW			
[The Resistance of the Reactor is :				$R_d = P_k \cdot (U_1 / Q_b)^2 / 1000 =$	0,0165	Ohm	
Xd2 = Secondary Reactor Reactnce = Xd1*(Usec/U1)^2 * 1/1000 =					1,694	mOhm	
The effect is depending on the the square of the used secondary furnace voltage							
The power going through the Reactor equals the EAF-trf-appearant power							

	Furnace Transformer					
Production requirement is the base of the EAF-trf appearant power	S2 =	120	MVA			
The nominal increase of the winding temperature is specified as	Tw1 =	55	°C			
The maximum increase of the winding temperature is	Tw2=	65	°C			
Max.continuous appearant power of EAF-tr	S2max= 1,12*S2 =	S2max=	134,4	MVA		
At that time only 610 mm electrodes were used at the most high powered AC-furnaces						
To limit the arc length and also to reduce electrode temperature stress the current range was specified :						
	12 min =	52	KA	12 max =	68	KA
The max.secondary voltage is :	U2max =	$S2/3^{A0,5}/I2mir$	$1*1000 =$	1332,3	V	
Constant power range down to :	U2min =	$S2/3^{A0,5}/i2ma$	$x*1000 =$	1018,9	V	
A common short circuit voltage (based on the trf-design) is :				uk =	8%	
Simply for cost reasons a "Booster Transformer" was selected with an				uk2 =	21%	
The Reactor is part of the EAF-transformer:			U2 max =	1200	V	
	Constant Power Range to :		U2 min =	1000	V	
	Lowest Tap :			750	V	
			Pk2 =	850	KW	
	Z2 =	$mk2*U2^A2/S2/1000 =$	2,520	mOhm		
	R2=	$Pk2*(S2/U2)^A2* 1/1000$	0,0085	mOhm		
	X2=	$\{Z^A2 - X^A2\}^{A0,5} =$	2,520	mOhm		
Using this design the arc length can not be changed by different reactor steps , the only possibility is to change the secondary currents or voltages .						

	The ARC-Furnac					
Tap-weight	Ga	170	t			
Shell Diameter	Di =	7,3	m			
Secondary Reactance	X3=	2,79	mOhm			
Secondary Resistance	R3	0,38	mOhm			
	U2=	1200	.V			
The total short circuit imp						
Z ges = ((Rstdtrf+R					7,01	mOhm
The Short Circuit Current		shc=	$U2/3^{0,5}/Z_{ges}$	98,82	KA	
The proposed secondary current is		12	58	KA		
The operating Z(mOhm) is then :				11,95	mOhm	
The "arc resistance" is :						
$R_{arc} = (Z_{oper}^2 - (F^*(X3 + X_{trf}^2 + X_{d2}) + X_{stdtrf} + X_n)^2)^{0,5}$						
Uarc = Rare * I2 =		Uarc phase volta				
Dare comb.= Rare * I2*3 ^A						
Pare total = Uarc comb. * 12 * 3 ^{A0,5} = Uarc * 12 * 3				Pare phase		
Larc(mm) = Uarc-40 = Uarc comb/3 ^{A0,5} .-40						

$$F = \frac{X_{ap}}{X_F}$$



Operating reactance under various arcing conditions.

MVA =	200,0	200,0	134,4	MVA =	120,0	134,4
LV(KV) =	275,0	34,65	33,00	LV(V) =	1200,0	1000,0
uk(%) =	0,000	22,00	0,000	uk(%) =	21,000	
Pk(KW) =	0,0	600,0	0,00	Pk(KW) =	400,0	el. diam =
Xl(Ohm) =	0,000	0,000	0,000	12(kA) =	57,7	Xl(mOhm) =
R(Ohm) =	0,000	0,000	0,000	12 max =	77,6	R(mOhm) =
efficiency of reactor(%) =			0,00	meltd V=	1200,0	Vrefine =
EAF-TRF-TAPS:			0		0	647
	688	710	734	787	816	848
	910	945	980	1057	1101	1149
Calculated Values of the System				calc.no load voltage ml =		
Inner imped. of powerline,EAF-TRFsec.s.(mOhm)						0,116
Total line-imped.calc.at EAF-TRF Sec.S.(mOhm)						0,116
St.D.TRF.impedances at EAF-TRF Sec.side(mOhm)						1,746
Reactor effect at EAF-TRF sec.side (mOhm)						0,000
EAF-TRF impedance at EAF-TRF sec.side (mOhm)						2,520
Total Impedance at EAF-TRF sec.side (mOhm)						7,184
Maximum short circuit current (KA) =				101,258	262,854	Tg(s) =
Line voltage at sh.circ.curr. (KV) =				270,6	Delta U(%) =	
Max.line load (MVA) =				221,0	in % of Sh.Circ.Cap. =	
F =	1,423	1,394	1,367	1,340	1,220	1,206
F0 =	0,000	0,000	0,000	0,000	0,000	0,000
F =	1,423	1,394	1,367	1,340	1,220	1,206
Isec(KA) =	52,00	54,00	56,00	58,00	56,00	58,00
Z(mOhm) =	13,990	13,472	12,990	12,542	12,990	12,542
RA(mOhm) =	9,931	9,366	8,838	8,343	9,545	9,020
Parc(MW) =	80,6	81,9	83,1	84,2	89,8	91,0
Larc(mm) =	476,4	465,8	454,9	443,9	494,5	483,1
S3 (MVA) =	103,8	107,1	110,4	113,7	111,6	114,9
P3 (MW) =	83,7	85,3	86,8	88,1	93,5	95,0
Uarc(V) =	894,4	876,0	857,2	838,1	925,8	906,1
Uarc(V) phase volt.	516,4	505,8	494,9	483,9	534,5	523,1
Line P.F.=	0,739	0,726	0,712	0,698	0,767	0,752
HV-Pow F=	0,744	0,730	0,717	0,703	0,771	0,757
EAF-P.F3=	0,807	0,797	0,786	0,775	0,838	0,827
EAF-P.F4=	0,807	0,797	0,786	0,775	0,838	0,827
P.F.5 =	0,933	0,928	0,924	0,919	0,946	0,941
arc stability fact.	9,93	9,37	8,84	8,34	9,54	9,02
arcstab. F.Köhle	1,87	1,76	1,66	1,57	1,80	1,70
arc react. XL	2,937	2,706	2,497	2,307	1,267	1,183
arc resistance RI	9,931	9,366	8,838	8,343	9,545	9,020
arcstab.at line	1,38	1,31	1,23	1,16	1,33	1,26

Figure 1.09

Linecalc.	Powerline-TRF	St. D. TRF	Reactor	EAF-Transformer	Furnace-data
HV(KV) =	400,0	400,0	-----	HV(KV) =	30,0
MA =	200,0	200,0	165,0	NVA =	105,0
LV(KV) =	400,0	31,00	30,00	LV(V) =	960,0
uk(%) =	0,000	10,80	0,000	uk(%) =	7,140
Pk(KW) =	0,0	413,0	0,00	Pk(KW) =	450,0
Xi(Ohm) =	0,000	0,115	0,00	I2(kA) =	63,1
Ri(Ohm) =	0,000	0,050	0,0000	I2 max =	75,8
efficiency of reactor(%) =			0,00	meltd V =	960,0 V
EAF-TRF-TAPS	583	602	0	0	550
	755	781	621	642	732
			808	837	85
Calculated Values of the System				calc.no load voltage md =	992,0 V
uk-line Step-Down-TRF Sec.side(Ohm) =				refine =	992,0 V
acquiv. Step-Down-Transformer uk(%) =				15,016	0
Inner imped. of pow.line St. D. TRF. Sec. S. (Ohm)				Z	X
Powerline transformer, St. D. TRF. Sec. Side (Ohm)				0,000	0,081
HV1 line impedance, St. D. TRF. Sec. Side (Ohm)				0,000	0,000
HV2 line impedance, St. D. TRF. Sec. Side (Ohm)				0,125	0,115
Total line impedance, St. D. TRF. Sec. S. (Ohm)				0,203	0,196
Inner imped. of powerline, EAF-TRF sec. s. (mOhm)					0,083
Total line-imped. calc. at EAF-TRF. Sec. S. (mOhm)				0,207	0,201
St. D. TRF. impedances at EAF-TRF. Sec.side(mOhm)				0,531	0,531
Reactor effect at EAF-TRF. sec.side (mOhm)				0,000	0,000
EAF-TRF impedance at EAF-TRF. sec.side (mOhm)				0,627	0,626
Total impedance at EAF-TRF. sec.side (mOhm)				4,189	4,168
Maximum short circuit current (kA) =				136,726	335,775
Line voltage at sh.circ.curr. (KV) =				392,1	Delta U(%) =
Max. line load (MVA) =				234,9	in % of Sh.Circ.Cap. =
F =	1,486	1,462	1,439	1,417	1,254
F0 =	0,000	0,000	0,000	0,000	0,000
F =	1,486	1,462	1,439	1,417	1,254
Isec(KA) =	57,00	59,00	61,00	63,00	61,00
Zi(mOhm) =	10,048	9,707	9,389	9,091	8,811
RX(mOhm) =	7,759	7,399	7,061	6,743	6,460
Parc(MW) =	75,6	77,3	78,8	80,3	83,8
Larc(mm) =	402,3	396,5	390,7	384,8	378,9
S3 (MVA) =	93,5	96,5	99,5	102,5	106,1
P3 (MW) =	79,1	81,0	82,8	84,5	87,7
Uarc(V) =	766,1	756,1	746,0	735,8	725,6
Uarc(V) phase volt	442,3	436,5	430,7	424,8	418,8
Line P.F. =	0,814	0,805	0,797	0,788	0,782
HV-Pow.F =	0,822	0,813	0,805	0,796	0,787
EAF-P.F.3 =	0,847	0,839	0,832	0,825	0,817
EAF-P.F.4 =	0,847	0,839	0,832	0,825	0,817
P.F.5 =	0,888	0,883	0,877	0,871	0,866
arc stability fact.	7,76	7,40	7,06	6,74	6,46
arcstab. F. Kuehle	2,26	2,15	2,06	1,96	1,88
Factor Kx	0,8	0,8	0,8	0,8	0,8
arc react. XL	2,290	2,143	2,008	1,885	1,772
arc resistance Rl	7,759	7,399	7,061	6,743	6,460
arcstab. at line	1,86	1,78	1,69	1,62	1,55
					X total

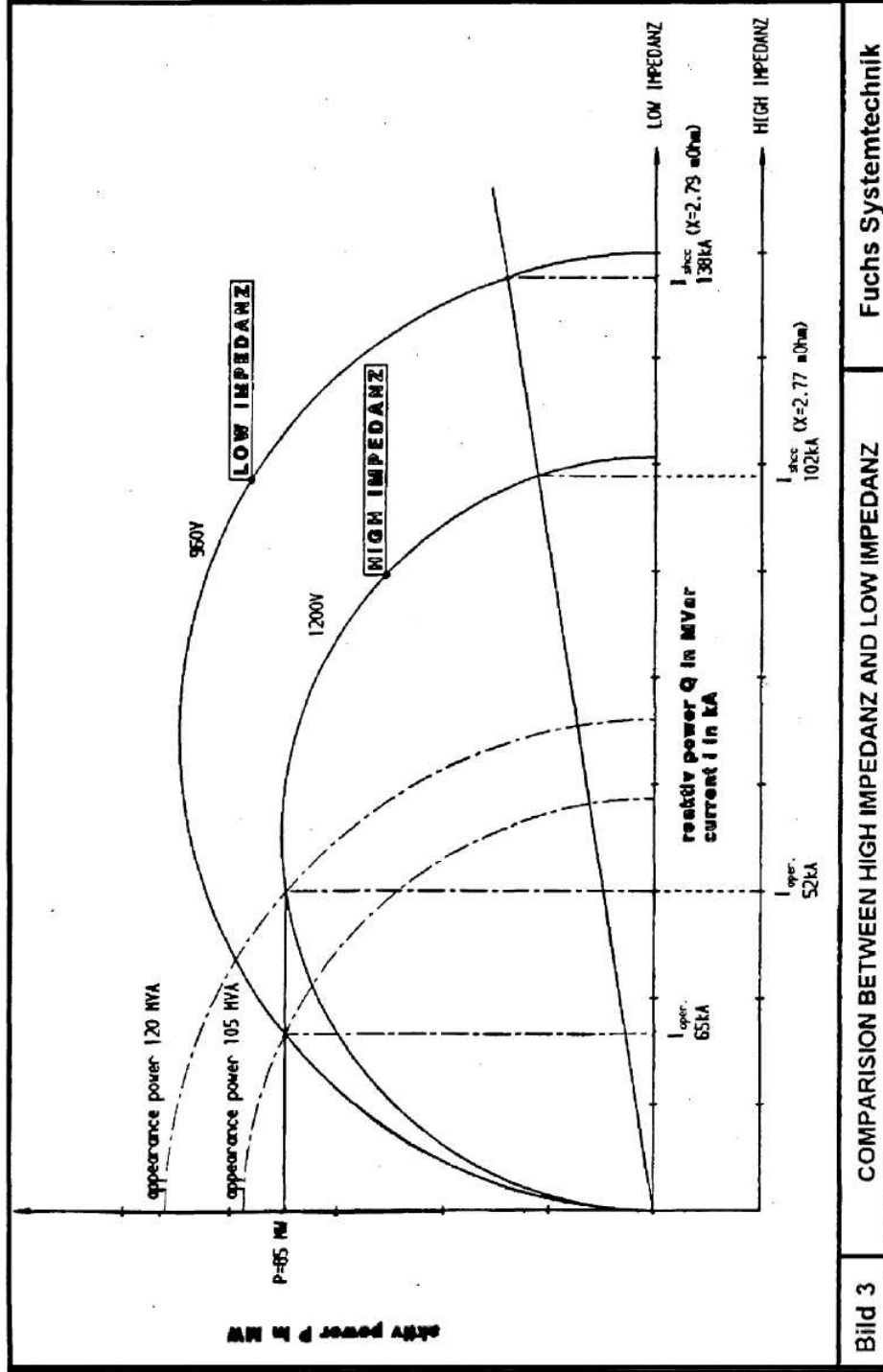


Bild 3

COMPARISON BETWEEN HIGH IMPEDANZ AND LOW IMPEDANZ

Fuchs Systemtechnik

	Low Impedance	High Impedance	Maximum High Imped.
Secondary Impedance (mOhm)	2,77	2,77	2,77
Secondary Current (KA)	63	58	52
Measured Active Power (MW)	85	85	85
ARC Power (MW)	81	82	82
Transformer Rating (MVA)	105	120	120
Secondary Voltage	960	1200	1350
Short Circuit Current (KA)	138	98	89
Sh.Circ.Curr./Operat.Current	2,12	1,96	1,71
Lorentz Force	183%	100%	82%
ARC Power/Transf.Rating	77%	68%	68%

Fonctionnement à Réactance variable ($X=0.6\ \Omega$ ou $X=0\ \Omega$) et Batterie de compensation en service

Harmonique de tension de rang 3 au niveau du Poste 225 kV - Tension U_{MUI}

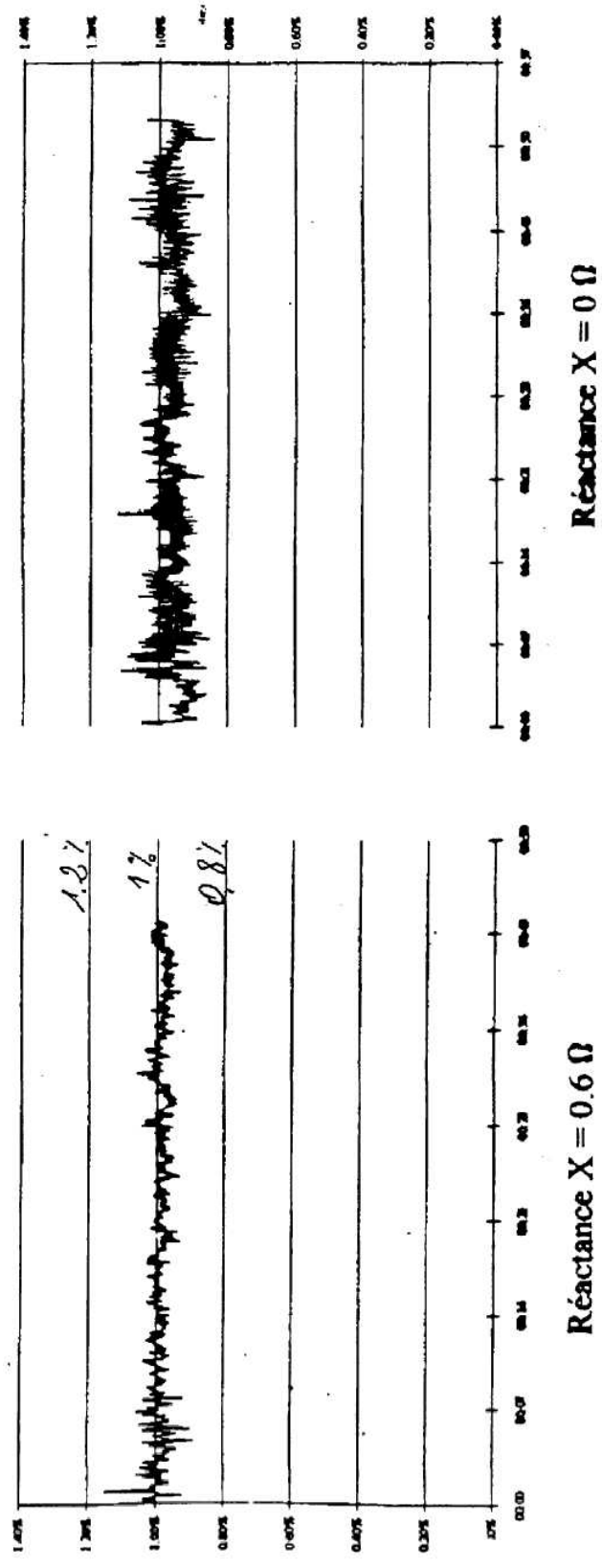


Figure 1.13

Fonctionnement à Réactance variable ($X=0.6 \Omega$ ou $X=0 \Omega$) et Batterie de compensation en service

Harmonique de tension de rang 5 au niveau du Poste 225 kV - Tension Uh/U1

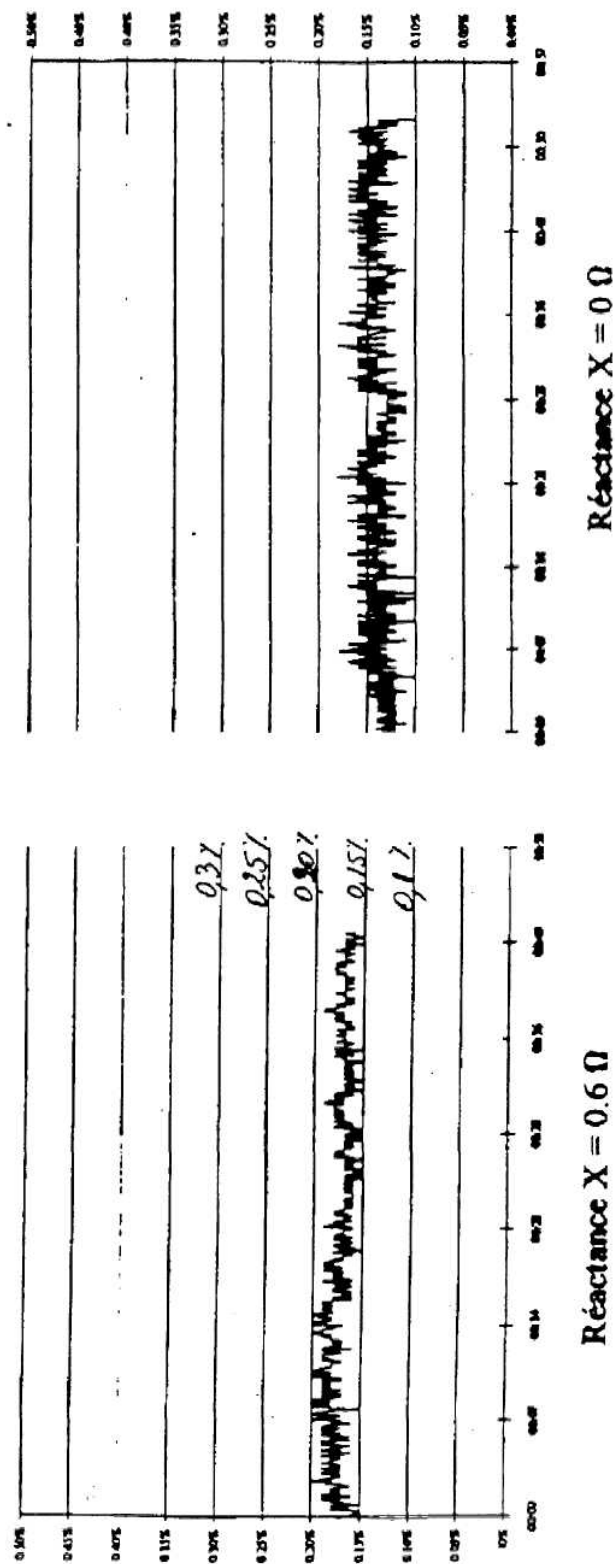


Figure 1.14

[illegible]

Figure 1.15a

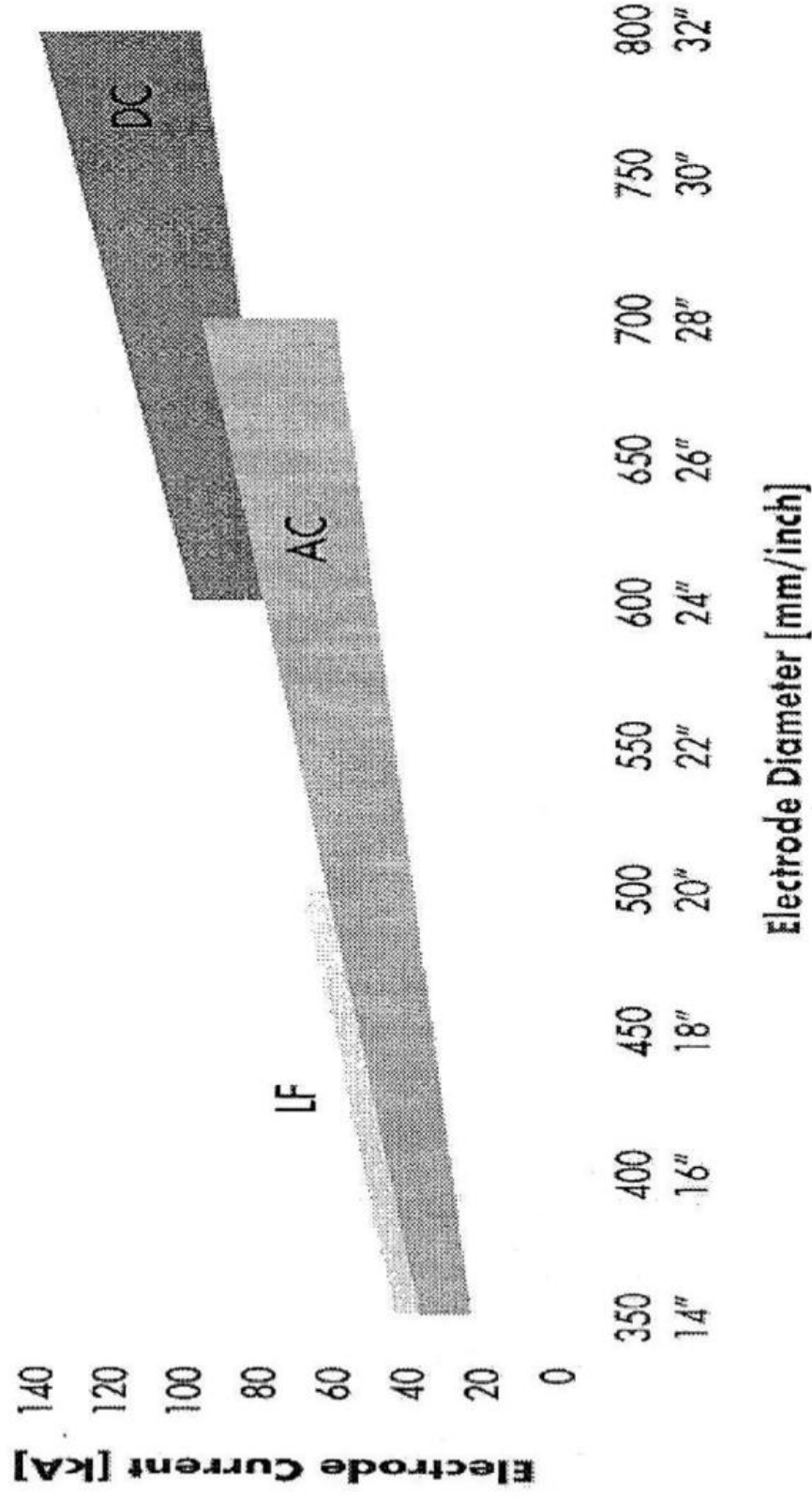
Example	Line c.c.	Powerline-TRF	Ca =	165.0 + Sec(MVA) =	30000	275 KV	
	HV(KV) =	275.0	275.0	St. D. TRF	Reactor	EAF-Transformer	
	MVA =	200.0	200.0	200.0	134.4	MVA =	Furnace data
	LX(KV) =	275.0	34.65	33.00	1350.0	1350.0	100.8
	uk(%) =	0.000	23.00	24.683	uk(%) =	7.500	750.0
	PK(KW) =	0.0	600.0	100.00	PK(KW) =	850.0	el. diam =
	X(Ohm) =	0.000	0.115	2.00	12(kA) =	51.3	X(mChm) =
	R(Ohm) =	0.000	0.050	0.0060	12 max =	77.6	R(mChm) =
	efficiency of reactor(%) =	0	0	85.00	meltd V =	1000.0	Reactor (%)
	EAF-TRF-TAPS	0	0	0	0	0	100
		900	950	1100	1150	1200	850
						1250	1350
						1300	70
						1050.0 V	55
						1050.0 V	0
						refine =	
						X	R
						0.044	0.000
						0.000	0.000
						0.000	0.000
						0.125	0.050
						0.167	0.050
						0.040	0.000
						0.153	0.046
						1.268	0.017
						1.561	0.005
						1.139	0.059
						7.228	0.476
						215.312	0.048
						273.5	0.538
						in % of Sh. Circ. Cap. =	0.508
						152.5	
						1.256	1.232
						0.000	0.000
						1.256	1.232
						52.00	54.00
						11.658	11.226
						7.285	6.793
						59.1	59.4
						338.8	314.3
						86.0	88.8
						62.5	63.0
						656.2	613.7
						378.8	366.8
						0.666	0.648
						0.670	0.652
						0.726	0.710
						0.822	0.810
						0.891	0.882
						7.29	6.79
						1.26	1.17
						1.868	1.705
						7.285	6.793
						1.01	0.94
						0.8	0.8
						6.33	5.88
						1.01	0.91
						1.555	1.418
						6.327	5.883
						0.88	0.82
						0.2	0.2
						6.87	6.39
						1.10	1.02
						0.844	0.778
						6.866	6.394
						0.95	0.89
						0.2	0.2
						5.94	5.94
						1.02	1.02
						0.715	0.715
						5.942	5.942
						0.82	0.82
						0.2	0.2
						refine <7	refine <8
						X incl. reactor	X incl. reactor
						incl. reactor	incl. reactor
						excl. reactor	excl. reactor
						excl. reactor	excl. reactor
						0.879	0.879
						0.82	0.82
						0.2	0.2
						X total	X total
						0.2	0.2

