

Technical Aspects of Chargers and Current Transformers and Methods for Supervision

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13.1 APPLICATION OF BATTERY CHARGERS

Battery chargers are employed for charging starter, traction, and stationary batteries as well as for supplying stand-by power. The demands for these devices are dependent on the operation conditions.

Charging starter and traction batteries is mainly conducted during recesses. Hereby the consumers are disconnected for charging batteries ([Figure 13.1](#)).

Charging for stationary batteries allows an ensured stand-by power supply for parallel and switch operation for DC consumers.

For switch operation ([Figure 13.2](#)) consumers are supplied by power through a rectifier or directly by three-phase supply. In the case of mains power failure, the most important consumers are supplied with energy by the battery until the mains power returns. A charger then charges the battery. If the charging process is terminated, a float-charge operation is activated so full capacity is available at any time.

For parallel operation the consumer and the battery are permanently operated in parallel and supplied by their common charger ([Figure 13.3](#)). In case of mains failure, the battery without interruption automatically supplies the consumer.

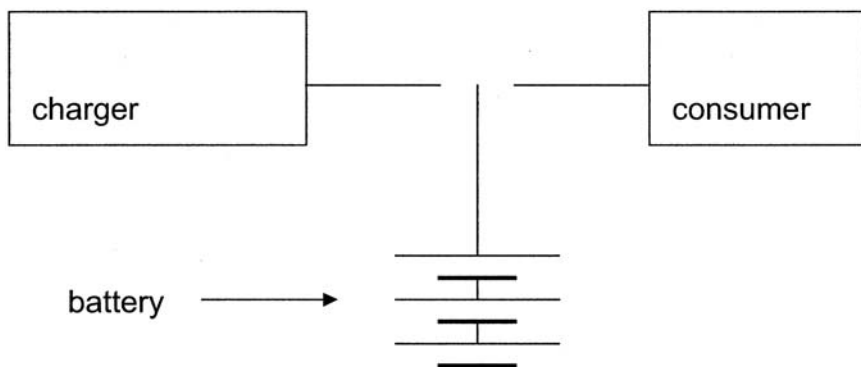


Figure 13.1 Charging operation for starter and traction batteries.

13.2 CHARACTERISTIC VOLTAGES OF LEAD-ACID AND NiCd BATTERIES

The characteristic voltage values for lead-acid and NiCd batteries are listed in [Table 13.1](#).

13.3 CONSTRUCTION AND FUNCTION OF BATTERY CHARGERS

Battery chargers can generally be divided into two main groups: controlled and uncontrolled devices.

13.3.1 Controlled Battery Chargers

13.3.1.1 Thyristor Controlled Chargers

These consist of the following:

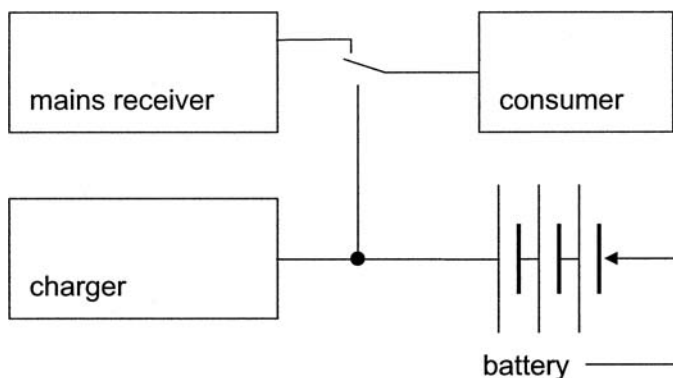


Figure 13.2 Switch operation for charging stationary batteries.

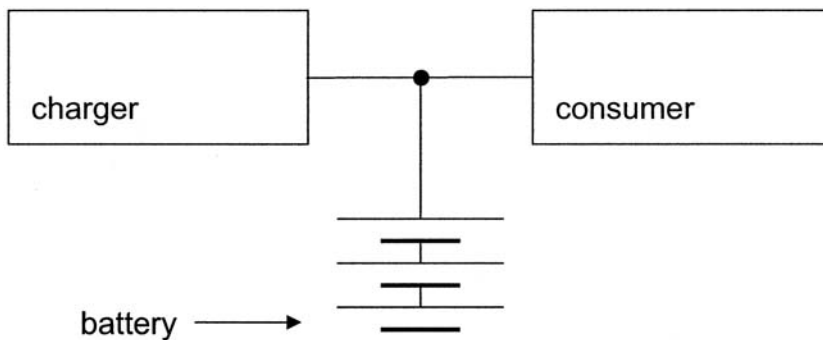


Figure 13.3 Parallel operation for charging stationary batteries.