Figure 1.15b

Example	Lineals.	Powerline-TRF	Ga =	St. D TRF	Reactor	30080	275 KV
HV(KV) =	275.0	275.0	-----	HV(KV) =	EAF-Transformer	Furnace-data	
LHV(KV) =	200.0	200.0	134.4	NVA =	120.0	134.4	100.8
LV(KV) =	275.0	33.65	33.00	LM(V) =	1350.0	1000.0	750.0
uk(%) =	0.000	23.00	24.683	Pk(KW) =	7,500		
PK(KW) =	0.0	600.0	100.00	pk(kA) =	850.0	gl.diam =	0.610 m
XL(X Ohm) =	0.000	0.115	2.00	I2(kA) =	51.3	XImChm =	3.100
RC Ohm =	0.000	0.050	0.006	I2 max=	77.6	RImChm =	0.350
efficiency of reactor(%) =	90	0	0	meltid V=	1000.0	Vrefine =	1000.0 V
EAF-TRF-TAPS:							
	0	0	0		0	0	100
	900	1100	1150		750	850	85
					1200	1300	70
Calculated Values of the System							
uk-line Step-Dwn-TRF Sec.side(Ohm) =				sale.no load voltage.mv.	1050.0 V		
				2.777	refine=	1050.0 V	
aequiv Step-Dwn-Transformer uk(%) =				25.777	Z	X	R
Inner imped. of pow.line St.D.TRF.Sec.S. (Ohm)							
Powerline transformer St.D.TRF.Sec.Side (Ohm)					0.000	0.000	0.000
HX1 line impedances.St.D.TRF.Sec.St.de (Ohm)					0.000	0.000	0.000
HV2-line impedance.St.D.TRF.Sec.St.de (Ohm)					0.125	0.115	0.050
Total line impedance.St.D.TRF.Sec.S. (Ohm)					0.167	0.159	0.050
Inner imped. of powerline EAF-TRF sec.s.(mChm)						0.040	0.000
Total line-imped.calc.at EAF-TRF.Sec.S.(mChm)					0.153	0.146	0.046
St.D.TRF impedances at EAF-TRF.Sec.side(mChm)					1.268	1.268	0.017
Reactor effect at EAF-TRF sec.side (mChm)					0.000	0.000	0.000
EAF-TRF impedance at EAF-TRF.sec.side (mChm)					1.139	1.138	0.059
Total Impedance at EAF-TRF sec.side (mChm)					5.671	5.651	0.471
Maximum short circuit current (KA) =					106.899	268.271	Ug(a) =
Line voltage at sh.circr.curr. (KV) =					273.0	Delta U(a) =	0.038
Mx.line load (MVA), =							0.710
F =	1.311	1.289	1.268	in % of Sh.Circ.Cap. =	0.648		
F0 =	0.000	0.000	0.000		1.164	1.152	1.141
F =	1.311	1.289	1.267		0.000	0.001	0.001
Isec(KA) =	62.00	64.00	66.00		1.164	1.152	1.140
ZI(mChm) =	9.778	9.472	9.185		66.00	68.00	70.00
RA(MChm) =	6.386	6.044	5.720		8.915	8.915	8.660
Parc(MV) =	73.6	74.3	74.8		5.412	5.412	5.528
Iarc(mm) =	355.9	346.8	337.5		75.1	80.6	81.3
S3 (MVA) =	101.2	103.9	106.5		367.1	357.2	347.0
P3 (MW) =	78.4	79.3	80.1		107.4	110.0	112.5
Uarc(V) =	685.8	670.0	653.9		86.0	86.7	87.3
Uarc(V) phase volt.	395.9	386.8	377.5		80.7	86.0	87.3
Line P.F.=	0.701	0.688	0.674		705.2	688.0	670.2
HW-Pow.F=	0.706	0.693	0.679		407.1	397.2	387.0
EAF-P.F3=	0.774	0.763	0.752		0.660	0.723	0.693
EAF-P.F4=	0.774	0.763	0.752		0.665	0.729	0.698
P.F.5 =	0.856	0.848	0.839		0.740	0.800	0.788
					0.800	0.788	0.776
					0.875	0.866	0.857
are stability fact.	6.39	6.04	5.72				
arestab.V.Kohle	1.51	1.43	1.35		6.17	5.84	5.53
are react.XL	1.740	1.616	1.501		1.46	1.38	1.30
are resistance RI	6.386	6.044	5.720		0.785	0.736	0.690
arestab.at line	1.13	1.07	1.01		5.412	5.169	5.528
Factor Kc	0.8	0.8	0.8		1.09		
NLC / X0	0.41	0.38	0.35		0.2	0.2	0.2
					0.19	0.17	0.16

SGL CARBON GROUP Information

Current-Carrying Capacity



Picture 1.16

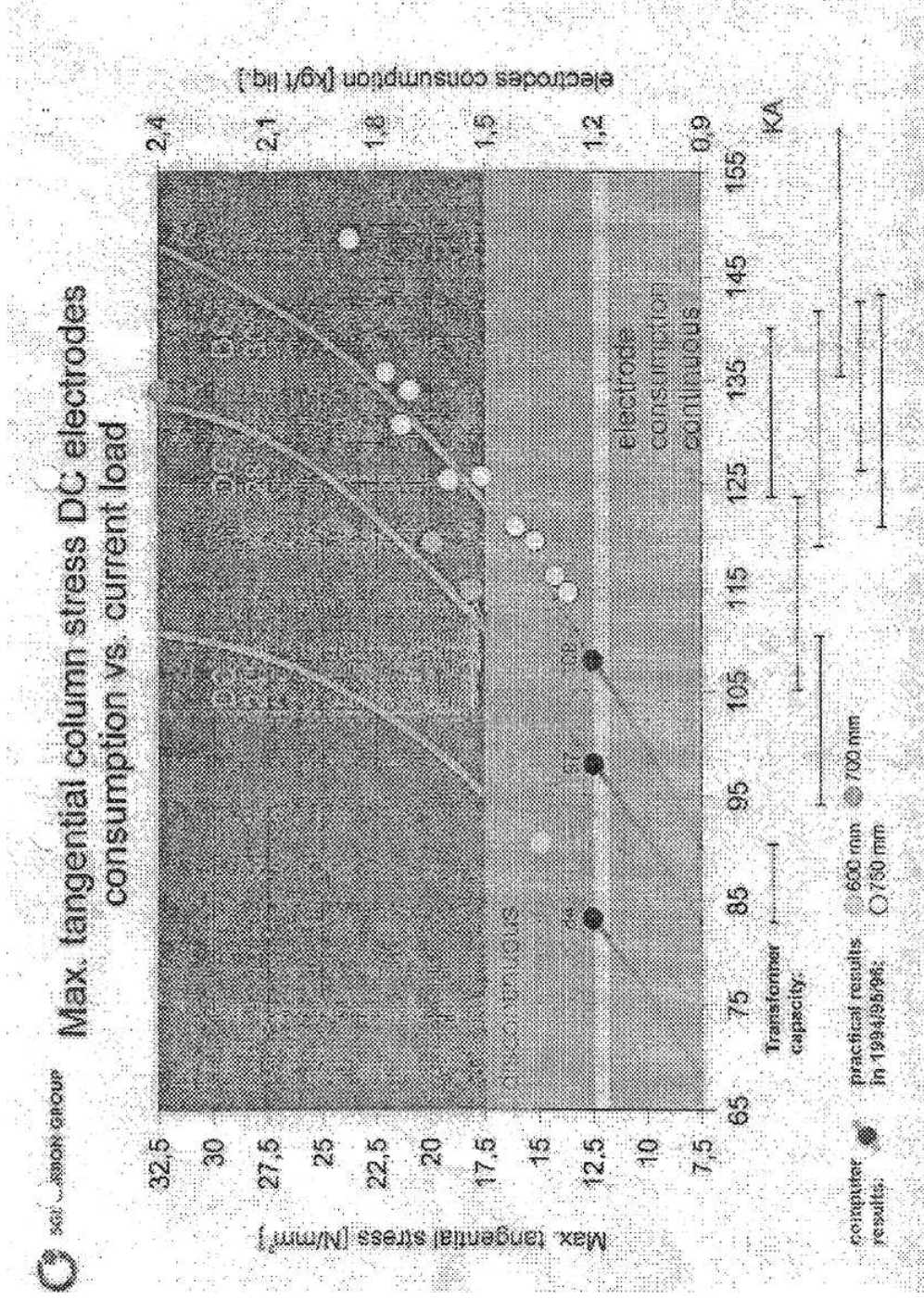


Figure 1.17

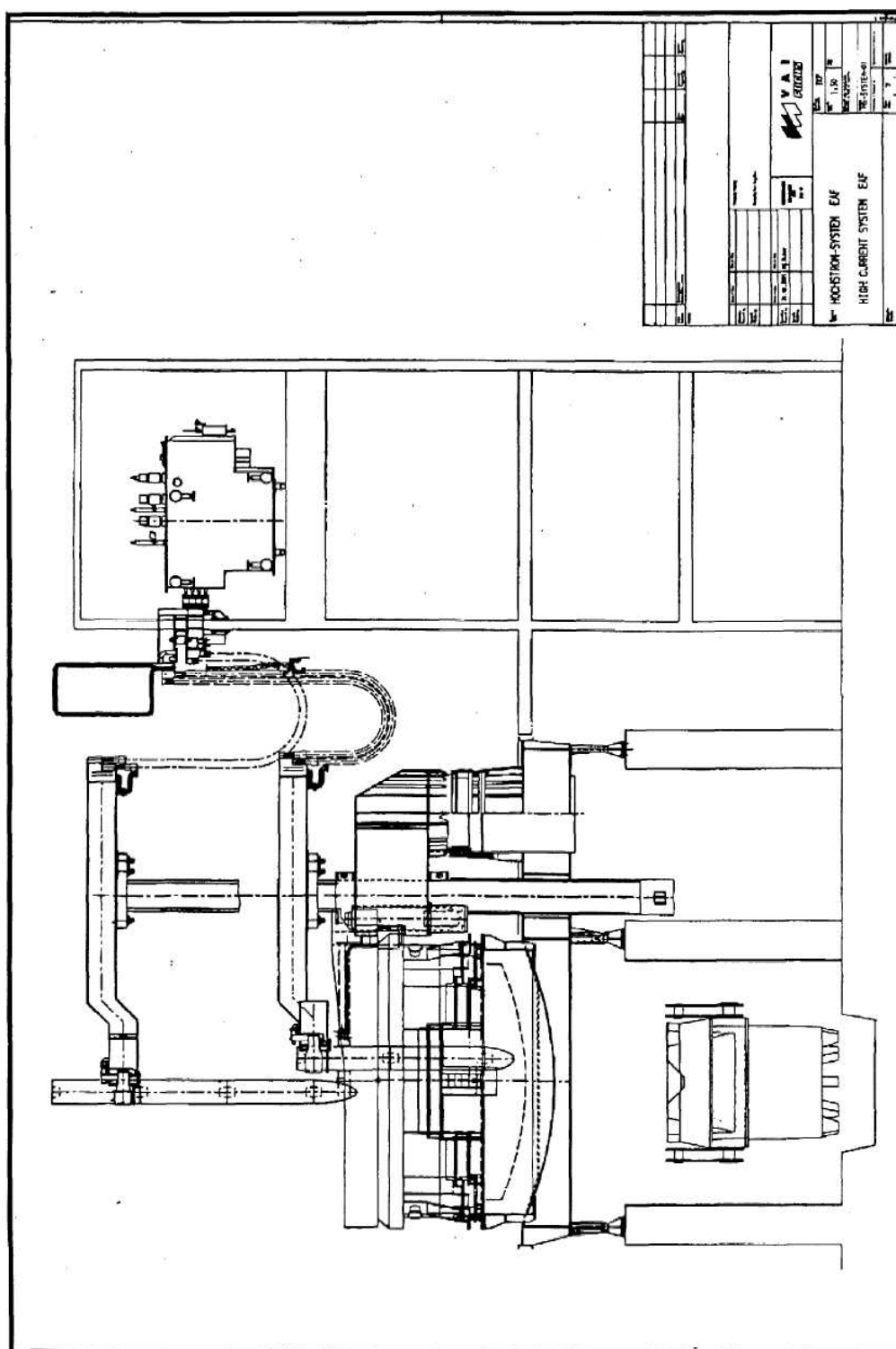


Figure 1.18

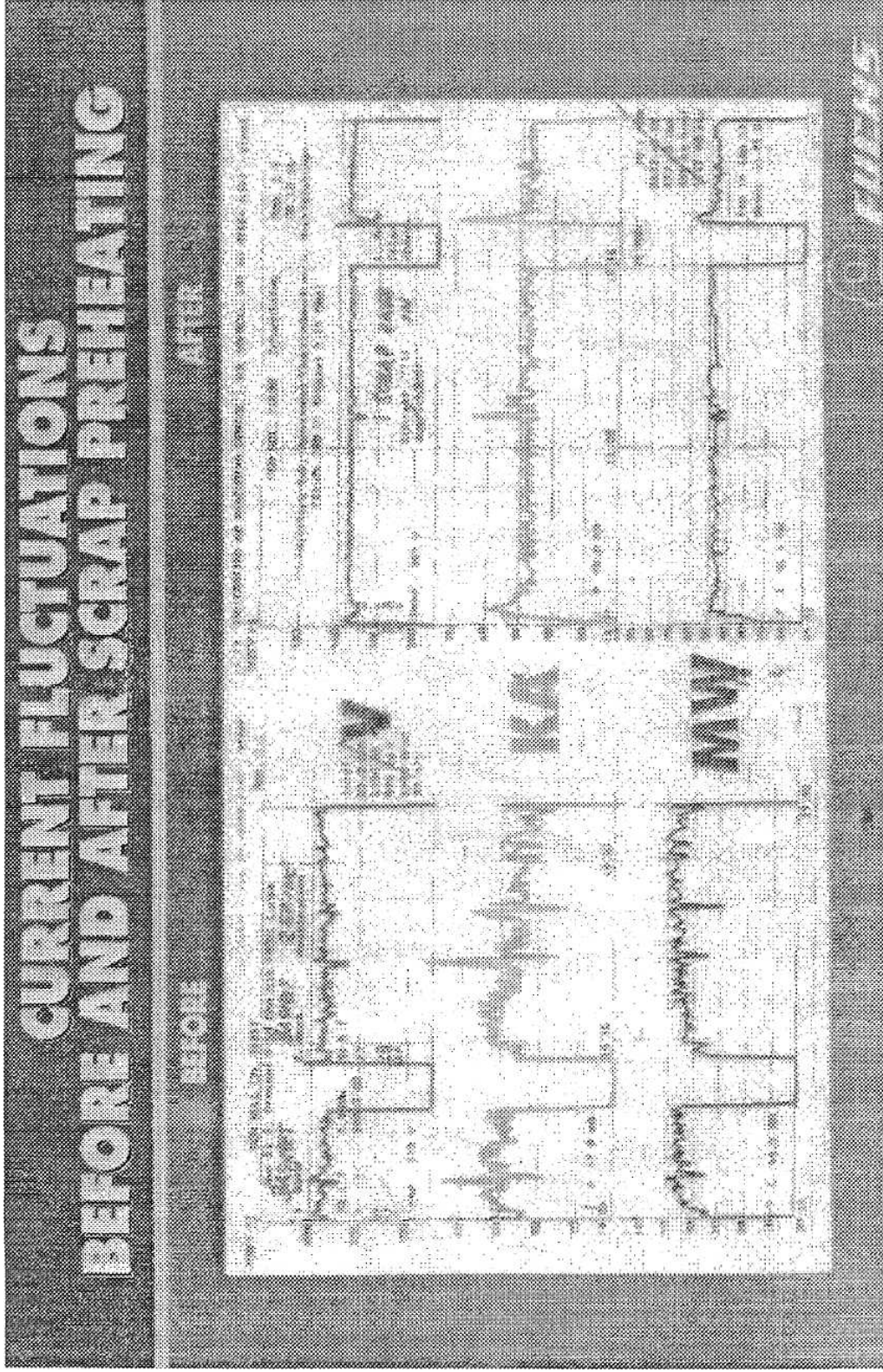
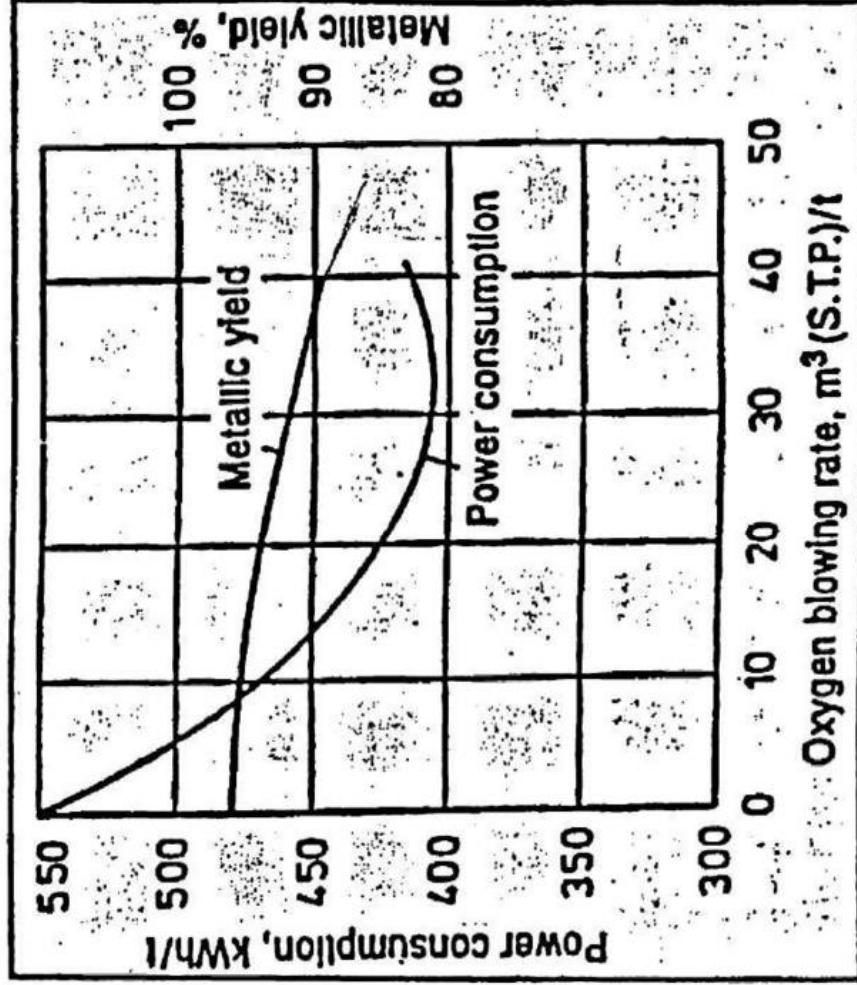


Figure 1.19

Effect of Oxygen on Metallic Yield

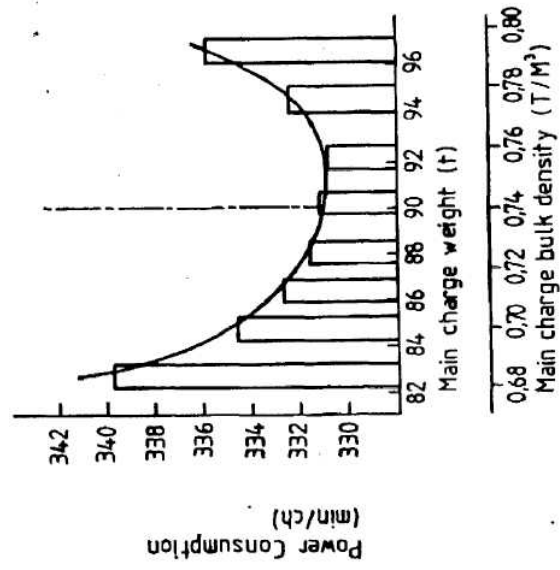
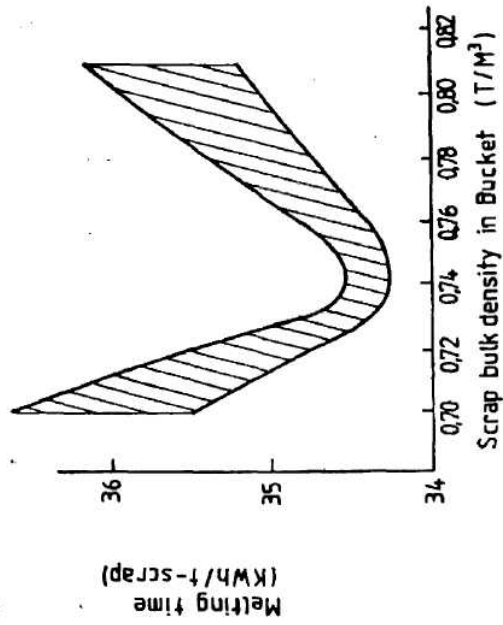
4 Japanese survey on electrical consumption
versus oxygen injection rate 1



STEEL TIMES / STEEL TIMES INTERNATIONAL

Figure 1.20
Power in
30m x 25m
72% yield
with 25%
plant electric
in 1960 and 1970

Optimum value of Scrap Bulk Density



Optimum value is 0,74 T/M³ in case of both Melting time (productivity) and Power consumption (Energy cost)

Quelle: Aichi Steel Works, LTD.

Figure 1.21

PANEL COMPARISON: Steel vs. Copper

(Heat Introduction vs. Temp. Differential/ Tension)

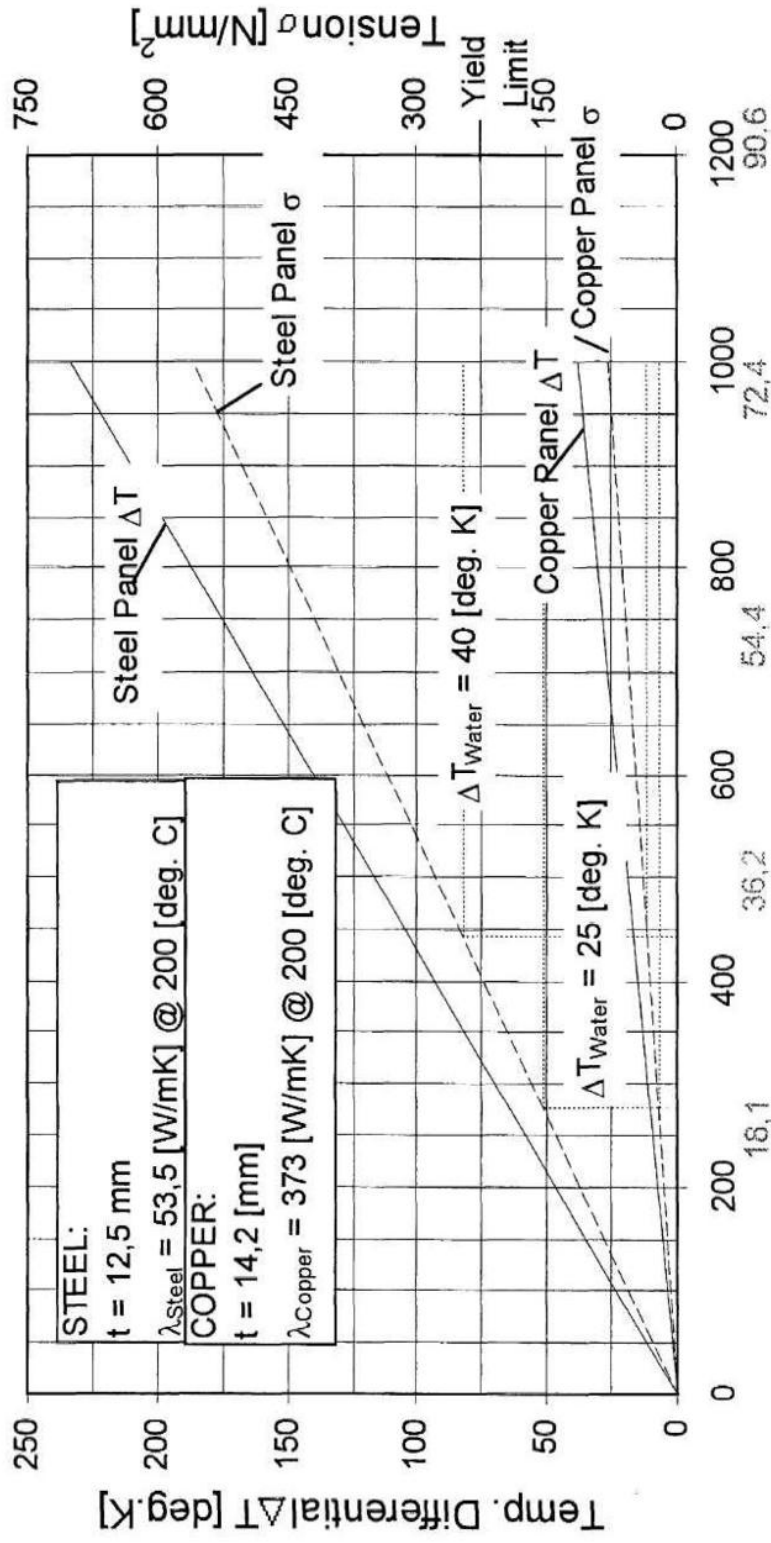


Figure 1.22

		Different Operating Points of High Impedance Furnaces			
	Furnace A	Furnace B	Furnace C	Furnace D	Furnace E
TRF(MVA)	33/33,6	120/134,4	120/134,4	188	240
U2m max (V)	700	1200	1350	1500	1616
Reactance	6.03	7	6.5	8.2	variable
I sec (KA)	30	52	58	72	86
MW	28	90	110	130	140/172/185
EAF-PF	0,78	0,79	0,88	0,71	0,73
Line-PF	0,78	0,72	0,78	0,67	0,73
SVC	X	--	--	--	X

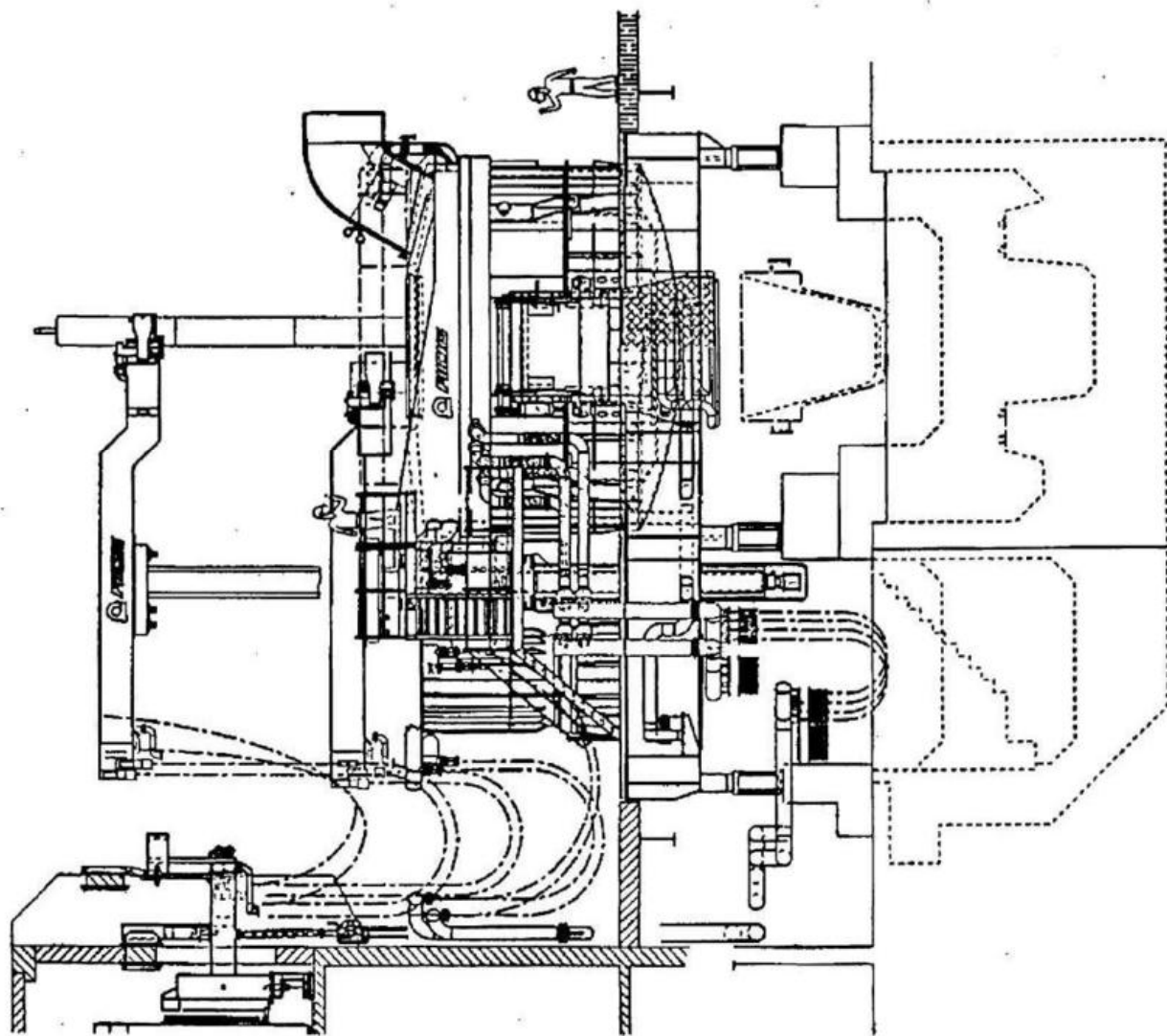
Figure 1.23

ANTI-CROOK - TAPPING SIDE

This technical drawing illustrates the anti-crook side of a tapping machine. It features a complex arrangement of mechanical parts, including a large flywheel on the left, a central shaft with various gears and pulleys, and a tapping head assembly on the right. The drawing uses solid lines for visible components and dashed lines to indicate internal mechanisms and the path of a tapping tool. A cross-hatched area on the right side represents a section of the machine's housing or a specific material being tapped. The overall design is detailed, showing the intricate mechanical structure of the device.

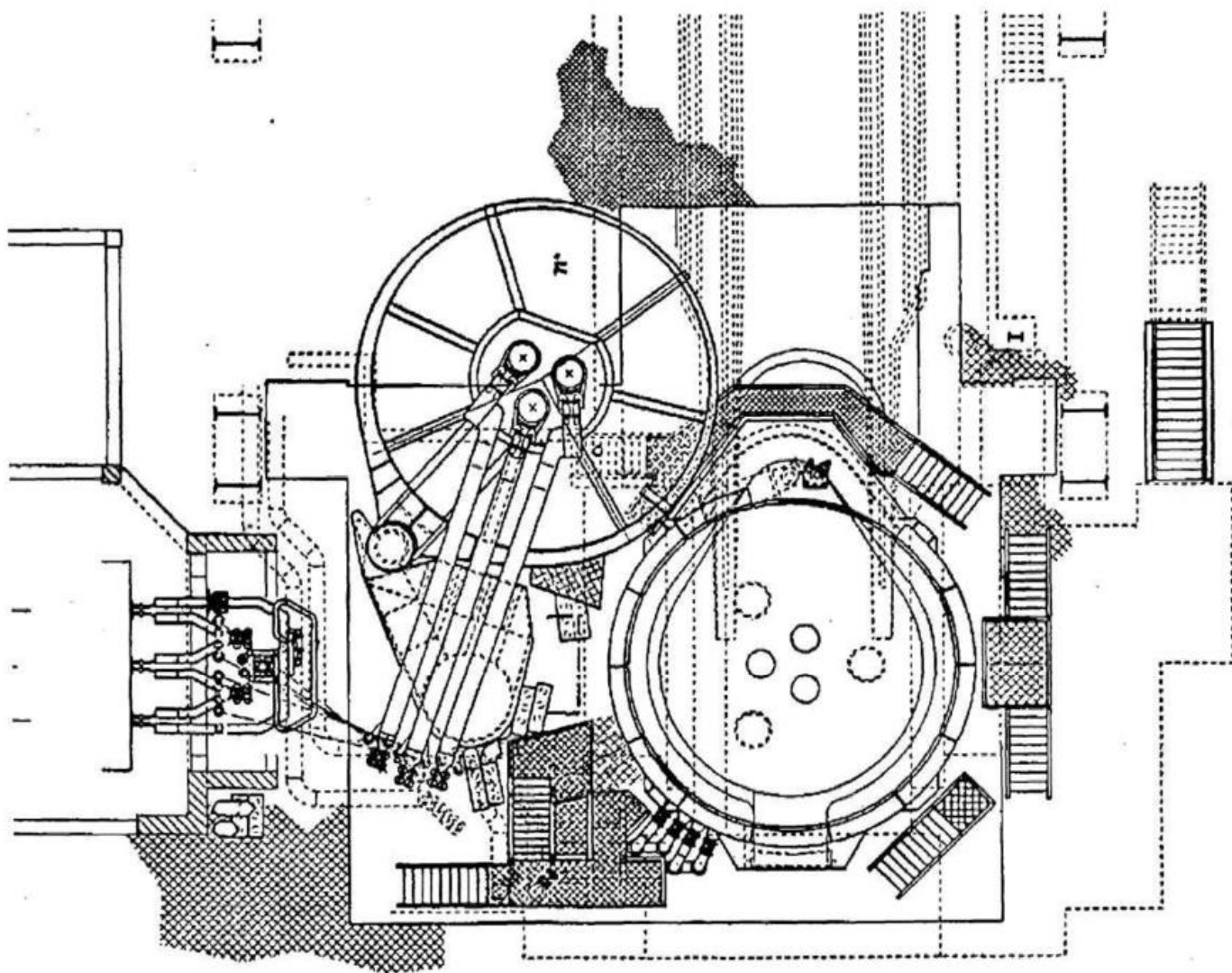
Bath stool capacity	C (I)	- 117.07
Total bath stool	C (I)	- 118.9
Bottom shell	D1(m)	- 7.318
Transformer rating	(MVA)	- 120
Secondary voltage	(V)	- 1200
Electrode diameter	(mm)	- 810
Electrode pitch circle	(mm)	- 1230
Charging volume (total)	(m ³)	- 130