- Transformer.
- Controllable rectifier.
- Control electronics.
- Smoothing filters.

They are applied for a wide current range and are, depending on the demanded power, one-phase or three-phase devices (Figure 13.4).

Transformer

The transformer (T1) adjusts the mains voltage to the desired DC voltage and simultaneously represents the galvanic separation between three-phase mains and DC output of the charger.

Rectifier

Line-commutating converters are employed as rectifiers. Three-phase types are preferably executed as fully controlled bridge circuit (V1-6), whereas for single-phase types the semicontrolled bridge circuit (V1-4) is employed.

Through application of controllable valves the rectifier acts as an actuator for the charging device's output voltage, which can be varied in a wide range. The valves employed are silicon semiconductors, such as power packs and thyristor modules (respectively thyristor diode modules).

Table 13.1 Characteristic voltage values for lead-acid and NiCd batteries.

	Pb battery	NiCd battery	Units
Nominal voltage	2.0	1.2	V/cell
Float-charge voltage	2.2–2.25	1.38–1.40	V/cell
Gassing voltage	2.4	1.6–1.7	V/cell
End-of-charge voltage	2.6–2.7	1.65–1.85	V/cell
Cutoff voltage	1.7–1.9	0.85–1.1	V/cell

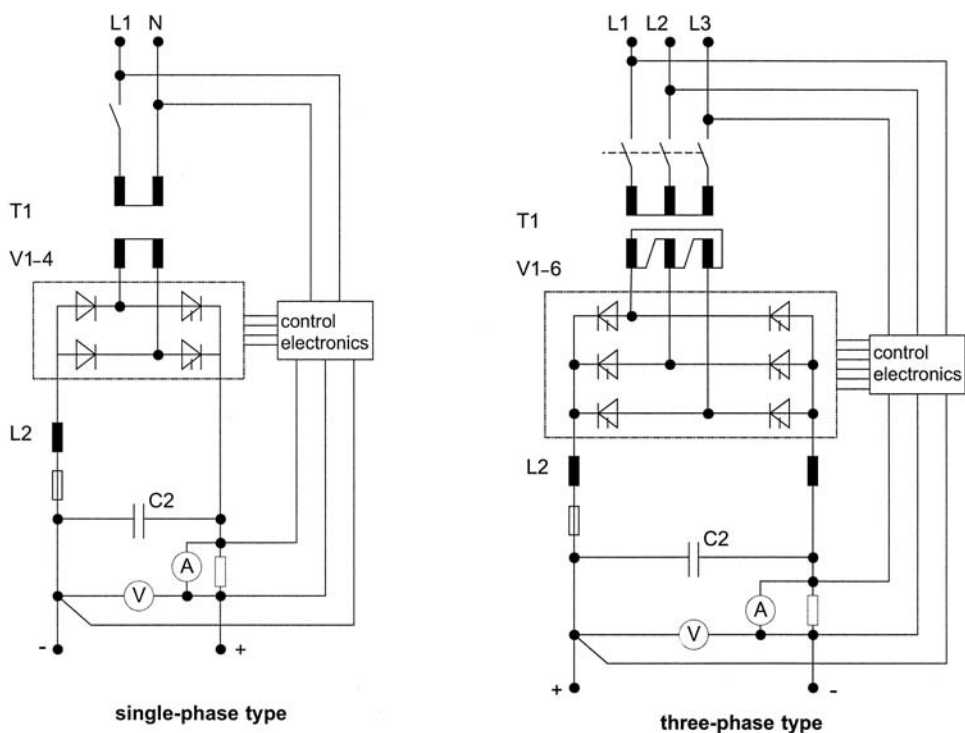


Figure 13.4 Thyristor controlled chargers.

Control Electronics

A control unit topped by trigger equipment for static power converters triggers the thyristors, so the output voltage of the chargers is independent of the mains and load fluctuations. An automatic switchover unit and a corresponding set point to the controller allow these devices to yield constant voltage or constant DC current.