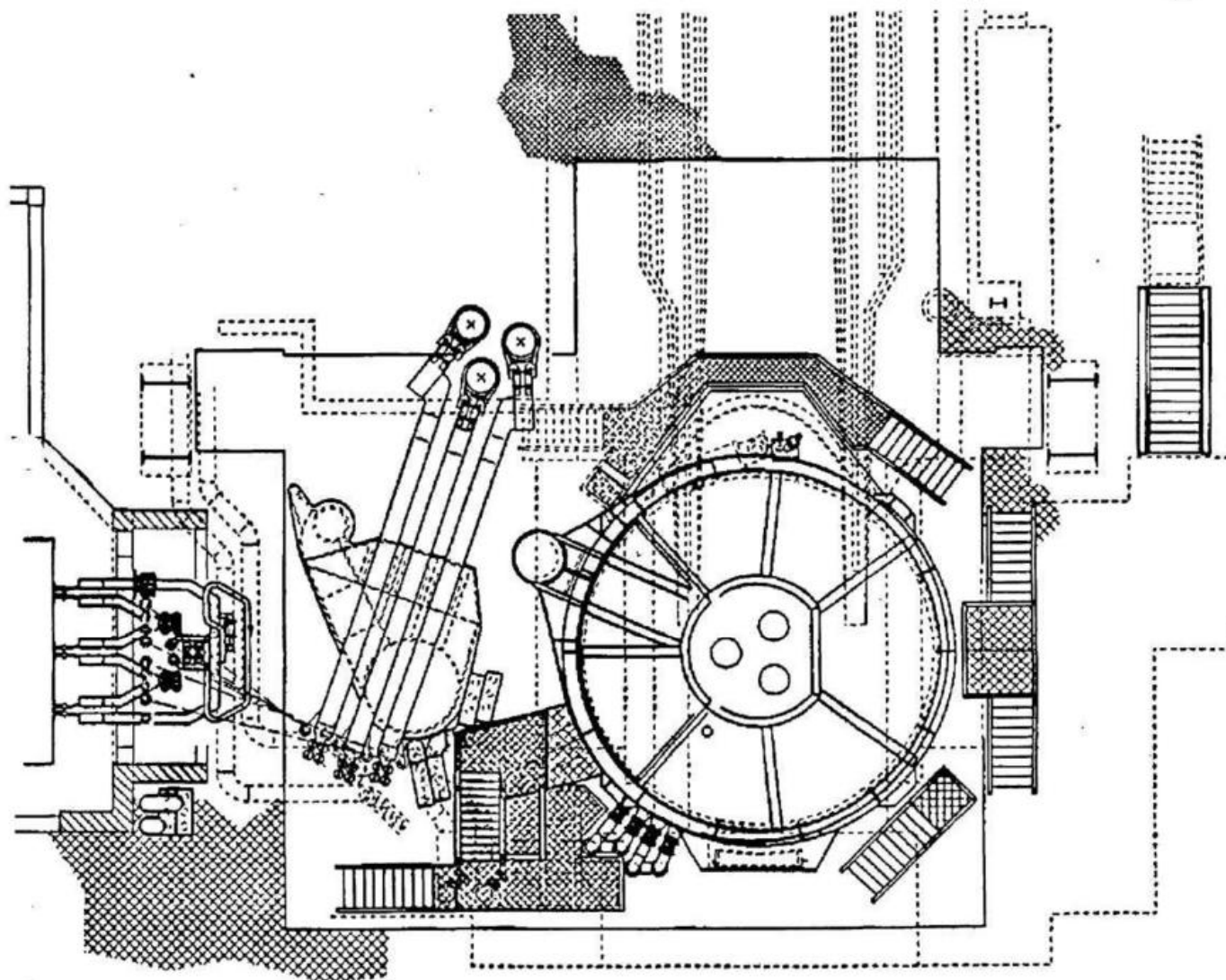




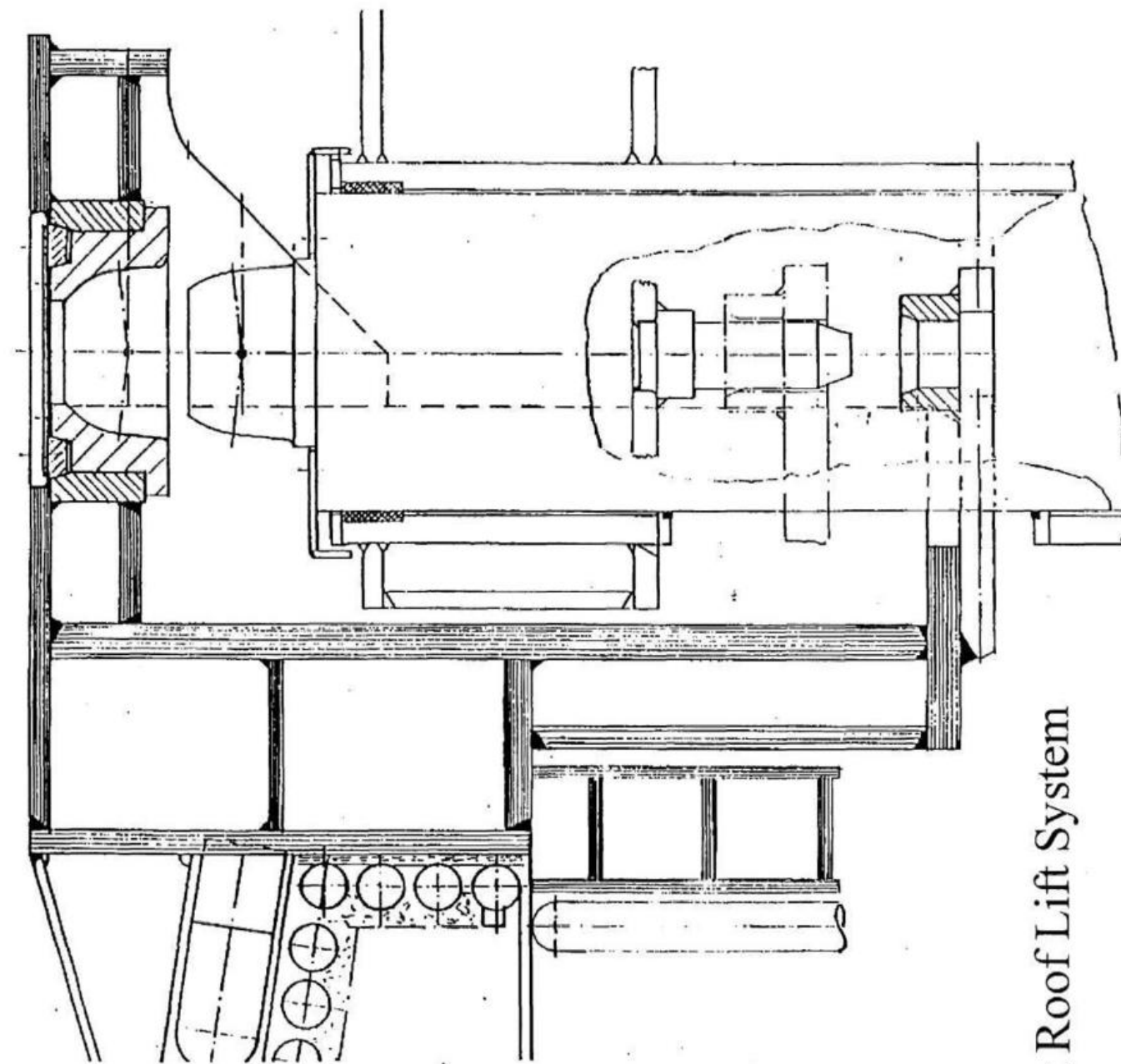
ISHLACKENSEITE - SLAG SIDE

165 t AC-EAF
120 MVA
U₂=1200 V

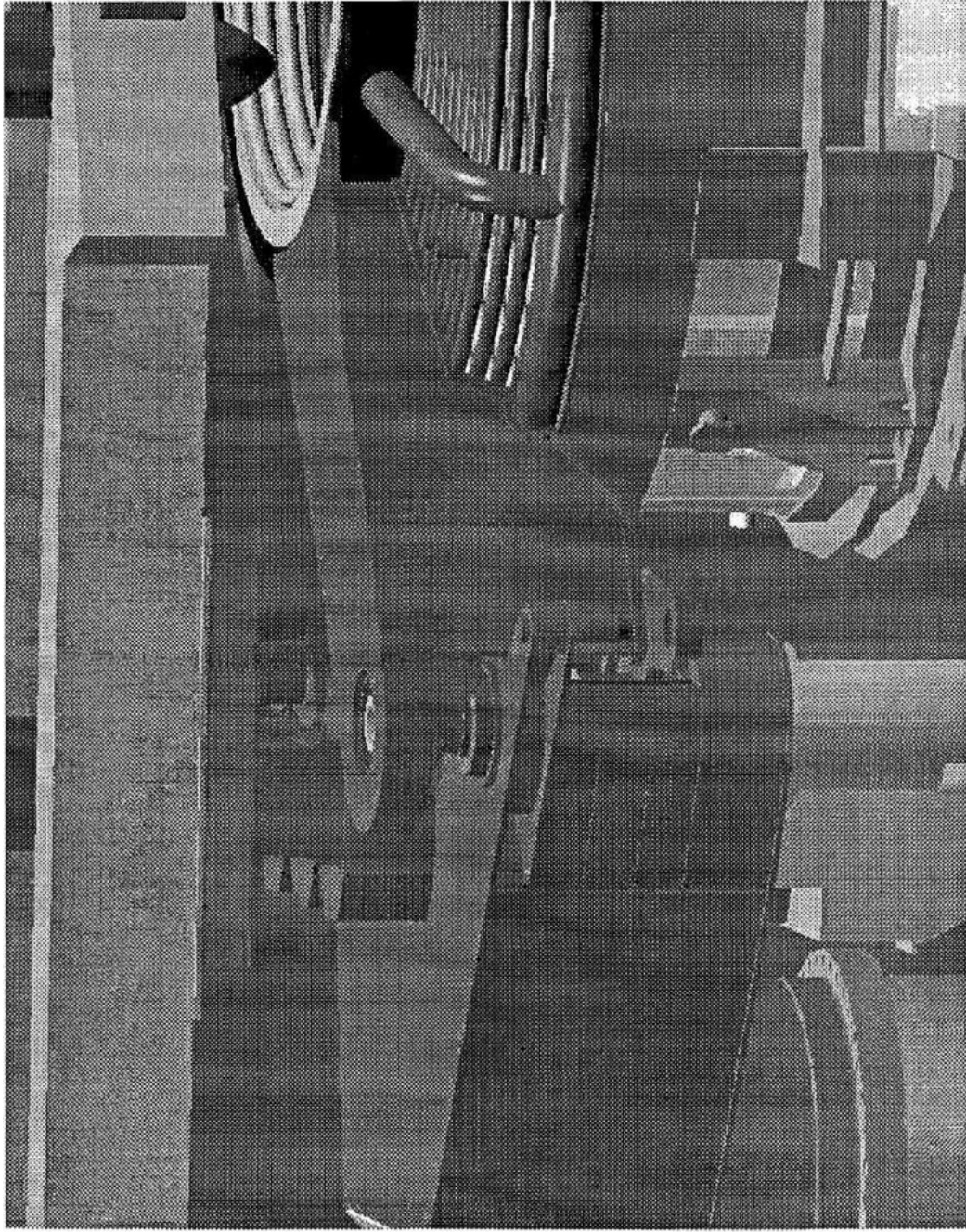




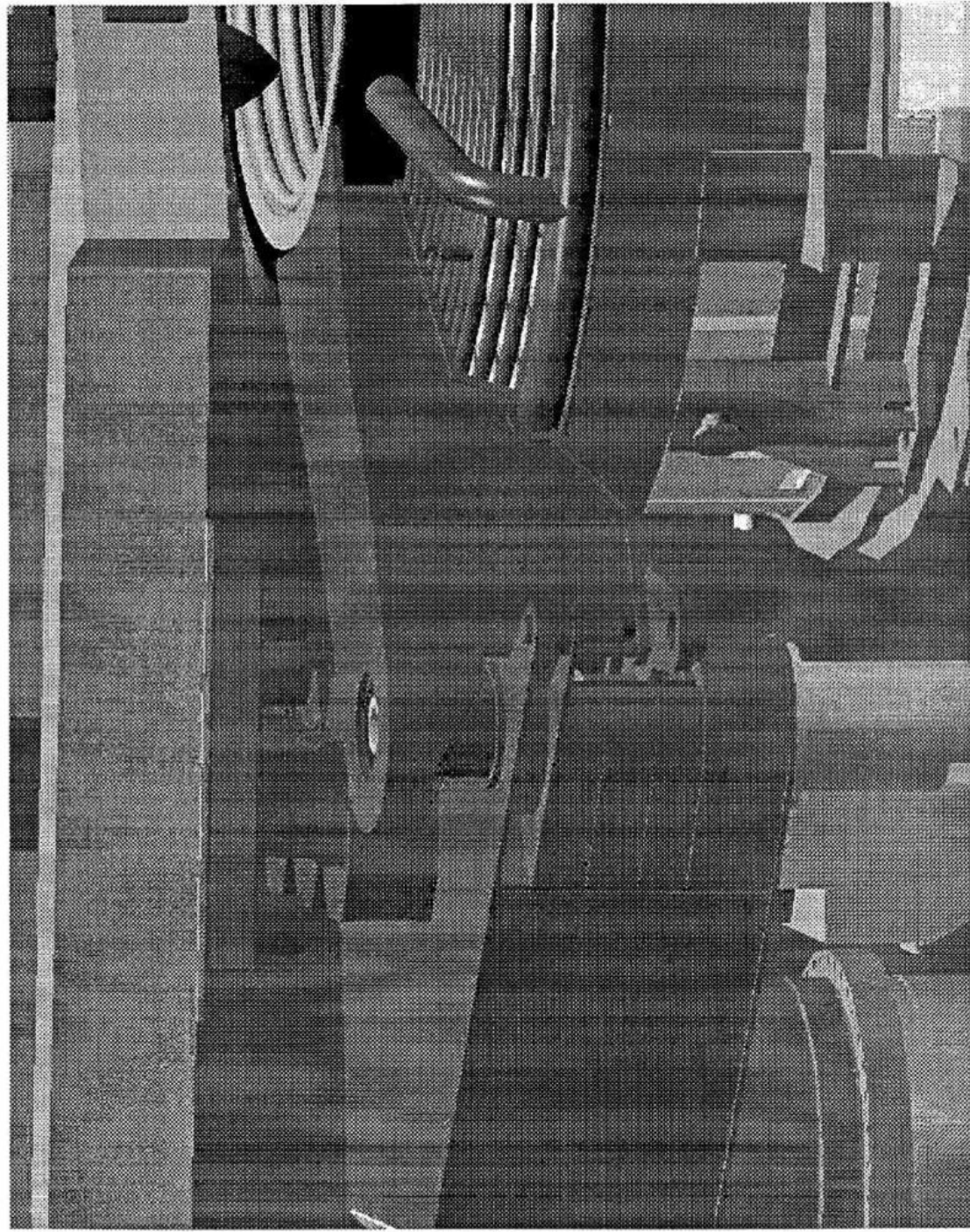
165 t AC-EAF
120 MVA
U2=1200 V



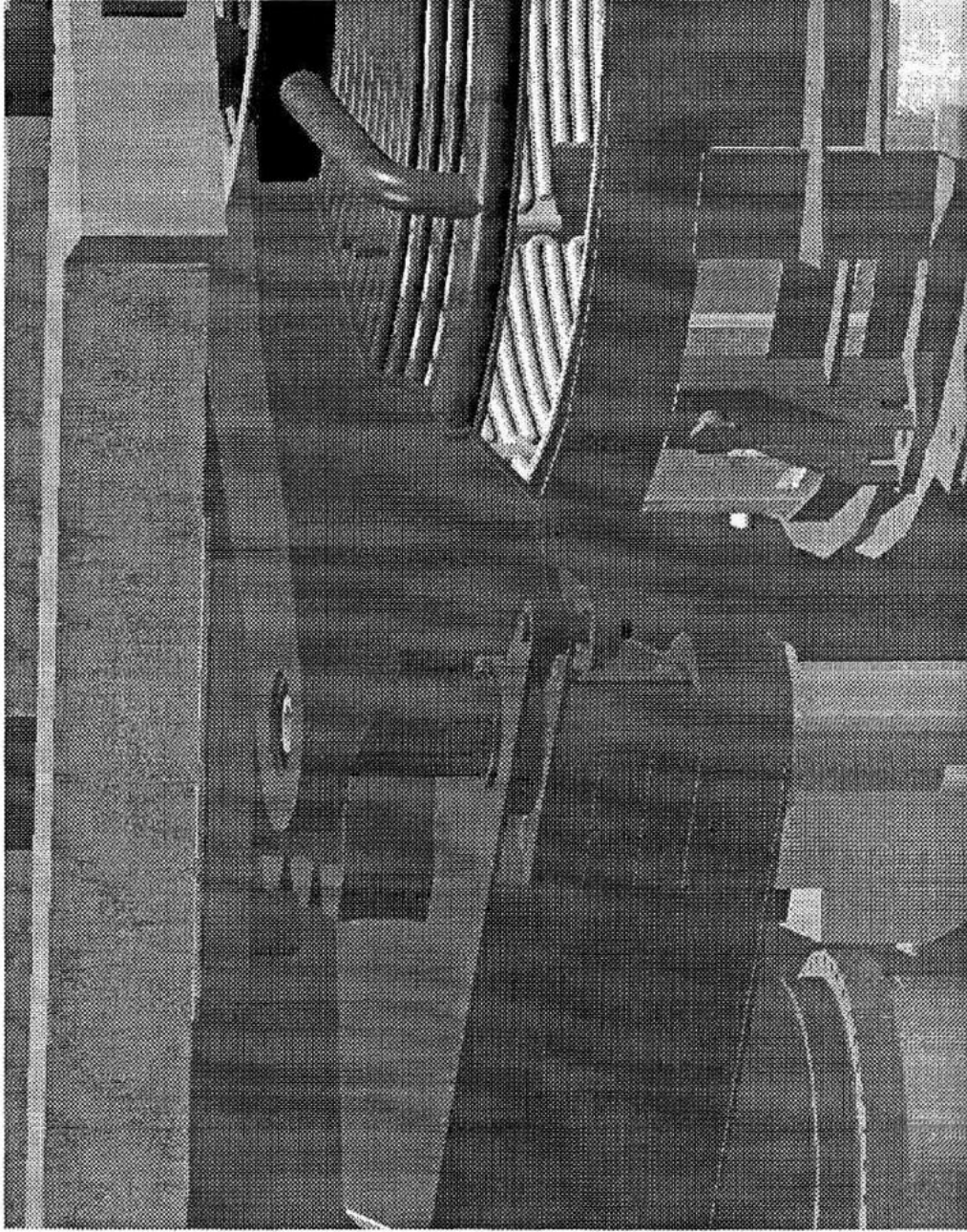
Single Point Roof Lift System



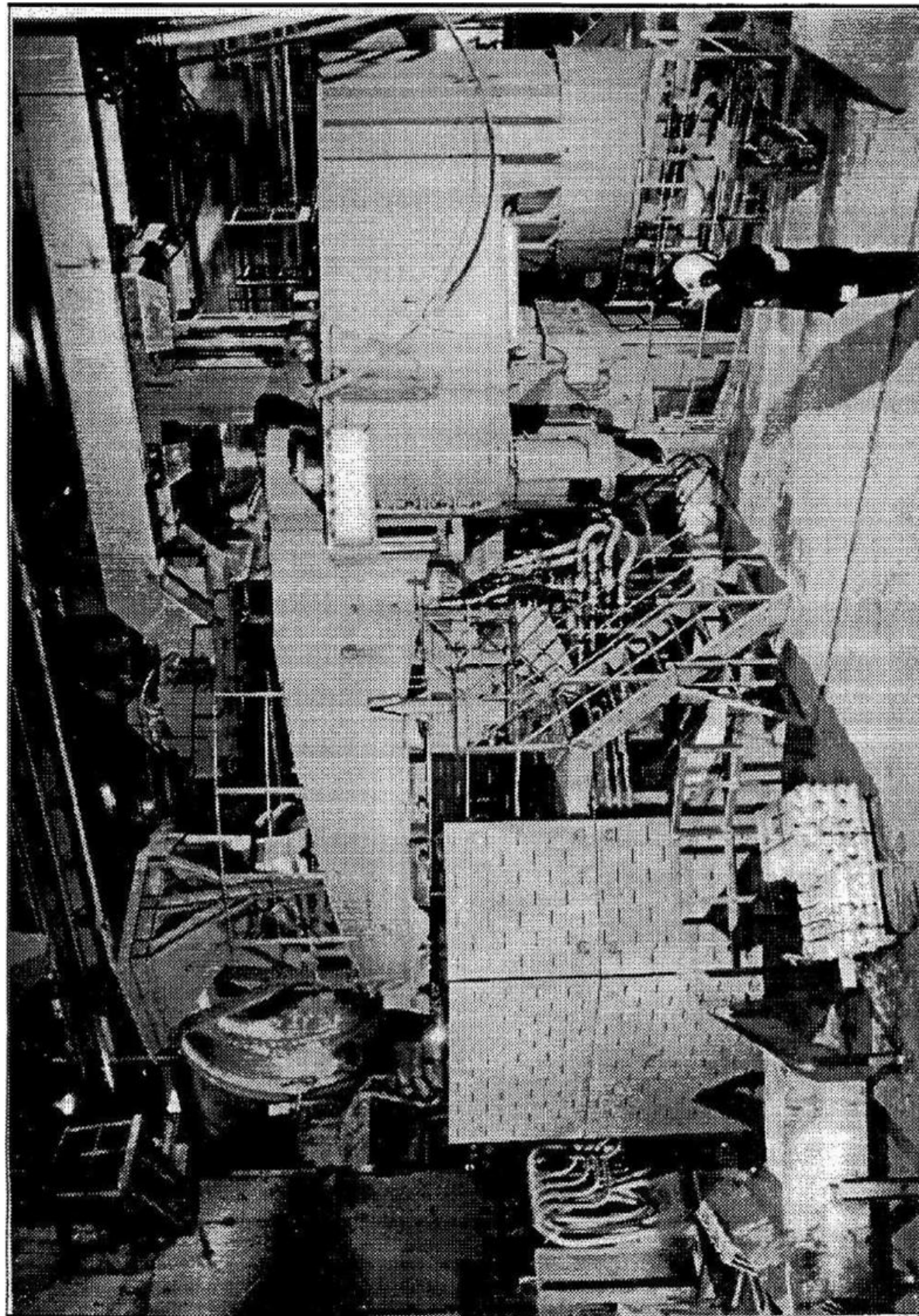
Roof Lift Cylinder 0 mm Stroke, Roof Completely disconnected



Roof Lift Cylinder 200 mm Stroke , Roof Engaged

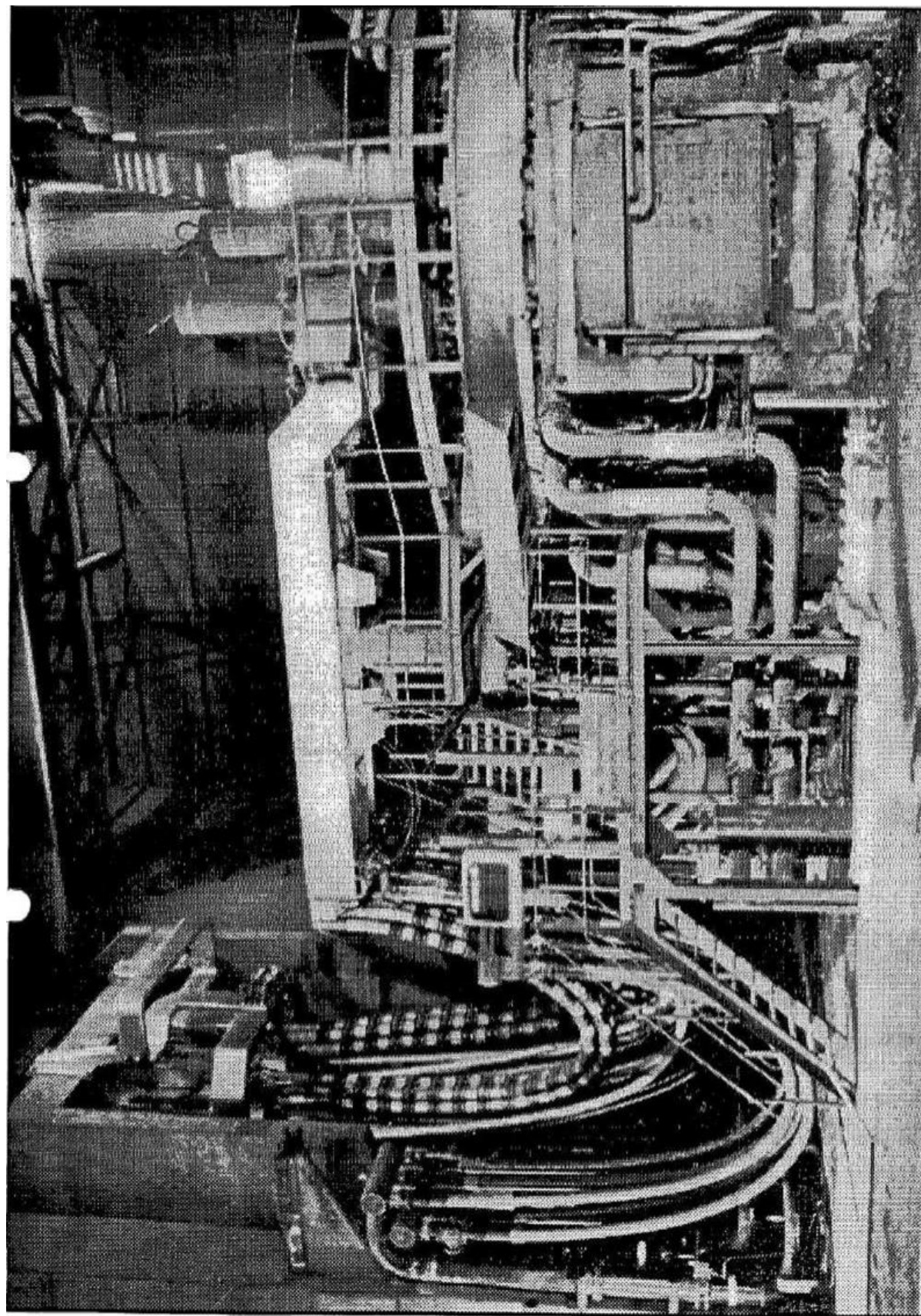


Roof Lift Cylinder 600 mm Stroke , Roof UP , Pin Interlocked



FSL

EBT - OFEN
165 to



FSL

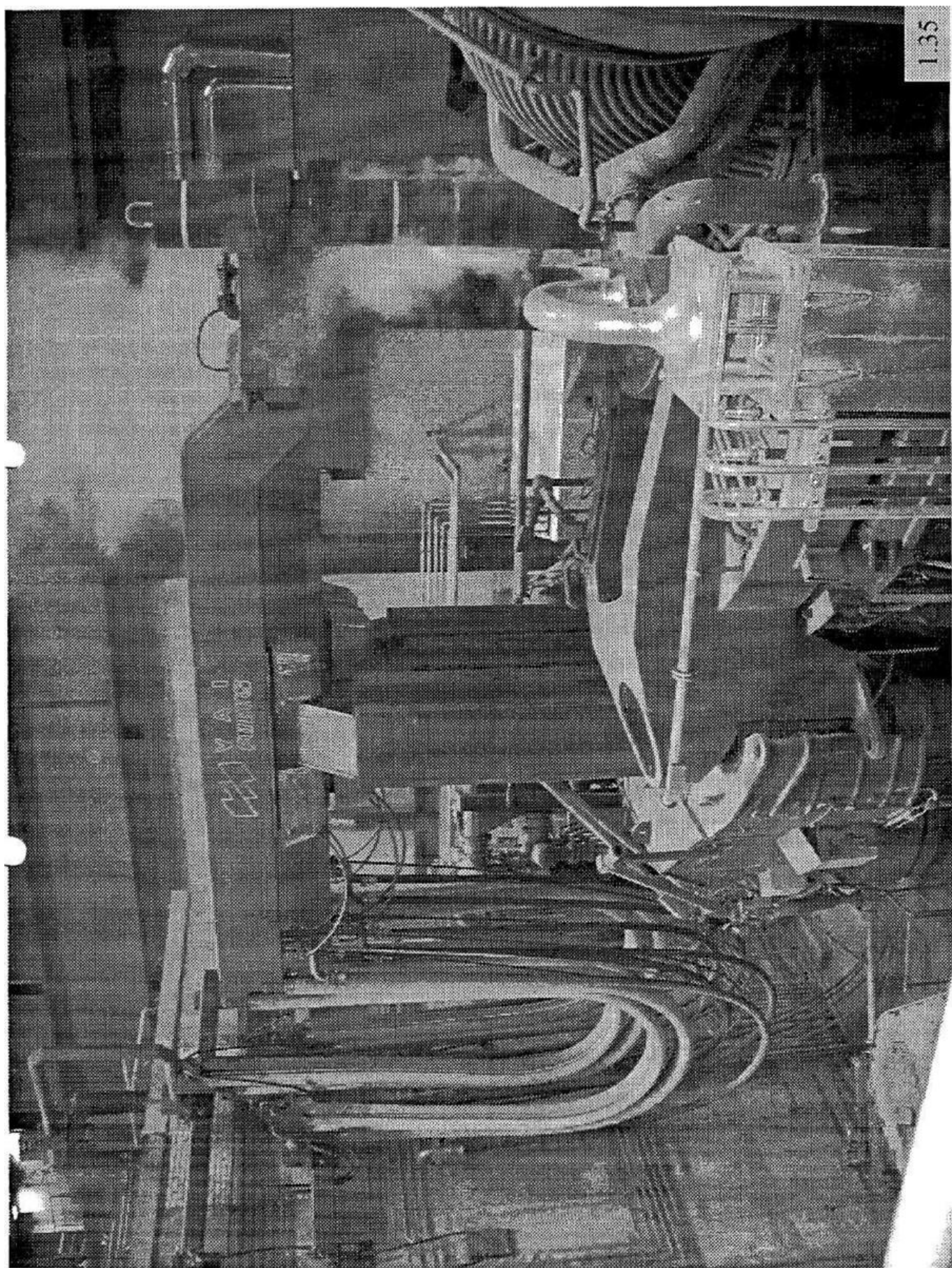
EBT - OFEN

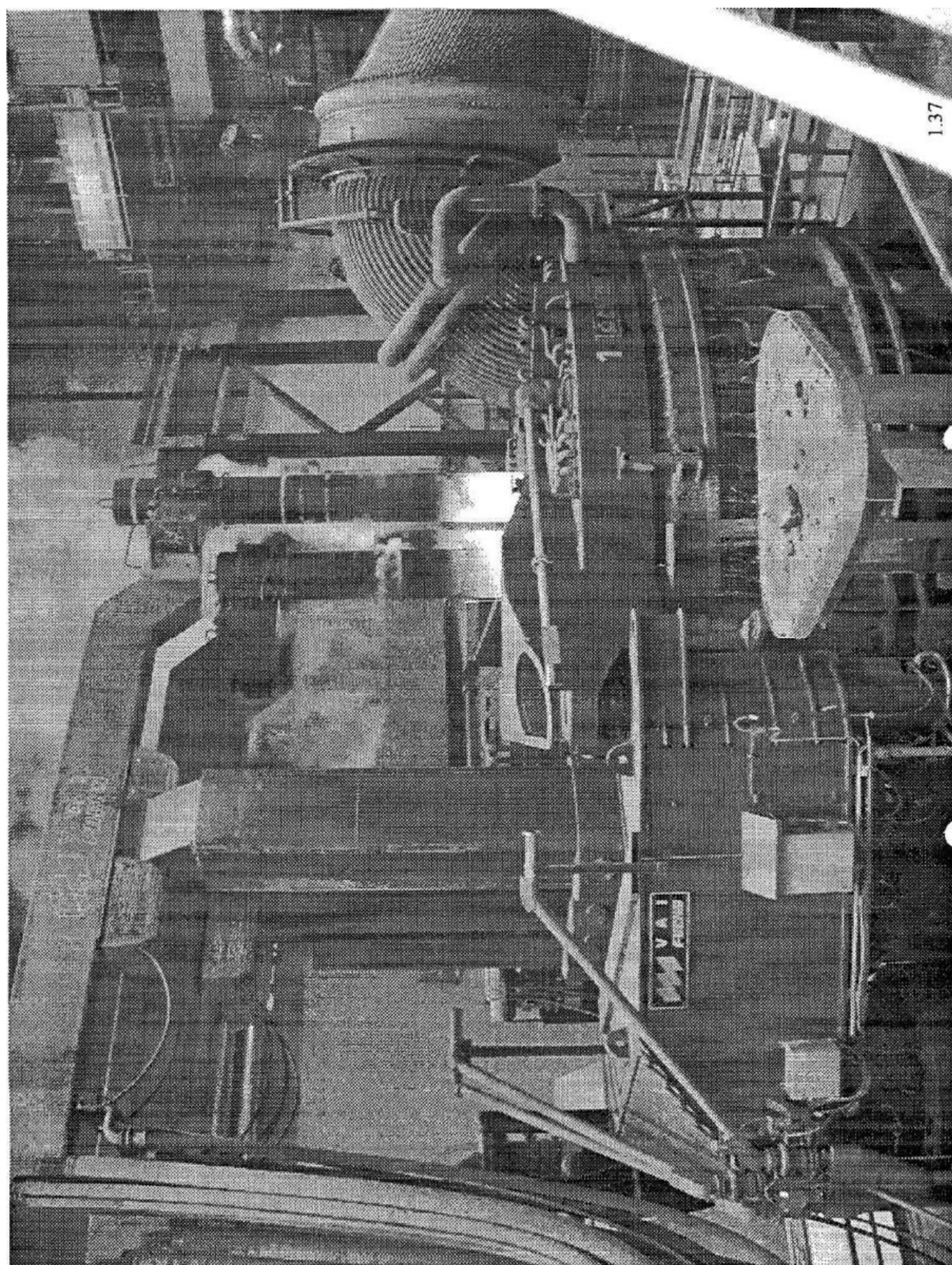
165 to

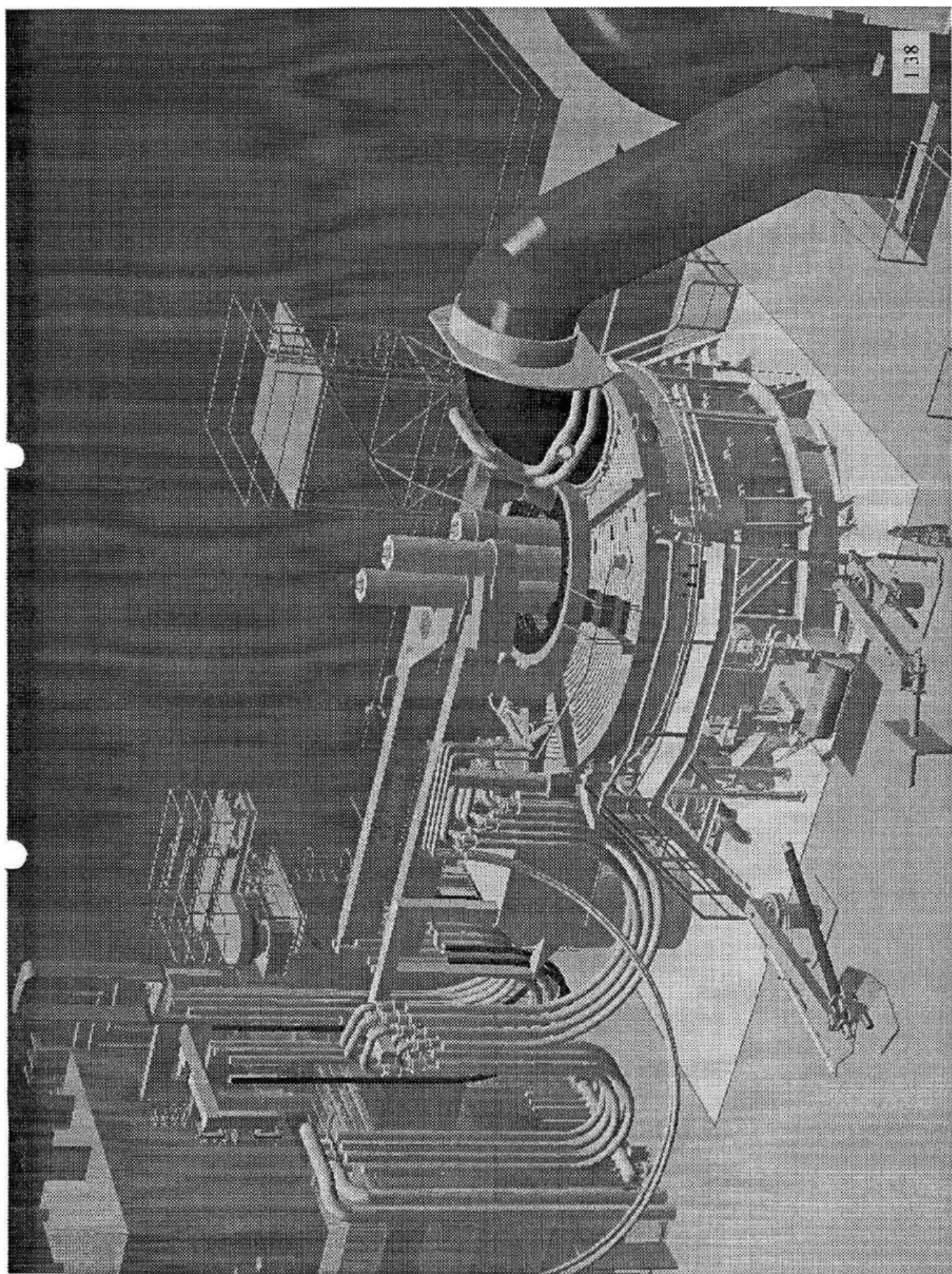
F 150 t
 dia
 shell height
 59,6 MVA
 r 1,5 Ohm
 W

The drawing is a technical cross-section of a large industrial machine, possibly a generator or motor, mounted on a large, curved structure. The machine is shown in a cutaway view, revealing internal components. Labels include 'FOUNDATION' at the base, 'GALLERY' for the upper walkway, 'RUNWAY' for the lower walkway, and 'MELT SHOP FLOOR' at the bottom. The machine is supported by a large, curved structure that is also labeled 'FOUNDATION'. The drawing is a technical cross-section, showing the internal components of the machine.

1.34







AC-EAF in Turkey - 250 t

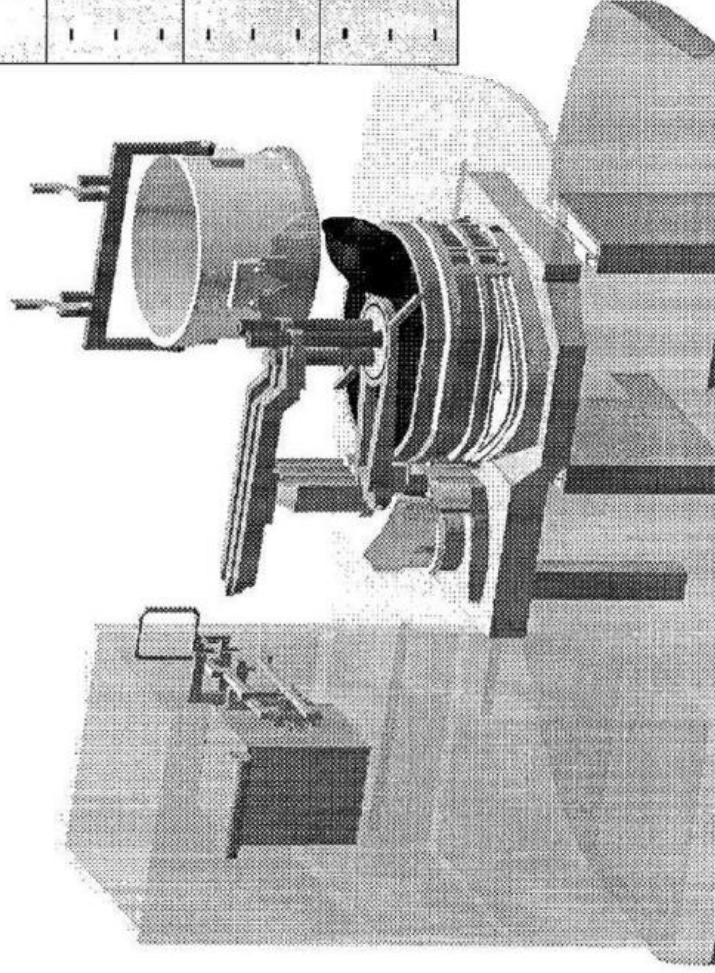
ULTIMATE FCE IN TURKEY
PROJECT. PLANT.

- Transformer	800 - 1.600 V	240 MVA
- Tapping weight		250 t
- Oxygen Total		40 Nm³/t
- Electrical energy		390 KWh/t
- TTT		50 Min
- Productivity		300 t/h
- Production		2.400.000 t/y
- 6 RCB / 3,5 MW	O2	2.800 Nm³/h
- 4 PC injectors	O2	400 Nm³/h
- Carbon injectors		4x60 kg/min

HIGH FCE WALLS

Design Data

- EOEBT design	9,3 m
- Panels high	3,2 m
- Roof high	1,4 m



Furnaces with Single Basket Charge

	OfenA	Ofen B
Tap Weight (t)	82	90
Shell Diameter (mm)	6700	6800
Shell Height (mm)	3500	3000
Transformer Rating (MVA)	110	100+20%
Sekundary Voltage Range (V)	813-1201	740-1025
Reactor (Ohm)	max.2,5	
Transformer Active Power (MW)	75	72
Average Power On-Time (min)	28	25
Tap to Tap-Time (min)	35	37
Elektrical Energy Consumption (kWh/t)	400	358
Gas (Nm ³ /t)	6	5,4
O ₂ - (Nm ³ /t)	33	31,8
Tapping Temperature	1660	1666
Lime (kg/t)	-	51,55
Electrodes (kg/t)	1,7	-
Production (t/h)	140	140

Ultimate EAF, Oxygen / Carbon Management Tools

The Ultimate

Characteristics
& Performance

Power Input

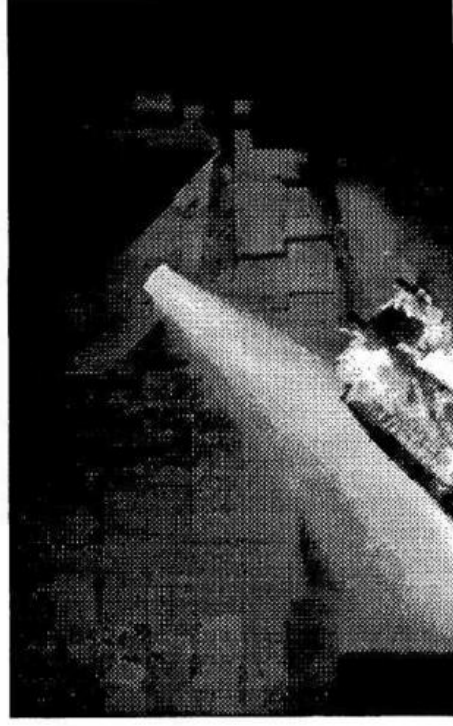
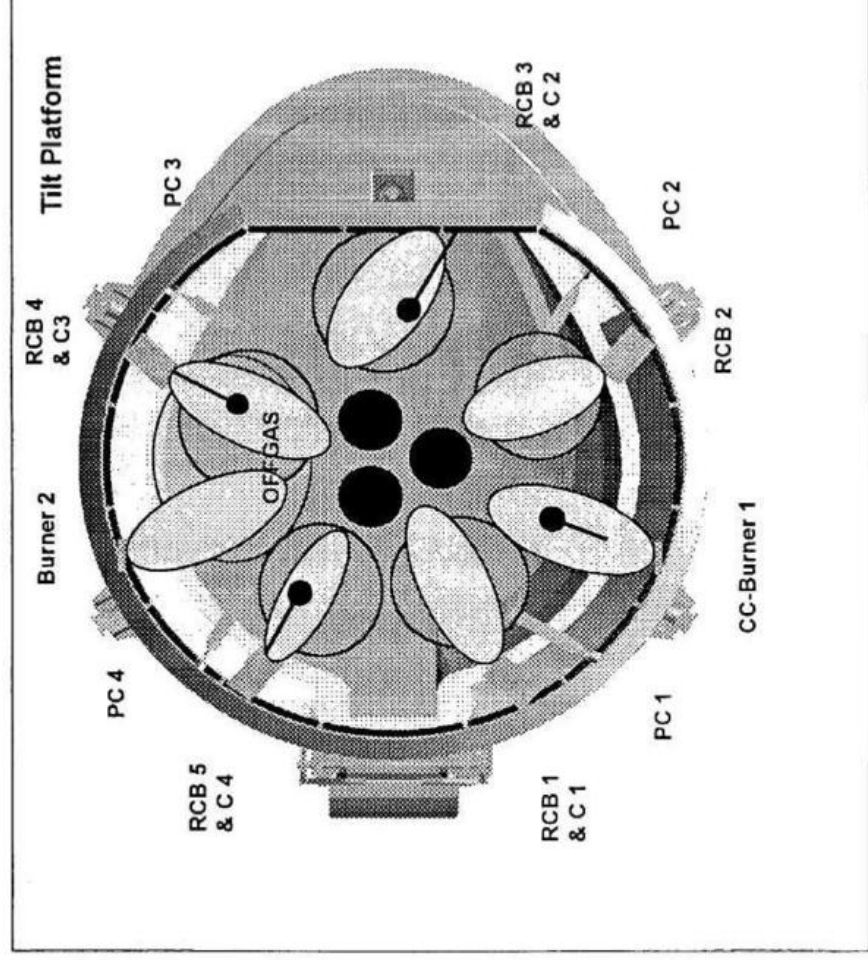
O2 Technology

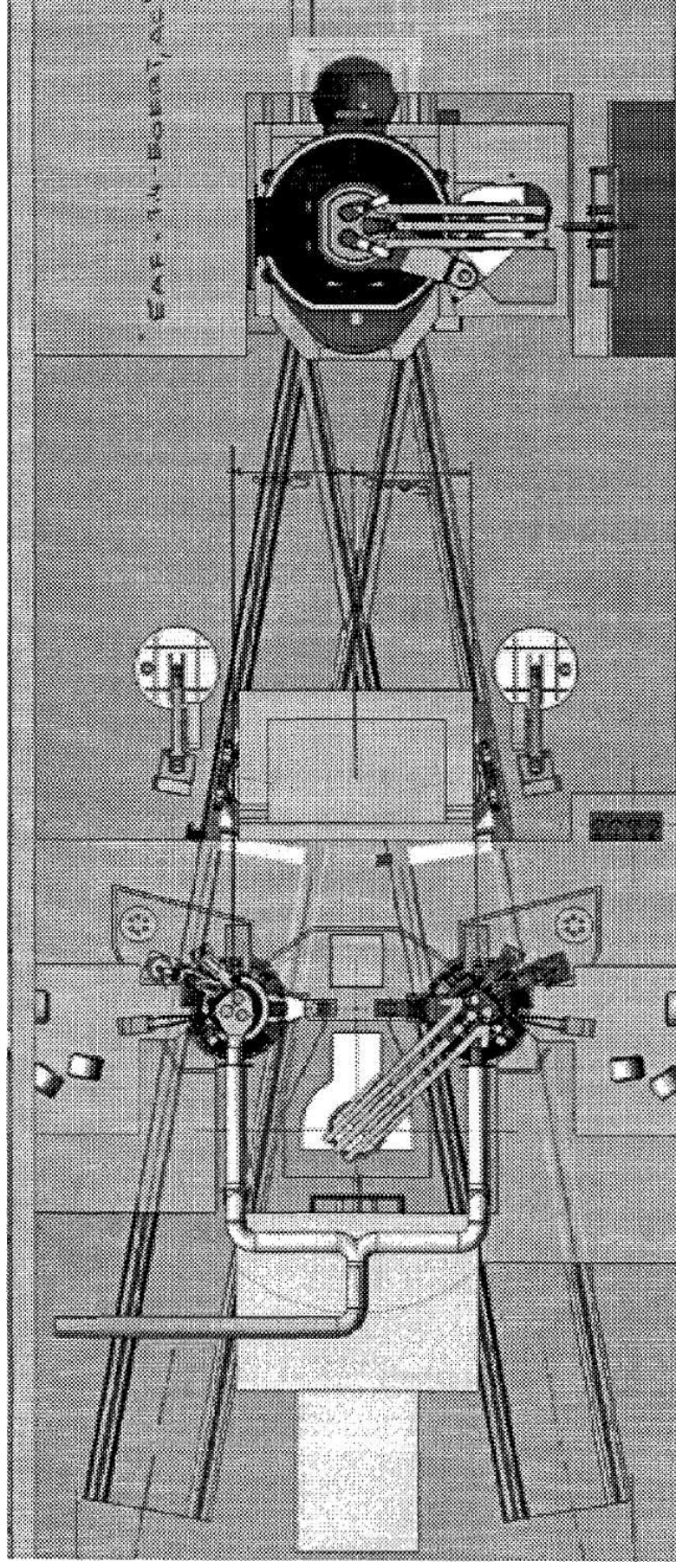
- RCB Lancing

- Burner Operation (for Scrap preheating and perforation)

- C-Injection System (for Oxygen penetration incl. C Injection)

- PC Injectors (for CO Post Combustion / Scrap preheating)

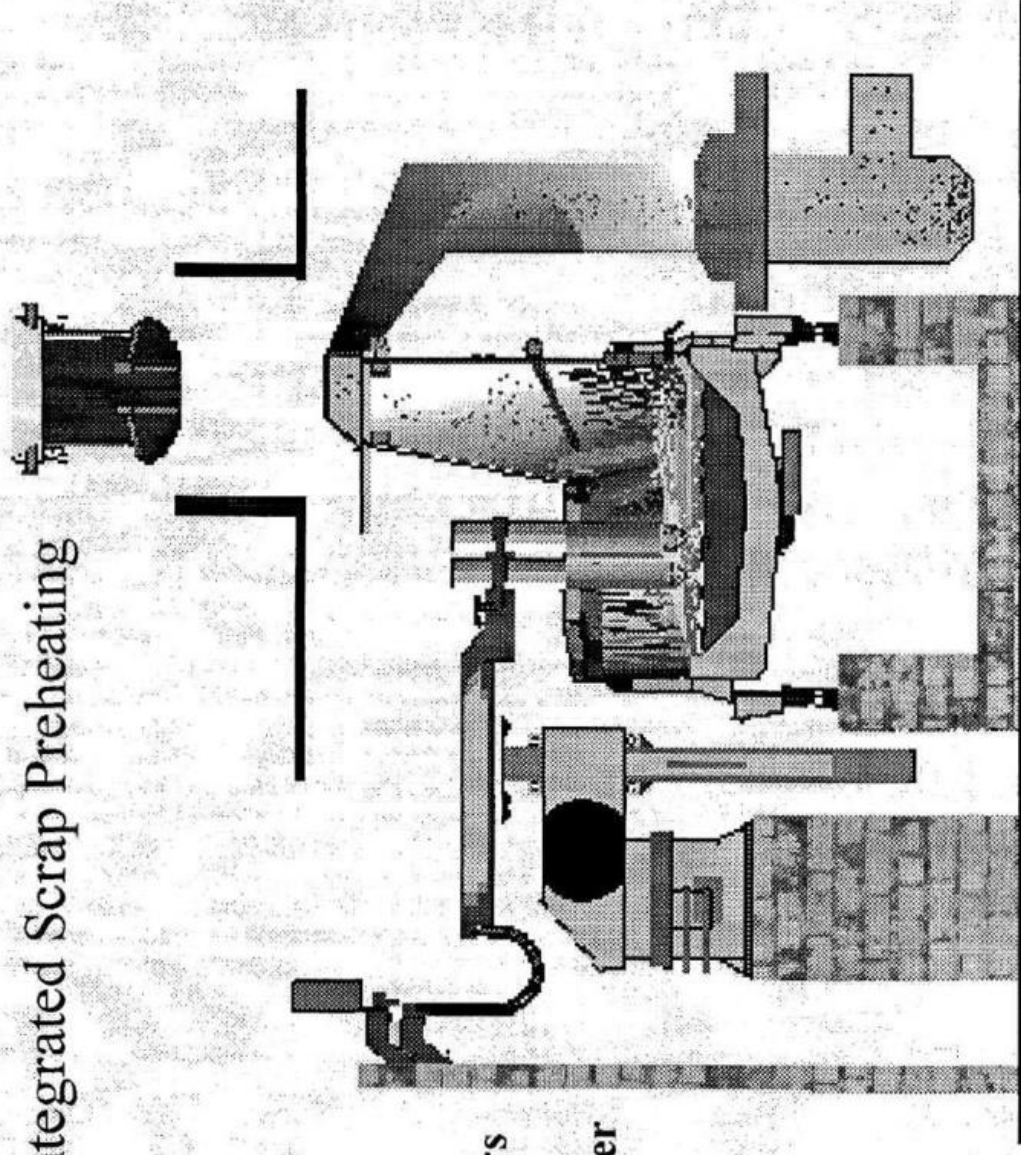




Lay Out of a Melt Shop for Single Basket Charge

Integrated Scrap Preheating

- Watercooled Shaft
- Watercooled Fingers
- Furnace Burners
- Post Combustion Burners
- Post Combustion Chamber
- Watercooled Duct
- Quench System
- Carbon Injection
- Baghouse



AC Finger Shaft Furnace

FUCHS FINGER SHAFT FURNACE

- Super Sonic Oxygen Injection
- Suction Air from Dedusting Fans
- Air Fans in Finger Housing
- Safety Fans PC Chamber Entry
- Shell Burners for fast Scrap Melting
- PC-Burners for Off Gas Treatment
- Requirement for finger damping system.
- Online maintenance.

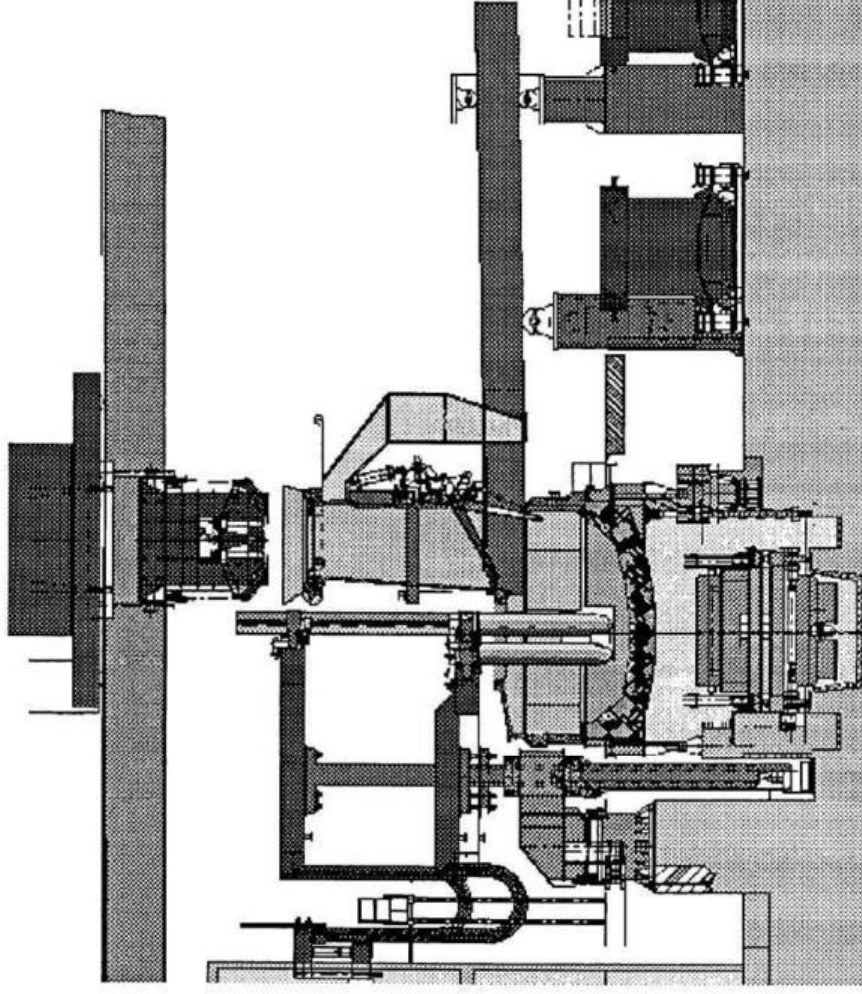


Figure 2.02

Shaft Emission Control

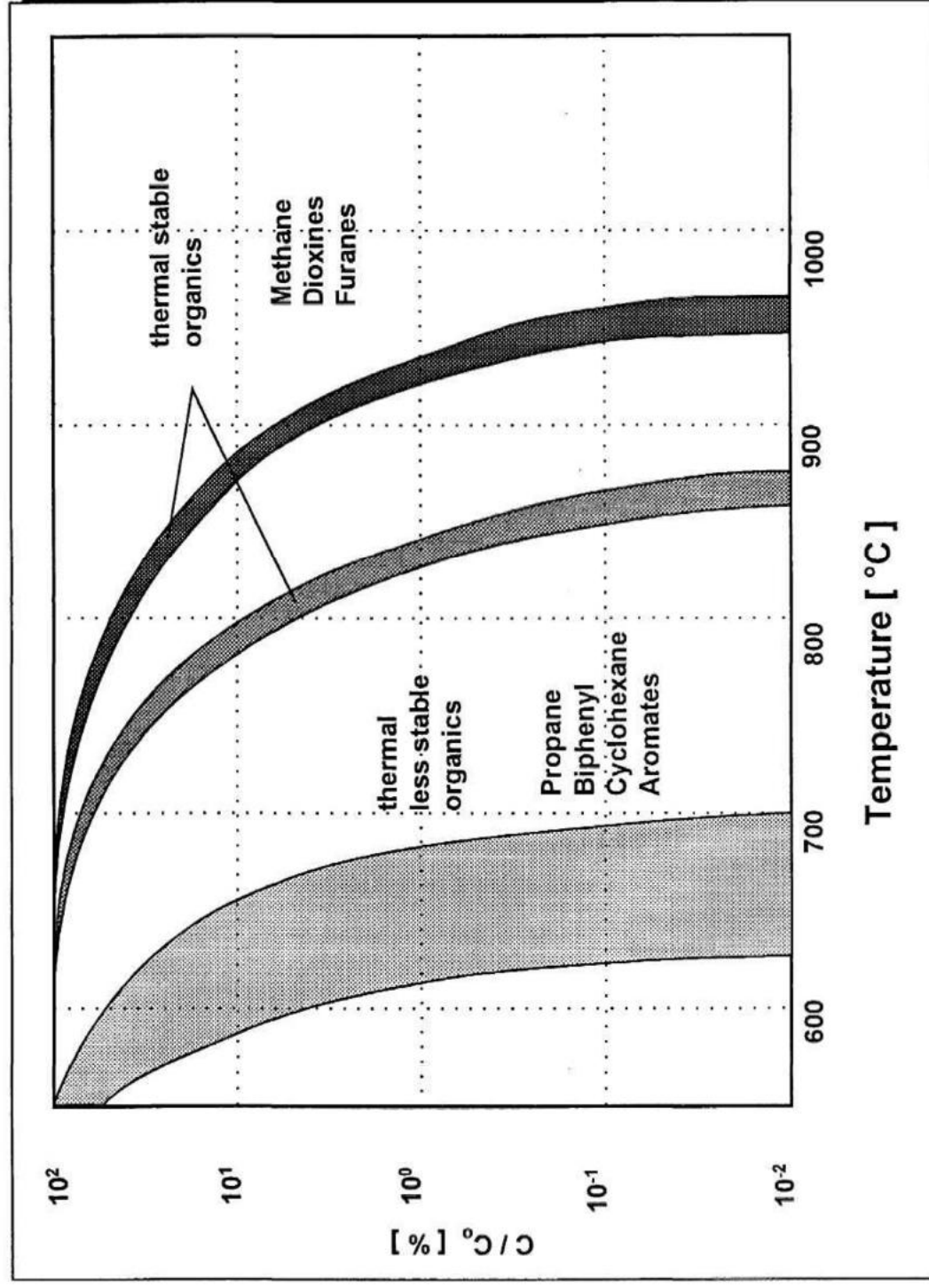


Figure 2.03

Shaft Emission Control

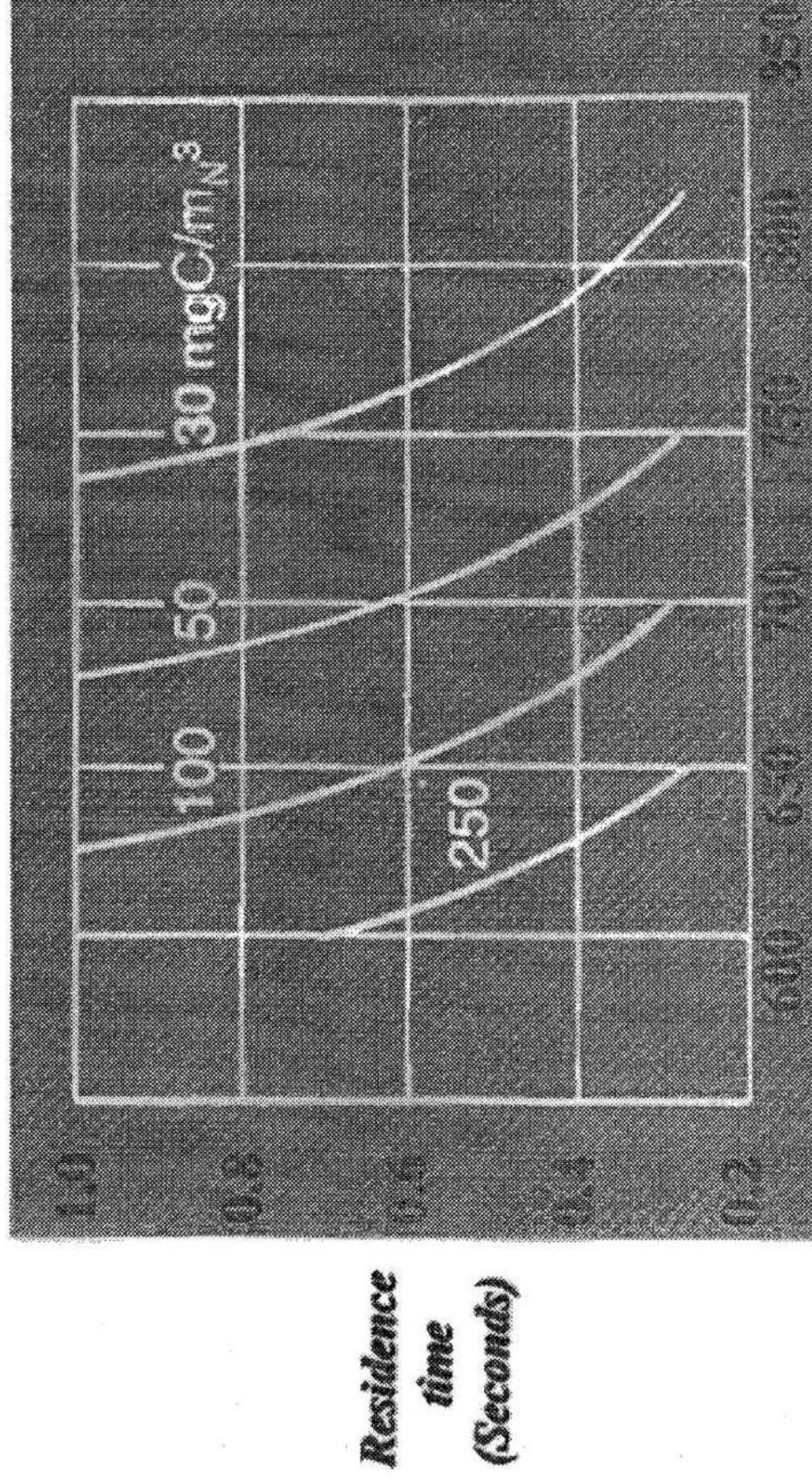


Figure 2.04

Shaft Emission Control

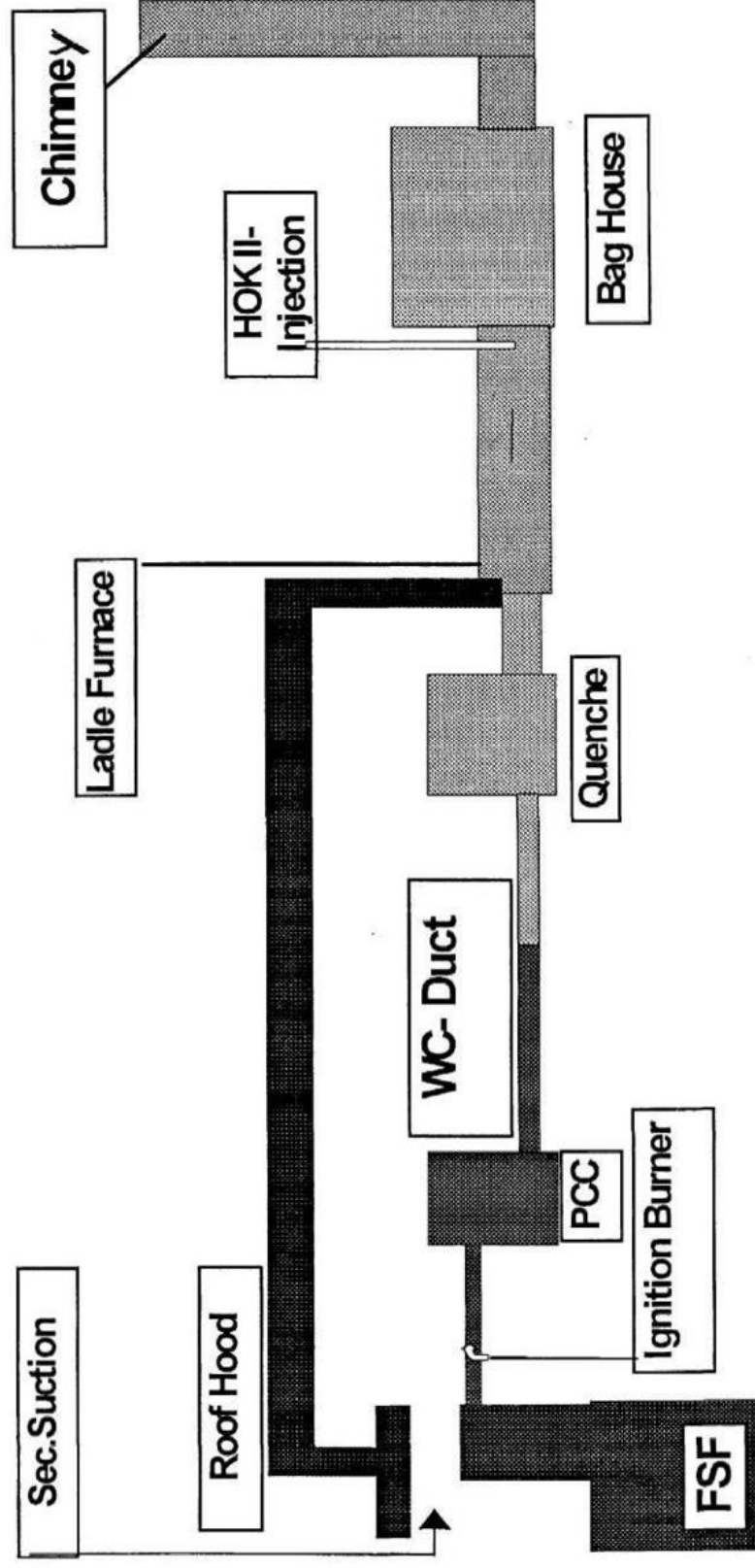


Figure 2.05

Shaft Emission Control

		measured	required
VOC'S	mg/Nm³	9	20
NOx	mg/Nm³	34	250
Dust	mg/Nm³	7,2	10
PCDD's	ng/Nm³	<0,1	0,5