According to DIN 41 772 there are two standard characteristics for controlled battery chargers:

1. For the IU characteristics (Figure 13.5) the output voltage is kept between 2.23 and 2.40 V/cell and below the charger's nominal current.
2. For greater loads, the voltage control is substituted by current control. By lowering the output voltage the charger yields a constant current of the magnitude of the device's nominal current.

The IU_{Ia} characteristics (Figure 13.6) is composed of an IU characteristic with an attached charging phase. Upon reaching a certain lower current limit, charging is continued at slightly increased voltage with constant current (I-charging phase).

Upon terminating the charging process, the device is automatically switched off (a phase). Criteria for this switching can be a fixed charging period or voltage change du/dt .

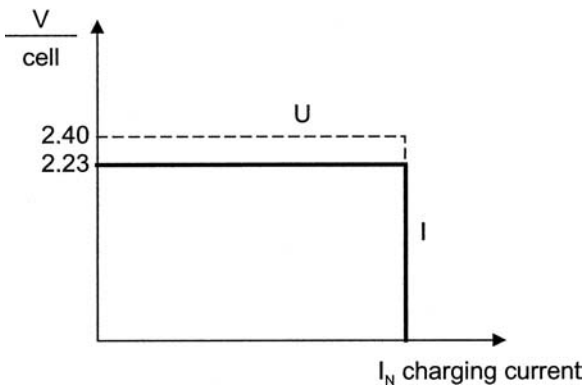


Figure 13.5 IU characteristics according to DIN 41 772.

Smoothing Filters

The rectifier superposes an alternating voltage on the DC voltage over the whole controlling range, which is greatest for an angle of 90 degrees. The alternating voltage has harmonics of the degree $v = pk$, ($k = 1, 2, 3, \dots$; $p = \text{pulse number}$). Therefore in three-phase types with fully controlled bridge circuits the 6th, 12th, and 18th harmonics, and in single-phase types the 2nd, 4th, and 6th harmonics are encountered (Figure 13.7).

The alternating voltage part is limited by a smoothing inductivity (L_2) on the direct current side in order to prevent excessive stress for the battery and the connected consumer. For higher demands, such as in the case of application for power supply systems with small batteries or sensitive consumers, often additional smoothing capacities (C_2) are necessary.

13.3.1.2 Transistor Controlled Chargers

Chargers with transistor series control are applicable for small loads as an economic alternative to thyristor controlled chargers (Figure 13.8). They consist of

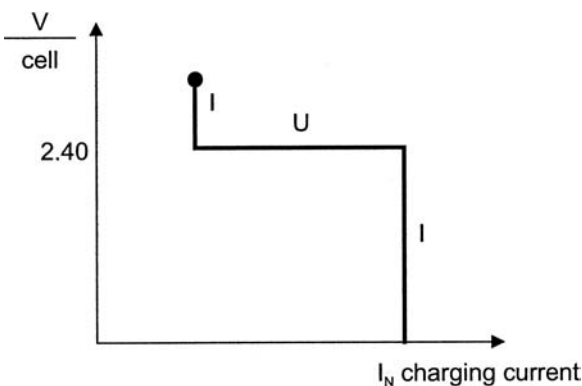


Figure 13.6 IUa characteristics according to DIN 41 772.

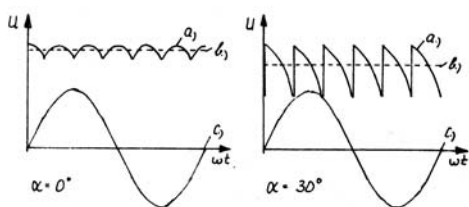


Figure 13.7 Voltage flow, three-phase bridge.