Figure 2.06

Shaft Cost Comparison

	EAF	Cost di	EAF	Cost di	FSEAF-RBT		FSEAF-RBT	Unit cost	
	20% more Power	(€/t)	Same Power				Nervacero	(€/unit)	
Tap-wght(t):	70.0		70.0		70.0		130		
TRF- Rating	80.0		65.0		65.0		105		
Average MW:	60.0		46.0		50.0		77		
P.ON-T(min):	28.0		36.0		27.0		32.9		
P.OFF-T:	13.0	2 bask.	13.0		12.0	2 bask	12.7	3 baskets/heat	
Total 02:	40.1	0.72	30.0	0.00	30.0		30	0.07	€/Nm ³
Ch. C(kg/t):	15.0	0.86	4.0	0.07	3.0		0	0.07	€/kg
Blown C. :	5.0	-0.15	5.0	-0.15	6.0		9.6	0.15	€/kg
Fuel (l/t):	5.2	-0.31	4.0	-0.45	8.0		9.58	0.11	€/l
el.en. (kwh/t):	362.0	1.17	395.0	2.18	324.0		327.3	0.03	€/kwh
Electr.(kg/t):	1.6	0.56	1.8	1.12	1.4		1.12	2.81	€/kg
Dust (kg/t):	20.0	1.43	20.0	1.43	13.0		Not known	0.20	€/kg
Yield(%):	0.89	2.47	0.9	1.22	0.91		0.922	100.00	€/t
Fix cost red:	102.4t/h	1.95	85.7	8.16	107.7		171.1 t/h	40.00	Fix cost/t
Flicker level:	100.0		100.0		60.0		60		
Cost Difference EAF-FSEAF:		8.70		13.59	Without offgastreatment				
		7.1		12.0	With offgastreatment and coke blowing				
					using	9	Nm³/t Gas, w-cooled Shaft		

Figure 2.07

100 t EAF
DC-Shaft
Furnace

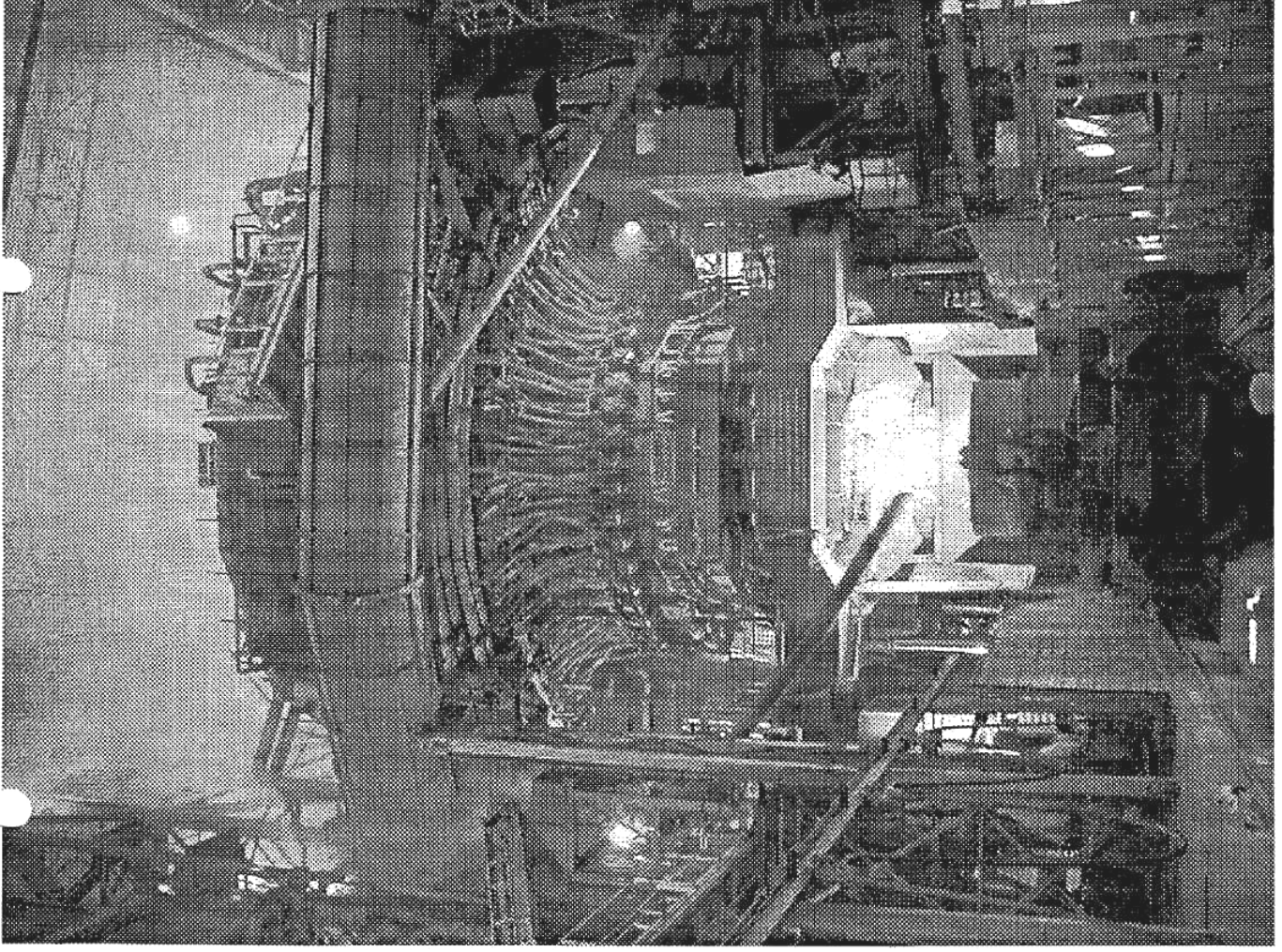
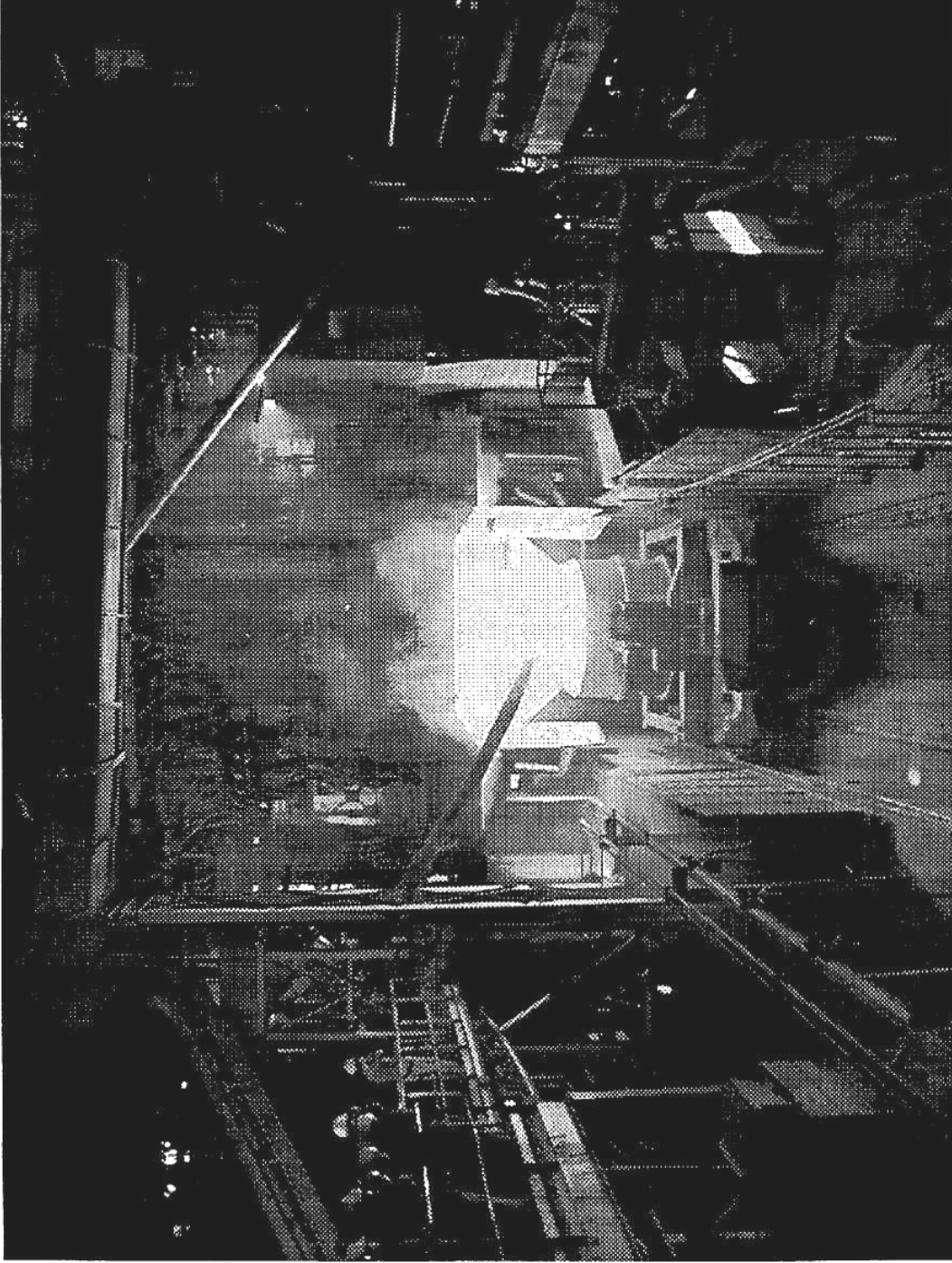


Figure 2.20



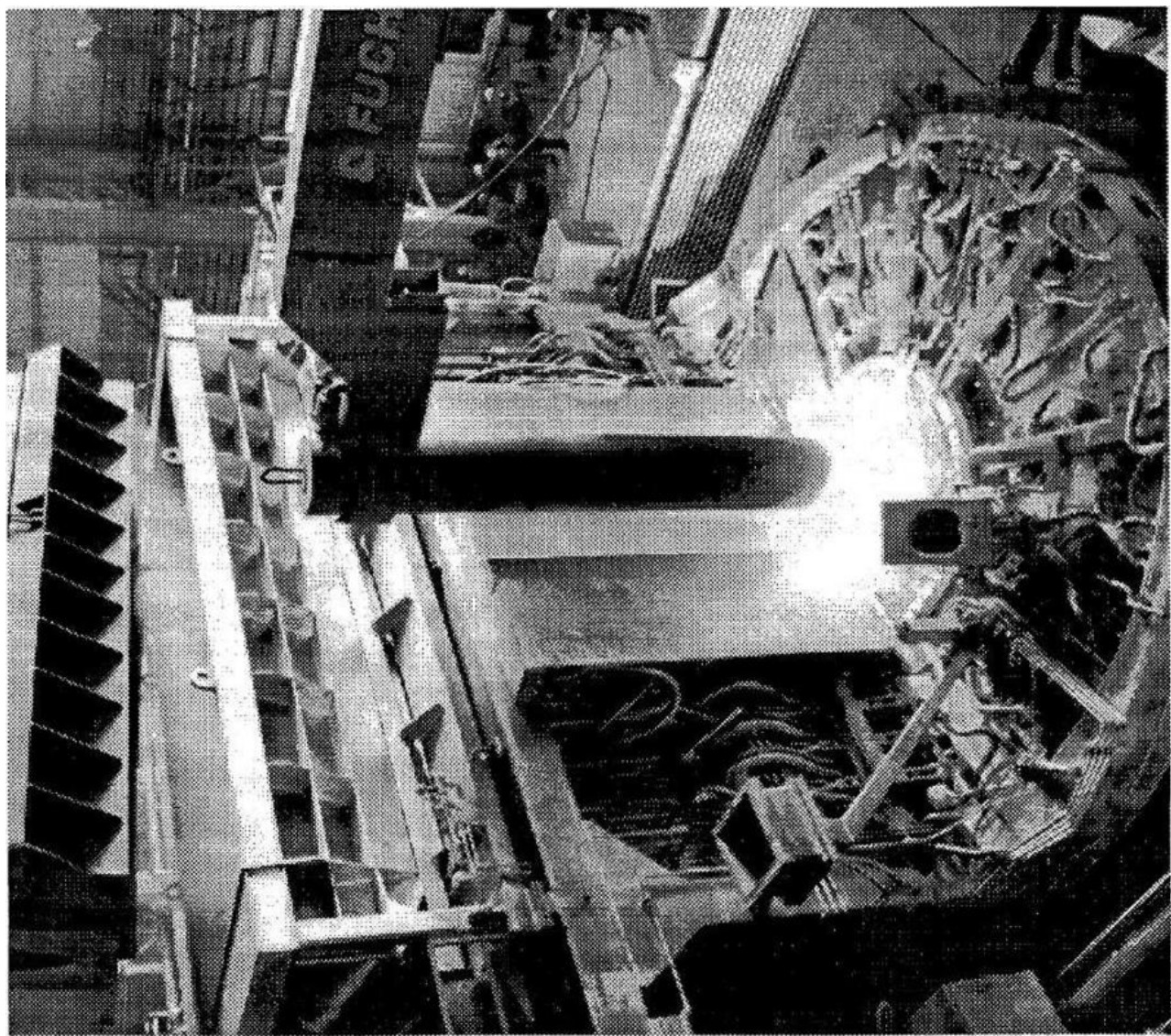
100 t DC-Shaft Furnace

Twin DC Electrode
Shaft EAF
135 MW



Figure 2.22

80 t DC
FSEAF



International Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Foaming Slag Control

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Foaming Slag Control

Klaus Kruger

For decades the operation of electric arc furnaces for steelmaking has been characterised by a variety of innovations. One of such innovations is the foaming slag practice which has been established since the end of the seventies (Figure 1).

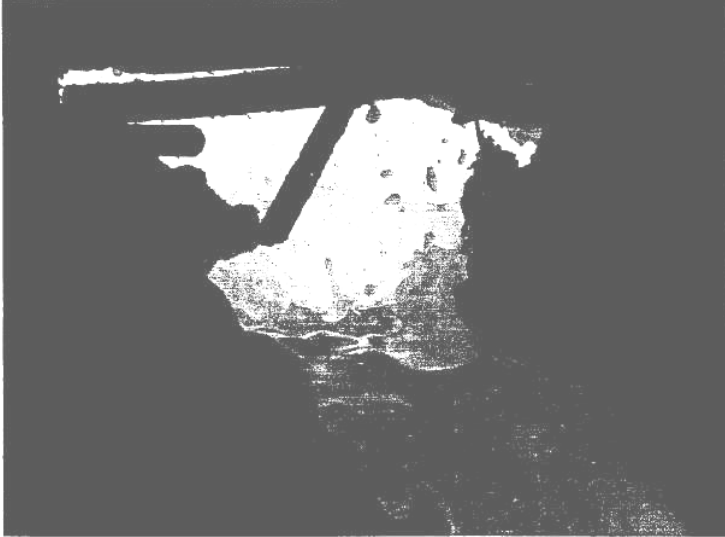


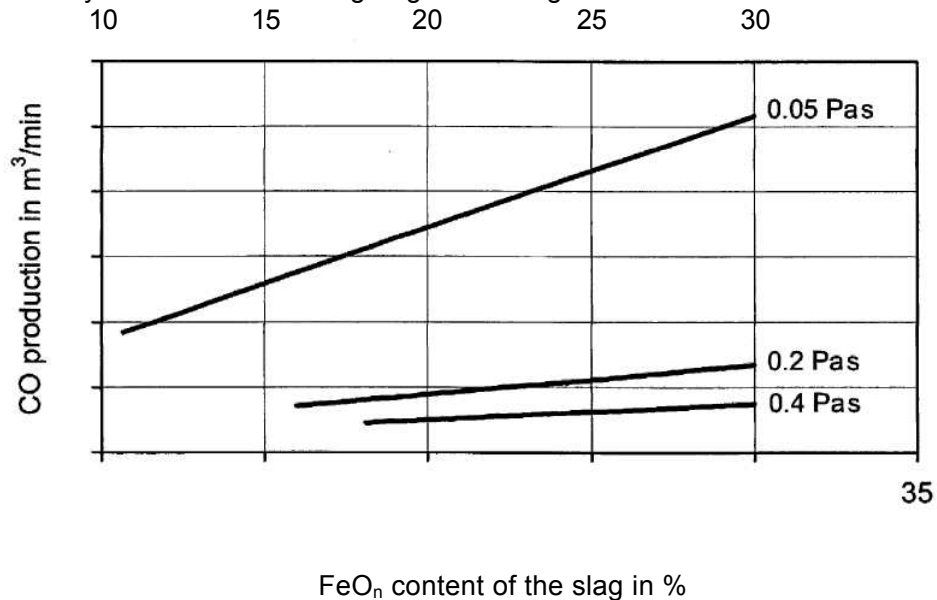
Figure 1. Foaming slag

1. The Slag Foaming Process

In the case of quality and carbon steels, the foaming slag is produced under suitable boundary conditions by carbon monoxide bubbles. These are formed as a result of the reduction of the iron oxide contained in the slag:



During foaming, the volume of the slag increases by the factor of 10 to 20, which means that 90 to 95 percent by volume of the foaming slag consist of gas.



35

Figure 2. Dependence of the foaming capability on slag viscosity [1]

In addition to the iron oxide content and the presence of carbon or fine coal, the foaming capability of the slag mainly depends on its composition (basicity), temperature and viscosity. These parameters are also interdependent. As an example, Figure 2 shows the especially significant viscosity dependency.

So far, the foaming slag practice has become established only for quality and carbon steels. In the field of stainless steels, recent approaches use suitable additions like calcium nitrate to obtain foaming slag, too.

2. Advantages of the Foaming Slag

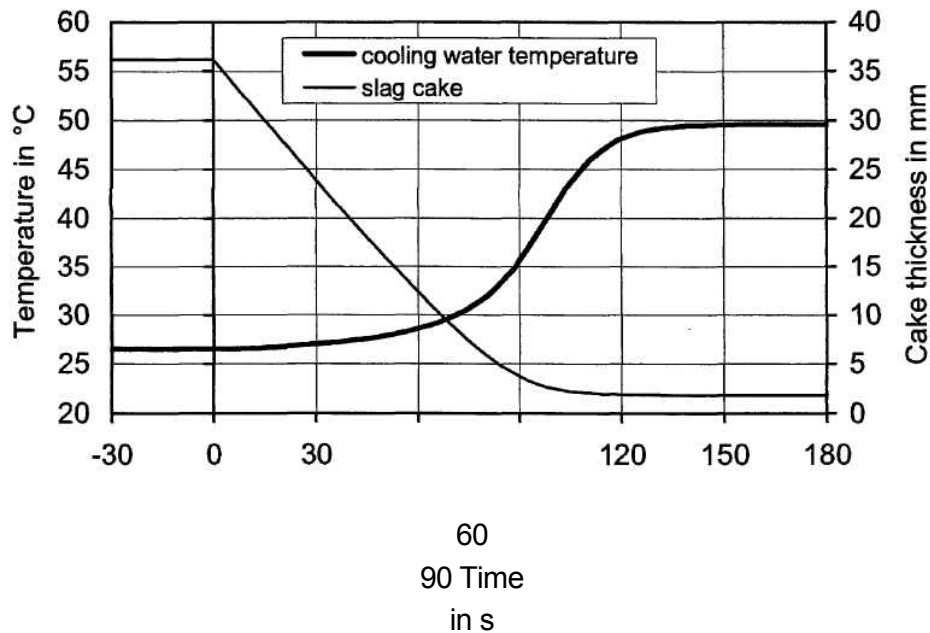


Figure 3. Reaction caused by free-burning arcs

A considerable portion of the electric arc energy is emitted by the arc column as radiation. If free-burning arcs are used, this radiation immediately strikes the furnace vessel. As can be recognised from Figure 3, the radiation results in the rapid melting of the slag cakes accompanied by considerable thermal losses. While the melting process may take as little as approximately 1.5 minutes, it will take approximately 30 minutes until the cakes have formed again [2].

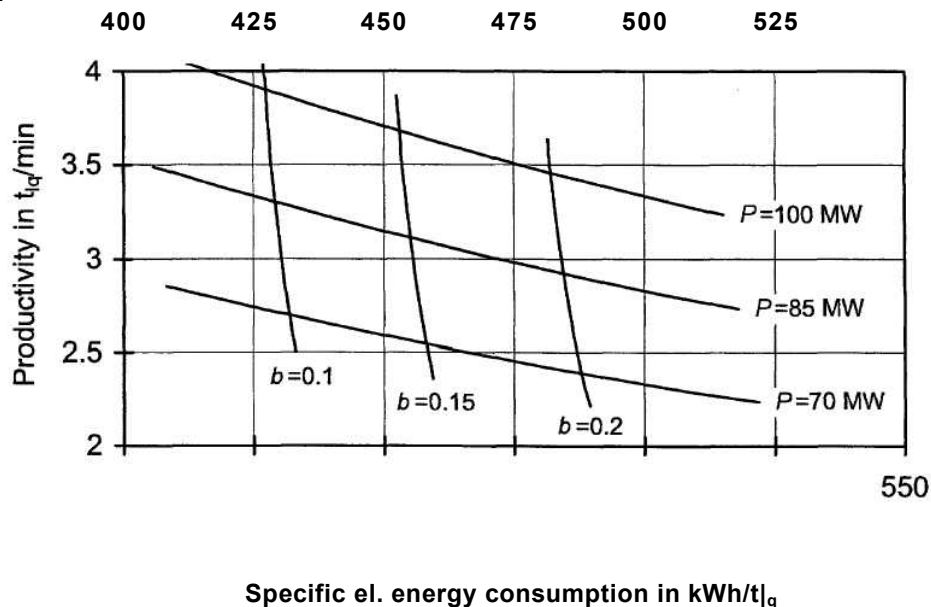


Figure 4. Relationship between energy consumption and productivity

Foaming slag is useful because it shields the electric arc. This makes it possible to melt with large arc lengths and high arc powers even in the flat bath period while still achieving a good energy transfer to the melt as well as an acceptable refractory wear. A higher electric arc power can result both in a reduced specific energy requirement and higher productivity (**Figure 4**). The decisive element in this process is the extent to which portion *b* of the direct losses increases with the power. Generally, the foaming slag is said to reduce the energy requirement by 10 to 30 kWh/t.

3. Conventional Foaming Slag Control

A certain amount of the carbon and oxygen required for the formation of the carbon monoxide bubbles is contained in the feedstock. Homogeneous and continued foaming, however, usually requires fine coal and oxygen to be fed.