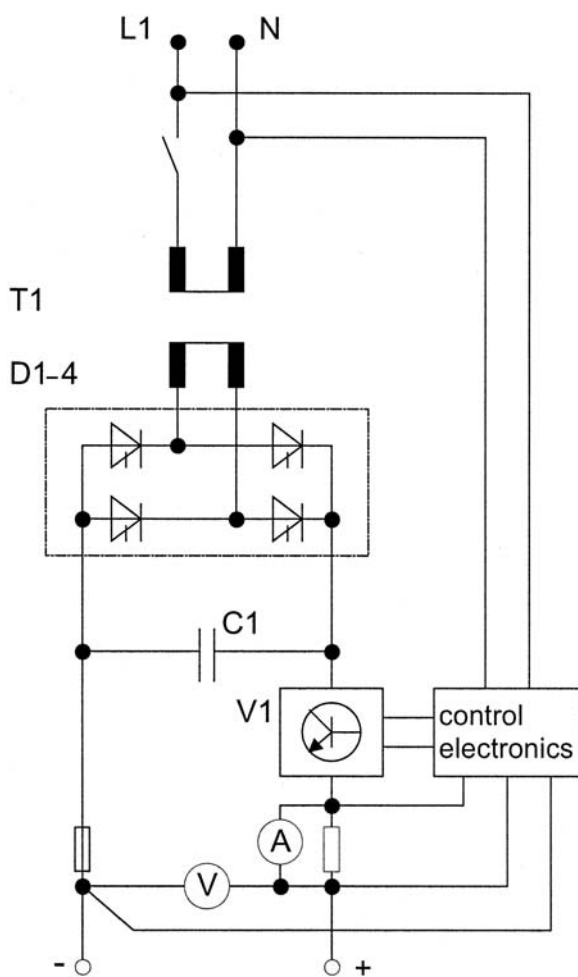


Figure 13.8 Transistor controlled charges.

- A transformer.
- An uncontrolled rectifier.
- A power transistor.
- Control electronics.
- The corresponding smoothing filters.

These devices' advantage is that their internal dynamic resistance is very low and therefore the voltage can be regulated very quickly. The losses in the series control are comparatively high and therefore the efficiency is low. Primary-chopped switching power supplies will more and more substitute these chargers (Figure 13.9). A more detailed description is therefore not made here.

13.3.1.3 Chargers with Primary-Chopped Switching Power Supplies

These chargers consist of

- Mains rectifier.
- Power stage.
- Ferrite transformer.
- Rectifier.
- Control electronics.
- Smoothing filters.

They are mainly employed for a power range of 24 V, 50 A. They are lighter than conventional devices and are more efficient. They can be of different design depending on power and demand. Figure 13.9 shows one example.

Mains Rectifier

The mains voltage is rectified by a diode bridge circuit (D1-4) and the capacity (C1) charged. This capacity is a smoother and an energy storage at the same time and delivers the input voltage for the mains supply circuit consisting of a power stage and a ferrite transformer.

Power Output Stage

The transistor (V1) is triggered by a frequency generator and “chops up” the rectified mains voltage with a frequency of, e.g., 20 kHz. It is at the same time a power output stage.

Transformer

The high-frequency AC voltage is separated galvanically from the mains and adjusted to the output voltage by a ferrite transformer (T1).

The high transformation frequency allows the transformer to be of very small design and therefore gains great advantages in weight and volume compared to devices with 50-Hz transformers.

Rectifier

Rectification and smoothing of the transformer output voltage is accomplished by a diode (D2) and a capacitor (C2), yielding a high-quality DC output voltage.

Control Electronics

Regulating mains and load fluctuations is attained by changing the pulse-duty factor triggering the transistor (V1). Transformers or optical couplers can accomplish