Fine coal and oxygen are injected using lances and/or injectors. The dosage is controlled either by means of an operating diagram or manually by the furnace operator. In an operating diagram the substance amounts are coupled to the melting progress through the energy consumption; whereas manual operation requires the operator to determine the required amounts on the basis of the furnace behaviour. Neither of the methods fully meets the requirements of the process. The rigid operating diagram does not respond to the varying operating conditions, while manual operation is based on individual assessment and requires high attention. There is considerable optimisation potential in both cases.

This explains why efforts are being made to develop an automated foaming slag control which must be capable of ensuring that the arcs are safely covered while keeping the consumption of fine coal to a minimum.

4. Slag Signal

The control requires a signal which objectively describes the current foaming slag level or the covering of the electric arcs. For this purpose, there are several approaches, especially for AC electric arc furnaces. The following parameters are used:

- thermal quantities,
- the bath level, measured by means of microwaves or laser,
- the light emission of the arc,
- characteristic values determined from current and voltage,
- the sound emission of the arcs, and
- the vibrations of the furnace vessel.

Reference Signal

When the suitability of the above-mentioned signals is to be examined, the question of their correlation with the actual slag level arises. To answer this question, a reference signal to describe the slag level would be useful.

Occasionally, the specific energy requirement is used as a reference. In this case batch mean values have to be considered. Because the energy requirement depends on various parameters, it does not directly reflect the slag level. On the other hand, the energy requirement is one of the most important operating parameters and certainly a decision criterion when the long-term use of a slag signal is considered.

Another approach was taken in studies performed on the 1351/105 MVA AC electric arc furnace of the ISPAT Hamburger Stahlwerke [3]. Here, an online classification by an expert was used as a reference. The slag level is recorded using a sliding control scaled from 0 to 10. Subsequent off-line assessments on the basis of the related video recordings confirm the reliability of the

assessment. This reference signal generated with high effort allows to examine how the potential slag signal correlates with the actual slag level during the batch process.

Thermal Quantities

The temperatures and the waste heat power of the water-cooled part of the furnace vessel react distinctly to free-burning arcs. Depending on the condition of the slag cakes, however, the reaction is delayed by up to 30 seconds (Figure 3). These quantities are thus not suitable for being used as input quantities for slag level control. If necessary, they may be used for subsequent analysis. The fact that further parameters such as the refractory condition or the CO post-combustion may be of considerable influence has to be taken into account in this connection.

Slag Level

The determination of the slag level through a direct measurement would seem to be an adequate method. In addition, it could also be used at the same time to determine the liquid heel amount. A method especially worthy of consideration is the measurement of the travel time of laser light or microwaves. To achieve good results, the beam should strike the bath surface vertically.

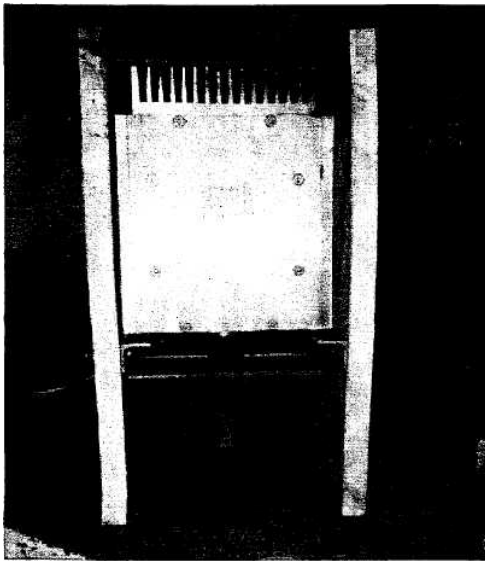


Figure 5. Microwave sensor [4]

Random tests with laser distance measurements performed through the furnace door from the top did not lead to useful results [3]. The movements of the bath and the reflection characteristics are considered to be the cause. Level measurement by means of microwaves was examined in more detail [4]. The related water-cooled sensor (**Figure 5**) is mounted on top of the furnace cover. The sensor has a measuring dot diameter of 70 to 100 mm and a resolution of 5 mm. The necessary direct view to the bath surface is ensured using compressed air.

The level cannot be inferred directly from the data measured by the sensor. Especially when the bath surface is troubled, the measuring data will be extremely noisy and need interpretation. In general, however, the level signal obtained seems to be useful.

Light Emission

The spectrum of the light emitted from the inside of the furnace is dominated by the IR portions, while the arc radiation is dominated by UV portions (**Figure 6**). It can thus be expected that free-burning arcs will be characterised by a high UV portion in the light emitted from the furnace.

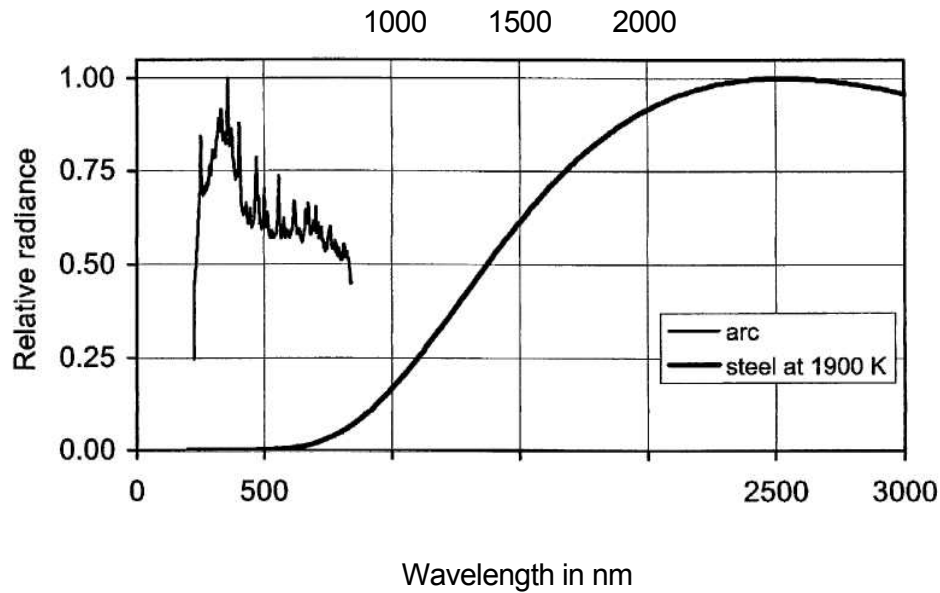


Figure 6. Spectrum of the emitted radiation

Figure 7 shows the radiation intensity recorded with a light measuring system in the 270 to 320 nm wavelength range. The light intensity shows a good correlation with the reference signal, i.e. the expert assessment of the slag level [3]. It also becomes obvious, however, that the light measuring system is very sensitive to changing visibility conditions and dirt. Its suitability for being used in a steel mill seems therefore limited. A more robust signal is obtained by determining the quotient of the UV and IR light intensities [5].

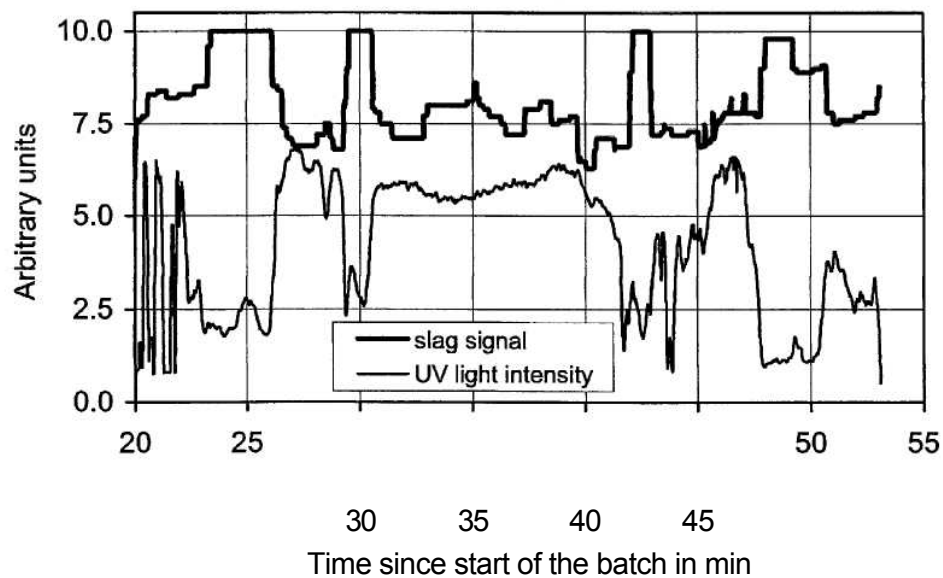


Figure 7. Foaming slag determination by means of UV light intensity

Electric Characteristics

Frequently, characteristic values determined from the time history of the electric quantities are proposed to describe the foaming slag level in AC arc furnaces. Among the values proposed are the distortion factor of the arc voltages [6], the reactive voltage of the arc [7] or the short-term fluctuations of the RMS current values [8]. The advantage of these characteristics is the availability of the underlying signals.

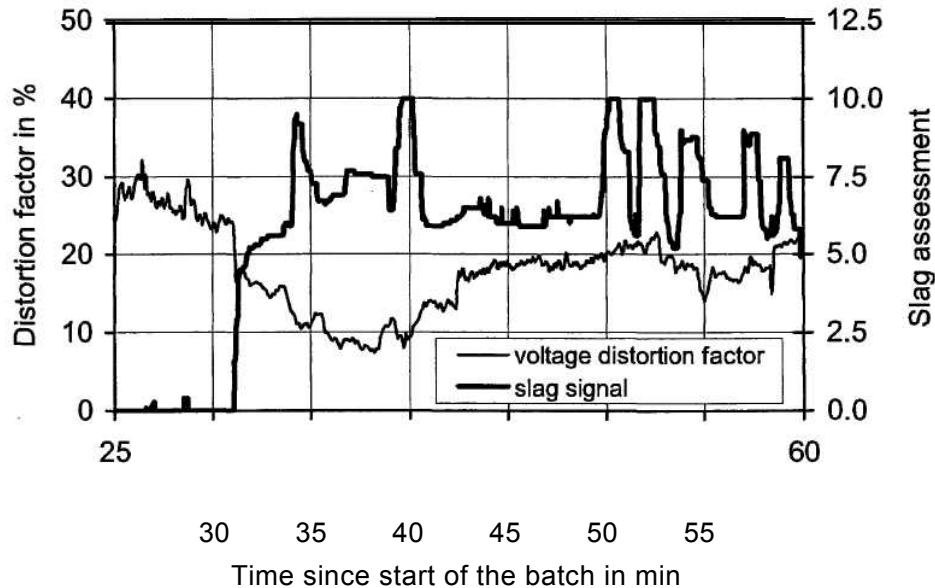


Figure 8. Foaming slag determination based on the distortion factor of the phase voltage [3]

Generally, the electrical characteristics stated above are correlating well with each other. Their suitability to describe the foaming slag level seems to depend significantly on the respective furnace and the production programme. The BFI (Betriebsforschungsinstitut), for example, reports that it has successfully used the RMS current value fluctuations

$$\text{filtered), } EFS = \frac{6(I^2)}{I^2} \quad \text{where } I \text{ is the phase current (20 ms RMS values, 10 Hz high-pass)}$$

in the 95 t/105 MVA AC electric arc furnace of ARES in Schiffange. Attempts performed by the BFI to use this signal for describing the slag level also in a DC electric arc furnace failed [8].

The foaming slag level produced in the 135 t/105 MVA AC electric arc furnace of the IHSW (ISPAAT Hamburger Stahlwerke) also cannot be satisfactorily assessed on the basis of the electrical characteristics [3]. As **Figure 8** shows, the voltage distortion factor reflects the melting progress, but does not correlate with the reference slag signal. The process applied by the IHSW is characterised by the continuous addition of sponge iron and the related long liquid bath phase.

Sound Emission

The sound emitted by the furnace or the electric arcs is another potential signal for describing the foaming slag level. The sound emission seems to be predestined for being used for this purpose, because experienced operators assess the slag on the basis of the sound.

In an **AC electric arc furnace**, the three arcs are fed by three 120° phase-shifted phase voltages. This means that during one 50 Hz period six arc cycles occur. Consequently a 300 Hz acoustic signal with the related multiples is to be expected. Asymmetric currents and sound transmission paths generate 100 Hz signals and multiples, while asymmetric anode and cathode half-waves result in 50 Hz components.

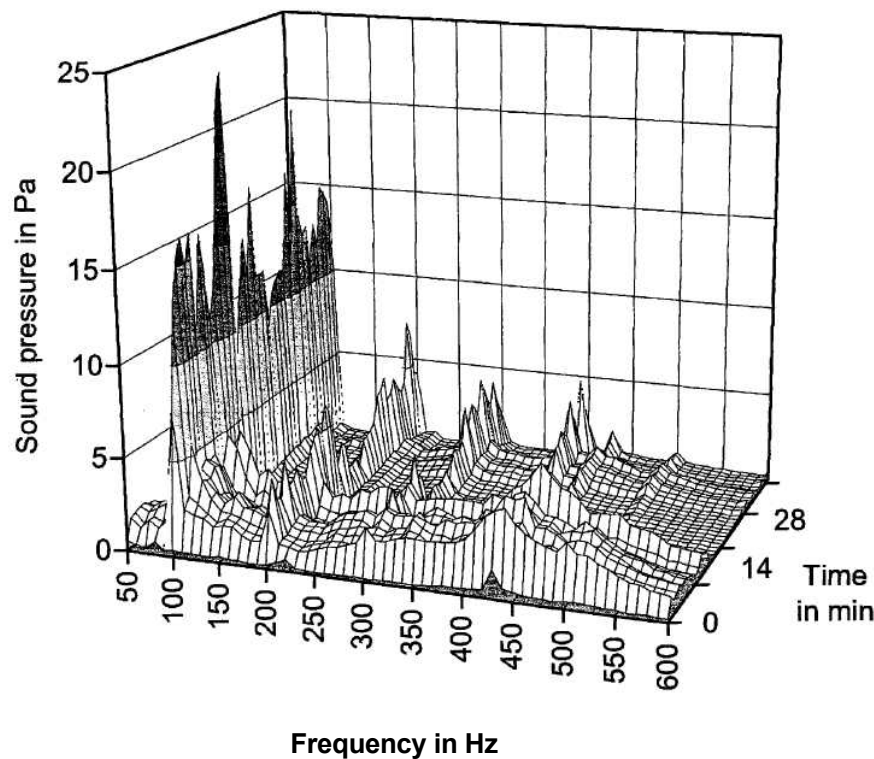


Figure 9. Sound spectrum in the course of a batch process [3]

The significant portions of the actual sound spectrum are in a range of up to 600 Hz. **Figure 9** shows the development of this portion of the spectrum in the course of the batch process. According to this, a rather continuous spectrum is produced during the scrap melting phase, whereas a line spectrum is forming during the flat bath phase. The line spectrum shown here is dominated by the 100 Hz line; in addition, the 200 Hz, 300 Hz and 400 Hz lines provide reproducible portions. The shape of the individual lines depends to a large extent on the arrangement of the electric arcs in relation to the microphone as well as on the sound propagation path.

Correlation studies show a clear correlation between the 200 Hz to 400 Hz lines and the slag reference signal. The 100 Hz line correlates, too, but the related correlation coefficient shows a significantly higher dispersion. The reason for this is the fact that the 100 Hz line of the examined furnace depends considerably on the sponge iron feeding rate. This phenomenon is observed independent of the slag level and certainly represents a peculiarity of the furnace examined [3].

Therefore, the signals of the 200 to 400 Hz lines can be used to describe the slag level as follows:

where p is the sound pressure and $1/\beta$ the regression coefficient. The verification of this signal using follow-on batches confirms the good correlation with the slag reference signal (**Figure 10**). Thus, a reliable signal for the description of the foaming slag level in the AC electric arc furnace examined is obtained.

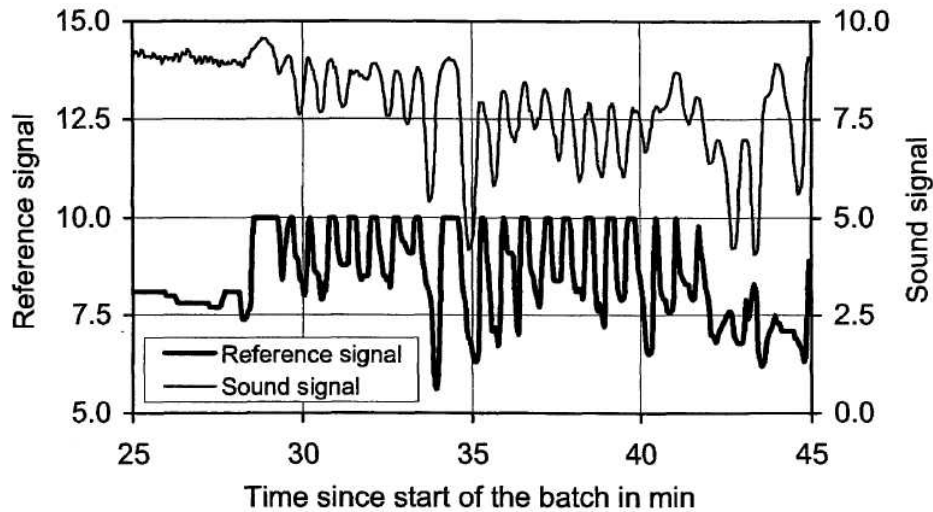


Figure 10. Comparison of the reference signal and the signal generated from the sound spectrum

The sound emission of **DC electric arc furnaces** is the result of the stochastic and deterministic (rectifier, current regulation) fluctuations of the current and the voltage. Similar to the AC electric arc furnace, the significant portions of the sound spectrum are found in the range of up to 800 Hz.

The suitability of the sound signal to describe the slag level of a DC electric arc furnace was demonstrated using the 100 t furnace of Boel in Hoogovens and the 140 t/110 MV shaft furnace of Cockerill Sabre in Marcinelle [9]. These demonstrations were based on a relevant section (100 to 150 Hz and 145 to 195 Hz, respectively) of the sound spectrum.

Vibrations of the Furnace Vessel

Finally, the vibrations of the furnace vessel to be detected by means of an acceleration pickup can be used as potential signals to describe the slag level. The vibrations behave quite like the sound, however, their dynamics seems to be lower [9, 10].

5. Integration into a closed-loop Control System

The slag signal can be used for two different purposes. One of them is the power regulation of the furnace. It would be possible to react directly to insufficiently covered electric arcs by reducing arc voltage and length. Refractory wear and excessive thermal losses would thus be prevented. The time delays resulting from a thermally based power regulation would then be avoided.

Furthermore, the slag signal can be used to regulate the feeding of fine coal aimed at forming a homogeneous foaming slag at minimum fine coal consumption. There are first approaches to achieve this aim [3, 11]; the prototype of the ISPAT Hamburger Stahlwerke is presented here as an example.

First, the controllability of the foaming slag by means of fine coal has to be examined. As to be expected, controllability is generally possible. The foaming reaction occurs with a time delay of approximately 10 to 15 seconds (**Figure 11**). Under unfavourable boundary conditions, however, such as high slag temperature controllability is limited. Further, the position of the carbon and oxygen addition is of significant importance [12].

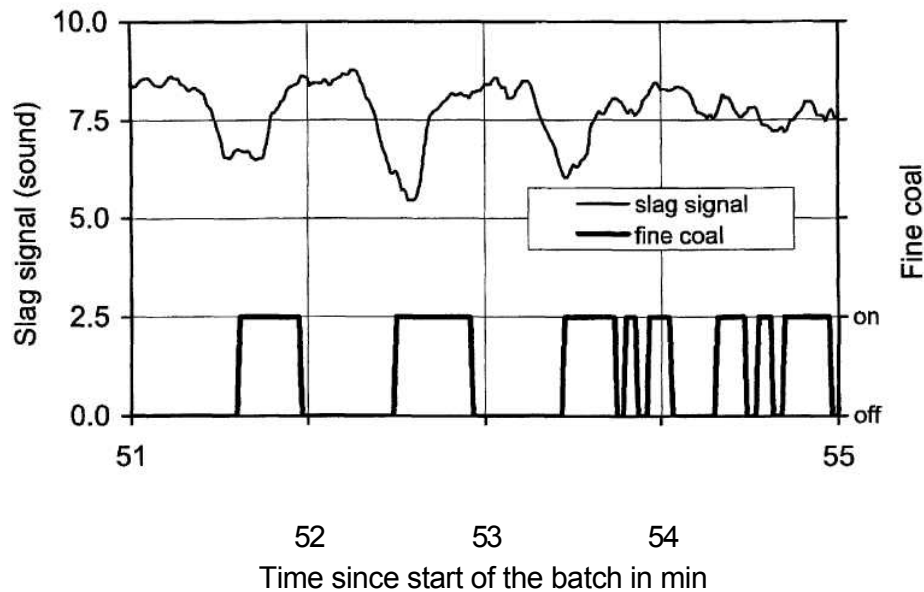


Figure 11. Controllability of the foaming slag

The regulation used by the IHSW is based on a PC; signal detection and processing is performed by means of a DSP card. The fine coal added by a carbon lance in pulses serves as the control variable. Approximately 11 kg of coal are fed per pulse. This quantity is adjusted by a metering slide at constant pulse duration. The feeding rate is a function of the pulse frequency.

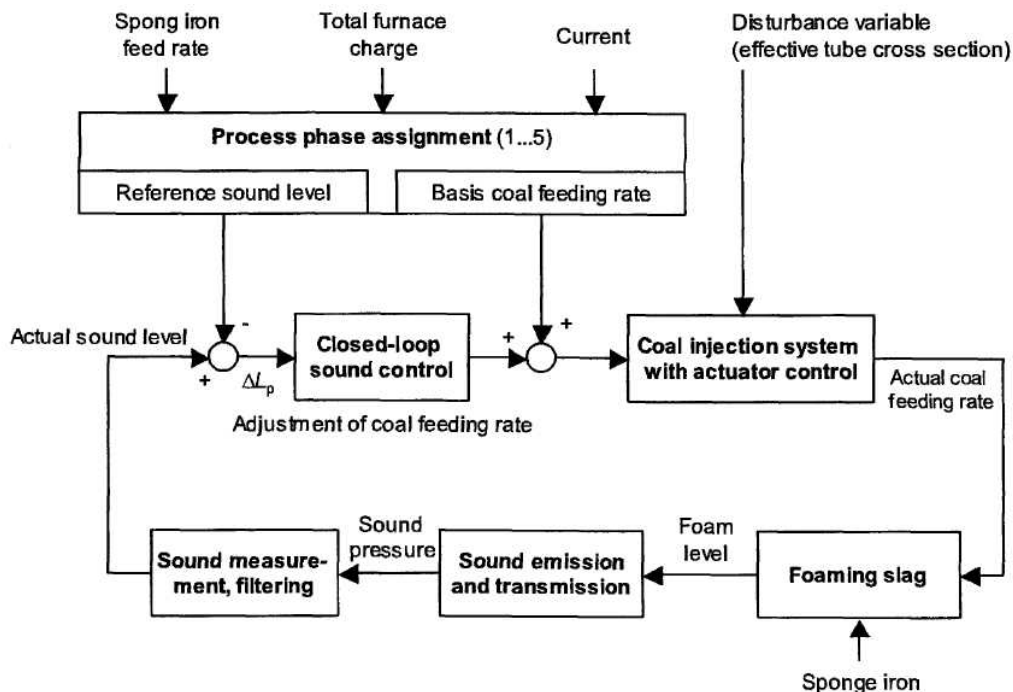


Figure 12. Block diagram of the regulated fine coal addition [3]

The fine coal is always added in the flat bath period. For regulation purposes, this period is subdivided into five characteristic process sections (start of flat bath, flat bath I, sampling, flat bath II, heating up). The current process section is recognised automatically on the basis of the operating parameters.

Based on conventional operation, the mean sound level and the mean fine coal feeding rate were determined for each process section. This results in the sound reference and nominal feeding rate values for the regulation (**Figure 12**). When the actual sound level deviates from the reference value, the nominal feeding rate is adjusted according to **Figure 13**.

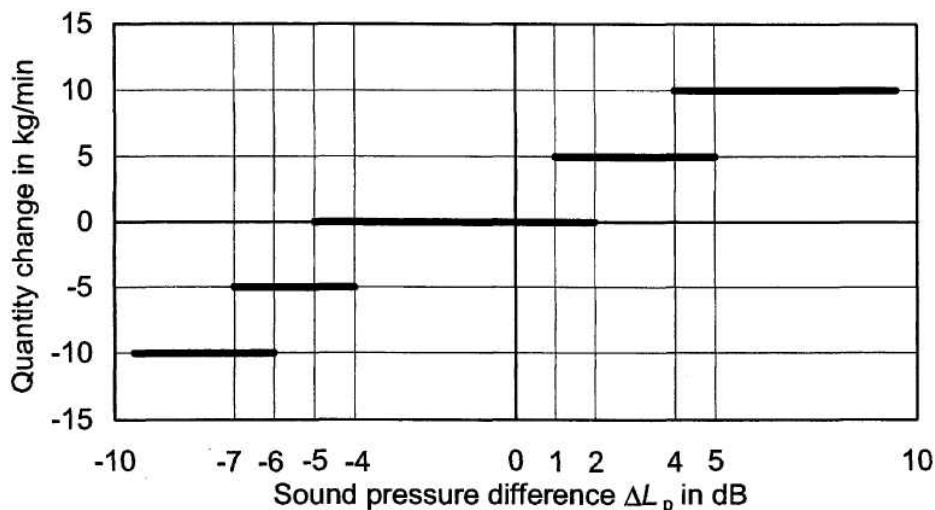


Figure 13. Adjustment of the coal feeding rate to the foaming slag level [3]

To test the described regulator, 385 one-basket batches were operated within a period of two months, alternating between manual and regulated operation. According to this test, the advantages of the described regulation is the increase in productivity (+1.4 %) and the reduction of the coal requirement (-6.1 %). The specific energy requirement did not change for the batches examined; the increased productivity is accompanied by an increased active power. There certainly is some improvement potential for the regulating system presented here, for example with respect to the necessary manual positioning of the lances and the discontinuous feeding of the coal. Solutions are available for both tasks. In general, there are no obstacles to a high-quality regulation of the foaming slag level in DC and AC electric arc furnaces.

International Symposium

Electrical Engineering of Arc Furnaces

October, 23 - 26, 2006, in Braunschweig, Germany

Graphite Electrodes for EAFs

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Graphite electrodes for electric arc furnaces

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- Joining
 - Types of joints. Recommended torque, Manual / hydraulic / robot joining
- R&D
 - Optimum electrode diameter, Crack propagation, Recent papers
- Your contacts @ SQL Carbon



C. Friedrich, Graphite electrodes for EAFs - Braunschweig, 2006 - 10 -26

Graphite electrodes for electric arc furnaces

Intro

SQL Carbon Group

- | | |
|----------------------------|--|
| • Business Unit | Carbon and Graphite, Specialties, SQL Technologies |
| • Group sales | 1069 M€ |
| • Group EBIT | 113 M€ |
| • Employees | 5263 @ approx. 20 plants worldwide |
| • Graphite electrode sales | 222000t |

Source: Annual report 2005

Lecturer

- Technical chemist (Universities Heidelberg & Montpellier)
- PhD # Federal Research Center Karlsruhe: Wastewater treatment, high pressure engineering
- SQL since 11/1999
 - RiP = Knowledge management 12/2000
 - RfTD-Assistant to VP 8/2002
 - Production = Green shop mgr 2/2004
 - Technical Service EU/NME/Africa 6/1005
 - R&D * New Business Development 10/2005



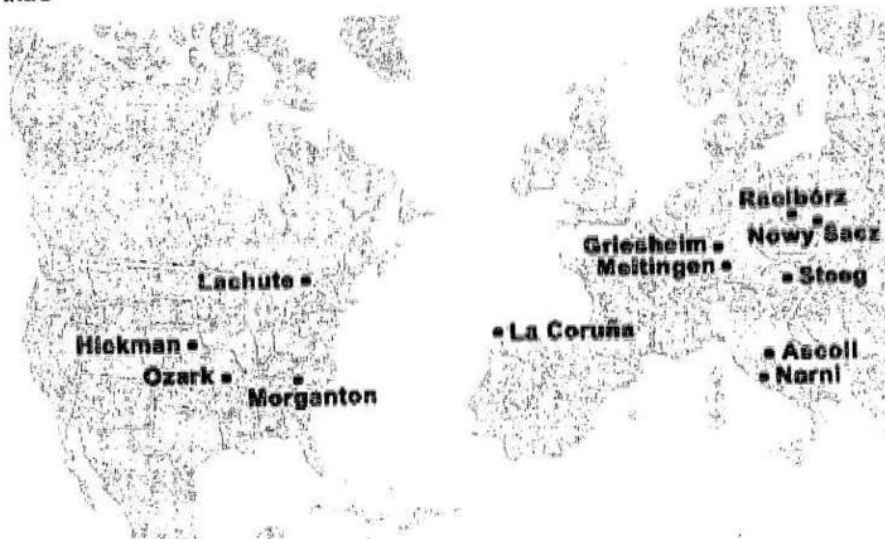
C. Friedrich Graphite ELECTRODES FOR EAFs - Braunschweig, 2006-10-26

Graphite electrodes for electric arc furnaces



CG production sites

Intro



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Graphite electrodes for electric arc furnaces

Production of graphite electrodes

Raw materials

- Coke
- Pitch



Processing

- Crushing
- Grinding
- Mixing



Forming

- Extrusion or
- Moulding



Baking

- Baking
- Impregnation



Graphitizing

- Formation of ordered graphite lattice



Machining

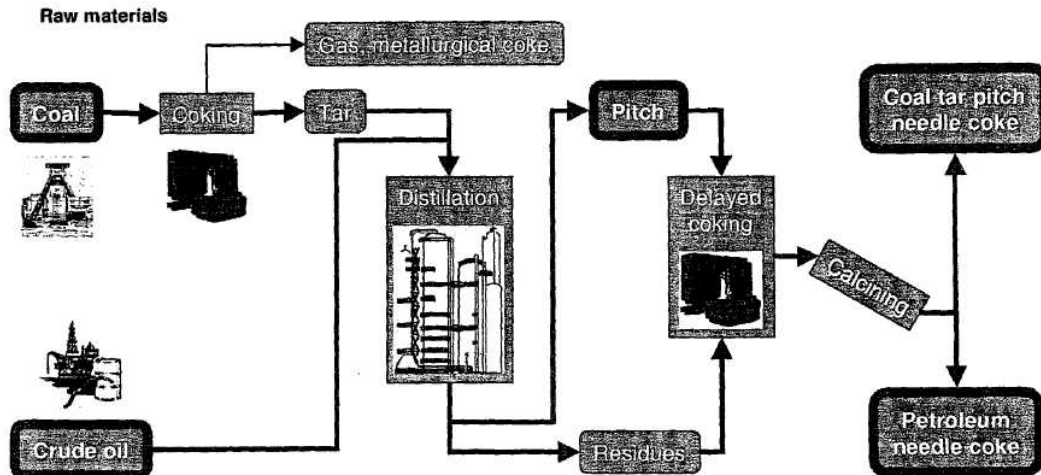
- Mechanical processing of materials



Graphite electrodes for electric arc furnaces



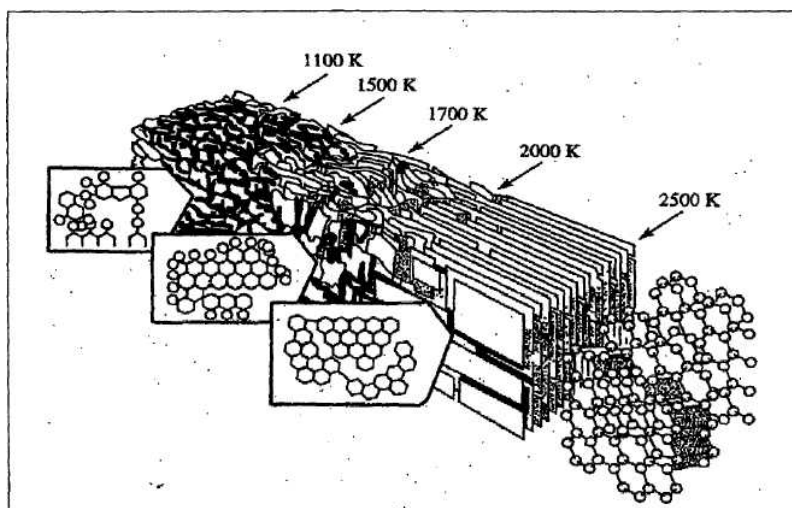
Production of graphite electrodes



Graphite electrodes for electric arc furnaces

Production of graphite electrodes

Formation of graphite lattice



Graphite electrodes for electric arc furnaces

Properties of graphite electrodes

Typical properties

		AC		DC	
Diameter	mm	300-450	500-600	600-750	800
	inch	12-18	20-24	24-30	32
Apparent density	g/cm ³	1.66-1.73	1.66-1.73	1.66-1.73	1.69-1.75
Porosity	%	17-20	17-20	17-20	14-19
Specific electrical resistance	Q·m	4.8-5.8	4.8-5.6	4.6-5.2	4.0-4.8
Flexural strength	N/mm ²	10-16	9-14	9-12	10-14
Thermal conductivity	W/(K·m)	160-200	180-230	200-250	240-300
Coeff. of thermal expansion (20-200 °C)	μm/(K·m)	0.4-1.0	0.4-0.9	0.3-0.8	0.3-0.6

All values measured at room temperature

C. Friedrich - Optima electrodes for EAFs • Braunschweig, 2006-10-26

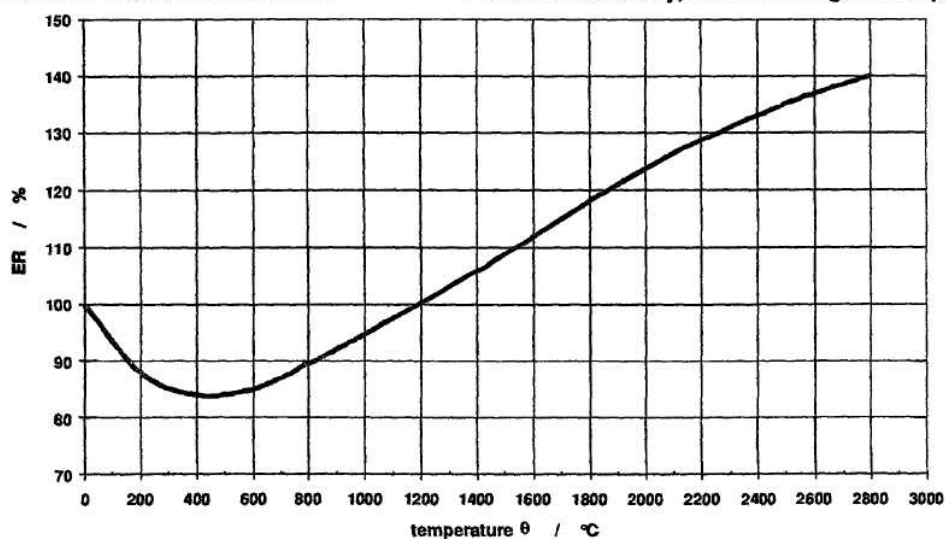


SGL CARBON GROUP

Graphite electrodes for electric arc furnaces

Properties of graphite electrodes

Electrical resistivity, relative change vs temperature



C. Friedrich - Graphite electrodes for EAFs • Braunschweig, 2006-10-26

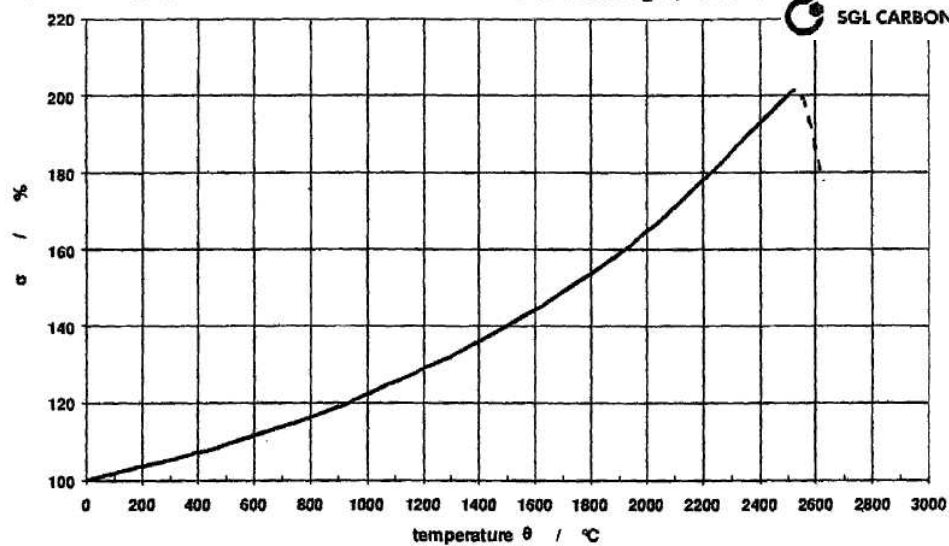


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Graphite electrodes for electric arc furnaces

Properties of graphite electrodes

Flexural strength, relative change vs temperature



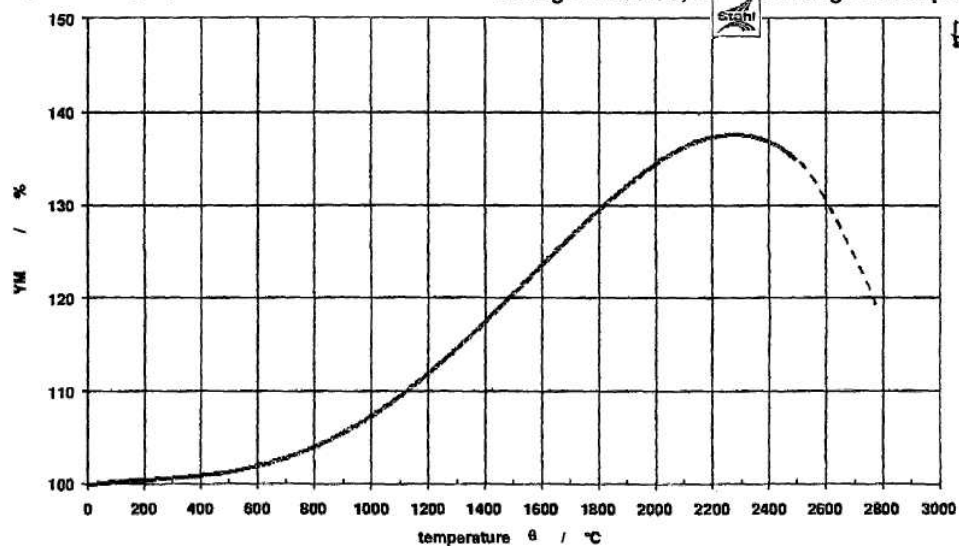
C.fttafcfb - OnpNtt «tK«odw lor EAFc- BrauMchmio, 2008-10-28



Graphite electrodes for electric arc furnaces

Properties of graphite electrodes

Young's modulus, relative change vs temperature



C. Frtdrich - GrapMtt ttacIKxhs tor EAFt - Braunichw.III, 5006-10-16



Graphite electrodes for electric arc furnaces

Properties of graphite electrodes

Dimensions

Diameter mm	Inch	Length mm	inch
300	12	1500,1800	60,72
350	14	1500,1800	60,72
400	16	1500,1800,2100	60,72,84
450	18	1500,1800,2100,2400	60,72,84,96
500	20	1800,2100,2400,2700	72,84,96,110
550	22	1800,2100,2400,2700	72,84,96,110
600	24	2100,2400,2700	84,96,110
650	26	2400,2700	96,110
700	28	2400,2700	96,110
750	30	2400,2700	96,110
800	32	2700	110

 SGL CARBON GROUP

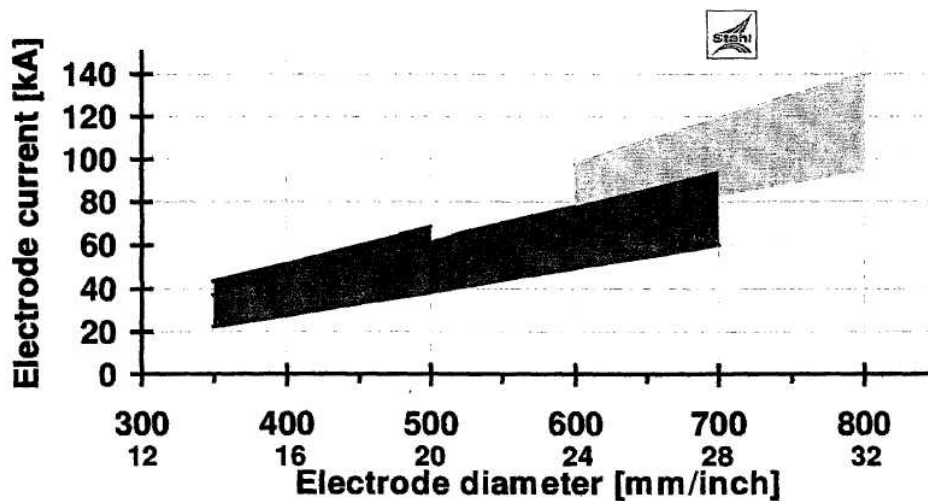


C. Madrid • Graphite electrodes for EAF • Braunschweig, 8006-10-26

Graphite electrodes for electric arc furnaces

Properties of graphite electrodes

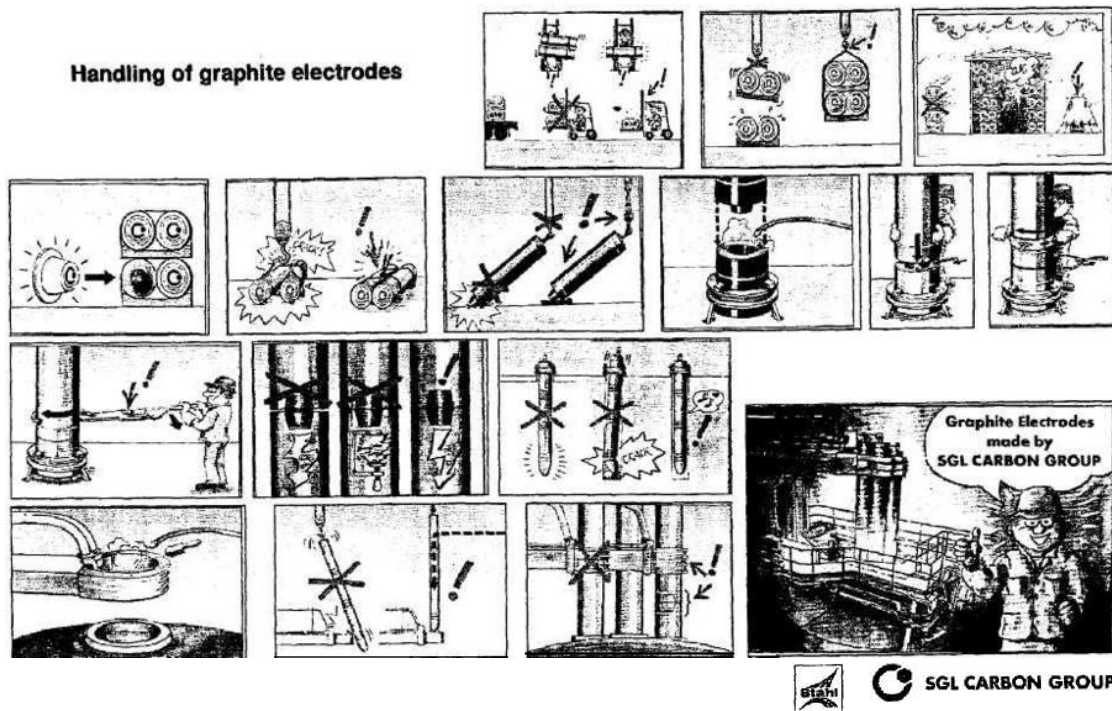
Current carrying capacity



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Graphite electrodes for electric arc furnaces



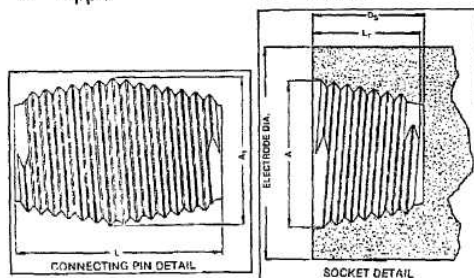
Graphite electrodes for electric arc furnaces

Joining of graphite electrodes

Taper joint

- Nipple

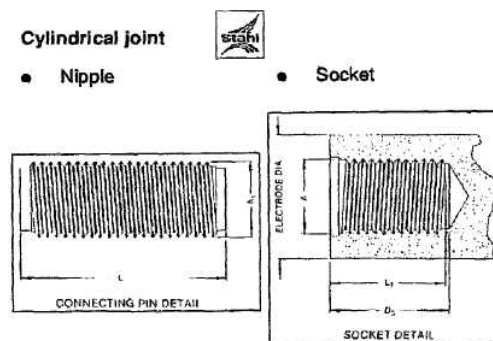
- Socket



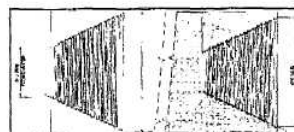
Cylindrical joint

- Nipple

- Socket



Male / female joint



Source: NEMA CG 1-2001, IEC 60259, JIS F7201

Graphite electrodes for electric arc furnaces

Joining of graphite electrodes

Diameter mm	inch	Torque Nm	ft lbs
300	12	650	480
350	14	850	630
400	16	1100	810
450	18	1500	1100
500	20	2500	1850
550	22	3500	2570
600	24	4000	2940
700	28	6000	4410
750	30	7500	5510
800	32	9000	6640

Recommended joining torque

C. ftadridi - GapHto •tecirodw to? EAFs • BmuladWMig, 3006-10-26



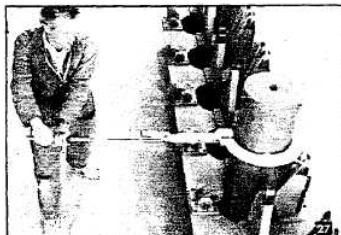
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Graphite electrodes for electric arc furnaces

Joining of graphite electrodes

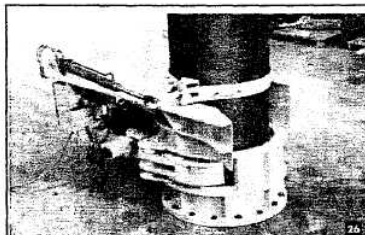
Manually

- Only for electrodes up to 450 mm (18")



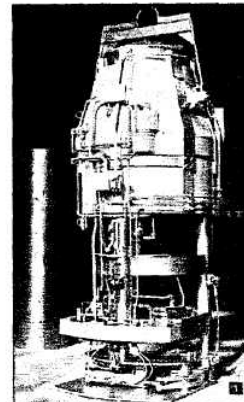
Hydraulic

- Suitable for all electrode-Ø



Robot

- On furnace
- Fully automatic



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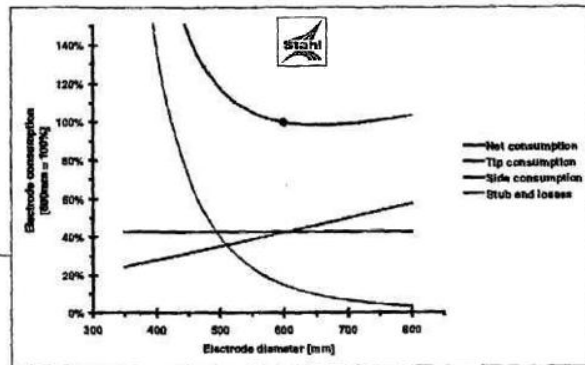
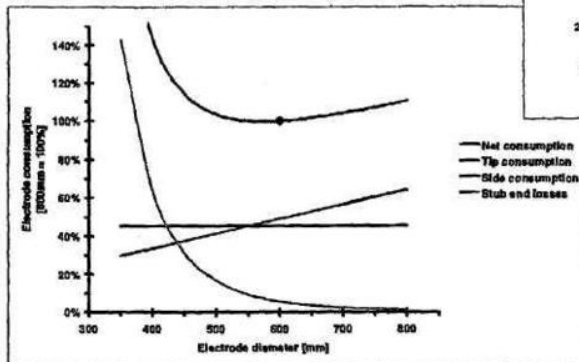


Graphite electrodes for electric arc furnaces

R&D

Optimum electrode diameter

- Individual furnace parameters influence consumption mechanisms



Source: MPT International 5/2005



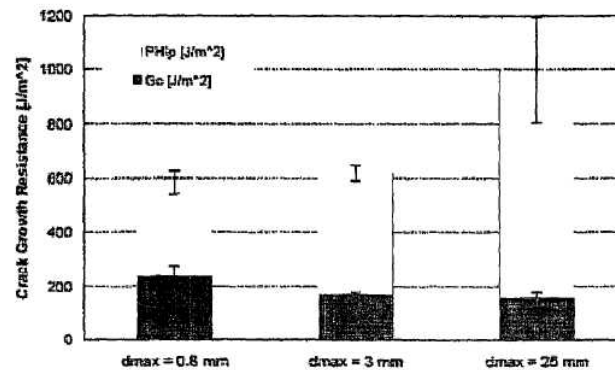
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Graphite electrodes for electric arc furnaces

R&D

Crack propagation

- Crack growth resistance R = Fracture toughness G_0 + 'Plastic' deformation energy Φ_p



Source: Carbon Conference 2006



Graphite electrodes for electric arc furnaces

R&D

Recent papers

- T. Seeger, T. Will, S. Baumann, K. Wimmer
Crack growth investigation of industrial graphite
Carbon 2006 - The International Carbon Conference, Aberdeen, UK, July 16-21, 2006, paper SA-862
- C. Friedrich, H. Fuchs
Auswahl des optimalen Elektrodendurchmessers fuer Drehstrom-Elektrolichtbogenofen stahl und eisen 126 (2006) 37-40
- C. Friedrich, H. Fuchs
Selecting the optimum electrode diameter for AC EAF's MPT
International 5/2005 38-41 (cover story) 15th IAS Steelmaking
Conference, Buenos Aires, Nov 8, 2005 Proc. 8th EEC,
Birmingham, UK May 10, 2005, 145-151
- C. Friedrich
Graphite electrodes climb the diameter ladder
Steel Times International 29 (2005) 25
- C. Friedrich
Graphite electrodes for electric arc furnaces
in: Handbook of Thermoprocessing Technologies, Eds. A. v. Starck, A. Muehlbauer, C. Kramer
Vulkan-Verlag, Essen, 2005, ISBN 3-8027-2933-1, Part II C 5.2, 713-715
- C. Friedrich
Supersized electrodes in the centerpoint of meltshop productivity
Furnaces International 2 (2004) 20

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Graphite electrodes for electric arc furnaces

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