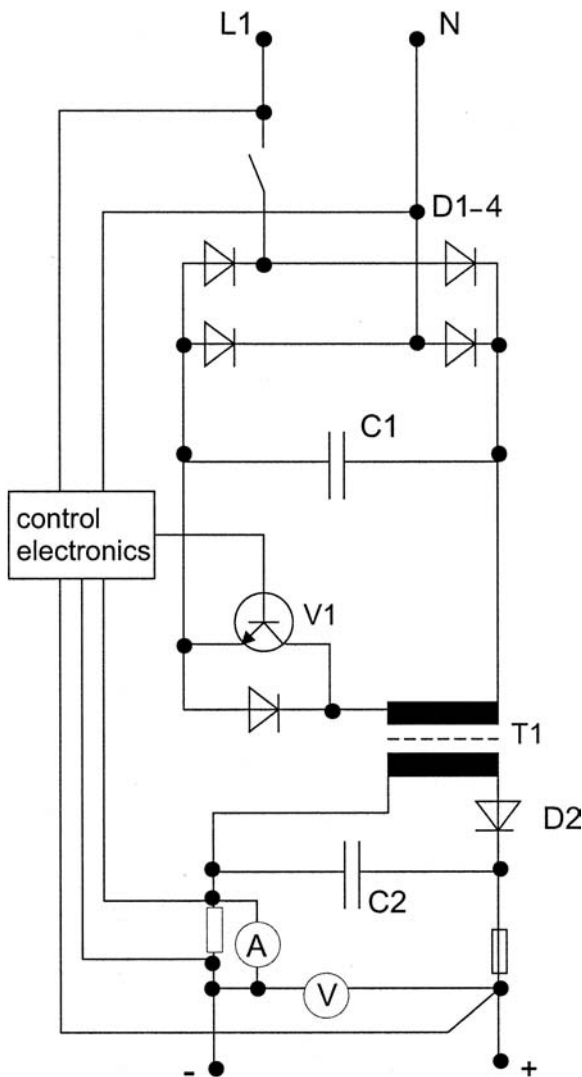


Figure 13.9 Chargers with primary-chopped switching power supplies.

transfer of the regulating signals. Regulation can be done according to an IU or IU/a characteristics.

13.3.2 Uncontrolled Chargers

These consist of a transformer and an uncontrolled rectifier. These devices are generally available in the same power ratings as controlled devices of the single-phase type or the three-phase type (Figure 13.10). Generally silicon diodes are employed as valves.

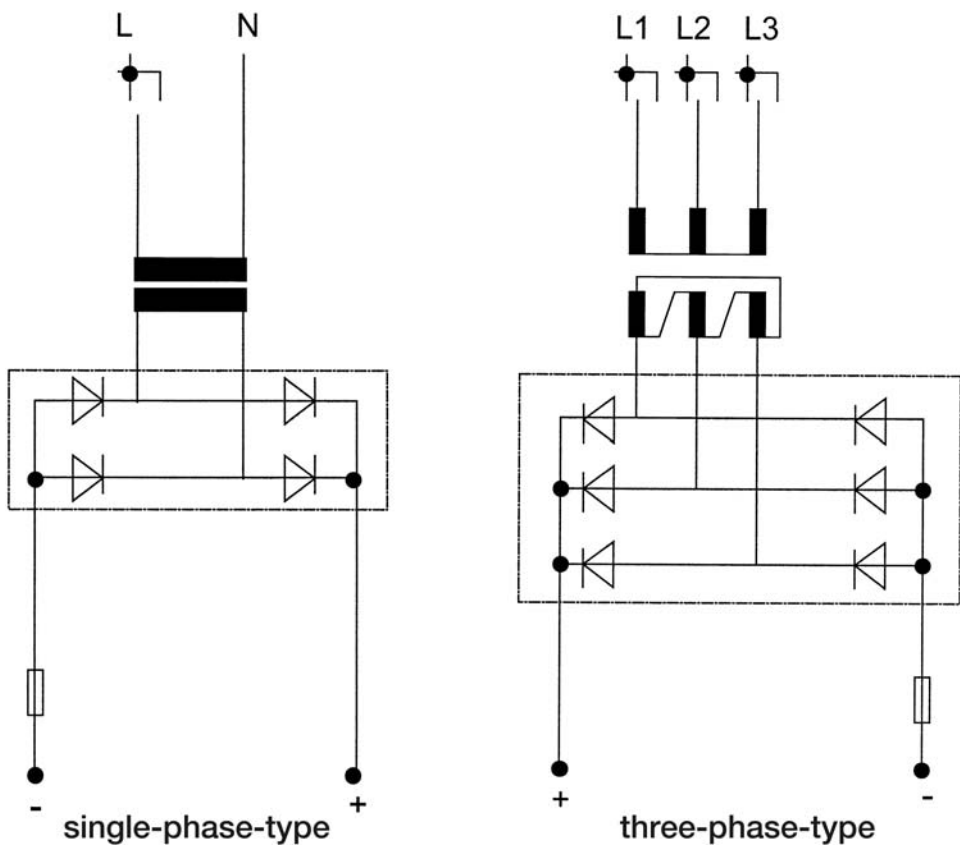


Figure 13.10 Uncontrolled chargers.

The output voltage of these devices is generally dependent on the mains voltage and the current of the load. The DC side output voltage therefore also changes when fluctuations of the mains voltage are encountered. The W characteristic is standardized according to a DIN standard (Figure 13.11) and passes the following three points for lead batteries:

- 2.0 V/cell at 1.0 N.
- 2.4 V/cell at 0.5 N.
- 2.64 V/cell at 0.25 N.

With the addition of an automatic switch-off step the W characteristic can be completed into a Wa characteristic.

13.4 CHARGERS FOR TRACTION BATTERIES AND STATIONARY BATTERIES IN SWITCH OPERATION

When charging a battery it is of great importance that the charge is carried out in a heedful manner and is terminated after a certain period of time. For the charging

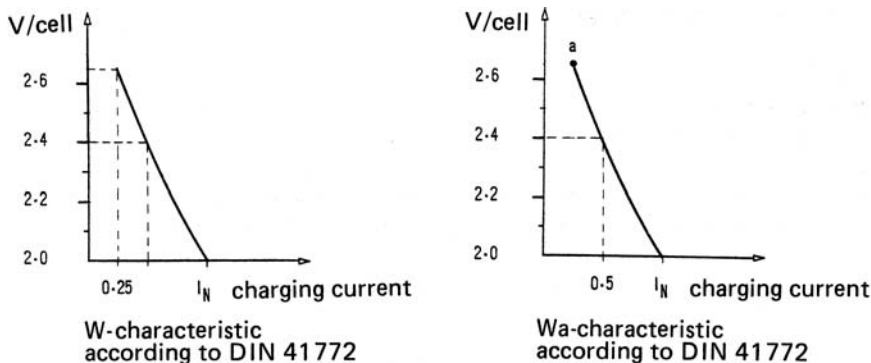


Figure 13.11 Characteristics of uncontrolled chargers.

process itself, controlled chargers with, for instance, an IUa characteristic or uncontrolled chargers with Wa or a switchable WO-Wa characteristic can be employed.

One of the most important requirements for recharging traction batteries is very short charging periods.

For a PzS-type battery of 80% discharged state, the following recharging periods are required:

- IUa: > 7.5 h.
- WOWa: > 8 h.
- Wa: > 14 h.

The permitted charging currents are treated in VDE 0510 (see [Table 13.2](#)). The charging methods and techniques are explicitly treated in Chapter 12.

13.5 CHARGERS FOR STATIONARY BATTERIES IN PARALLEL OPERATION

For a guaranteed power supply the battery is in many applications permanently connected parallel to the consumer. To supply power to the consumer and battery, controlled chargers that fulfill the following criteria are mostly employed:

- The battery has to be charged.
- State-of-charge of the battery must be maintained.
- Voltage tolerances of the consumer must be obeyed.
- Dimensioning of the charger must correspond to the consumers current.
- A charging reserve must be available for recharging the battery after a mains failure.

As the voltage step between the gassing voltage and cut-off voltage of lead-acid and especially of NiCd batteries ([Table 13.3](#)) is significant, great care must be taken not to exceed the permitted voltage tolerance of the consumer. This is mostly ensured for lead-acid batteries in many applications through proper choice of the number of

Table 13.2 Permitted charging currents according to VDE 0510.

		Device current (A) per 100 Ah				
Type of cell	Application	Allowed acc. to VDE 0510 W-char.			Spec. VARTA IUI-char.	
		2.65 V	2.40 V	2.00 V	2.40 V	I = const.
<i>Large surface cells</i>						
Gro	Stationary	6	12	24	80	8.5
GroE	Stationary	6	12	24	80	5
<i>Tubular plate cells</i>						
OPzS	Stationary	3.5	7	14	80	5
PzS (PzF)	Traction	4	8	16	80	5
<i>Grid-plate cells</i>						
GiS	Traction	4	8	16	100	5
	Starter	6	12	24	160	10

cells, the battery’s capacity, as well as limitation of the charging voltage to a float-charge voltage.

For application of NiCd batteries and charging lead-acid batteries above float-charge voltage the following measures are necessary:

- Employment of counter cells.
- Separation of the batteries’ cells into stock and additional cells.
- Application of DC converters.

13.6 SURVEILLANCE AND ADDITIONAL DEVICES

Chargers are equipped on more-or-less expedient surveying equipment depending on their application. These have to register irregularities quickly, protect the battery and the attached consumers, and thereby ensure safe operation of the devices.

The following describes functions and actions of the most important surveying equipment ([Figure 13.12](#)).

Table 13.3 Voltages of lead-acid batteries.

Voltage	Lead-acid batteries		NiCd batteries	
	V/cell	Variances	V/cell	Variances
Gassing voltage	2.4	+ 20%	1.7	+ 42%
Float-charge voltage	2.23	– 11.5%	1.4	+ 16%
Nominal voltage	2.0	± 0%	1.2	± 0%
Cutoff voltage	1.75	– 12.5%	1.0	– 17%

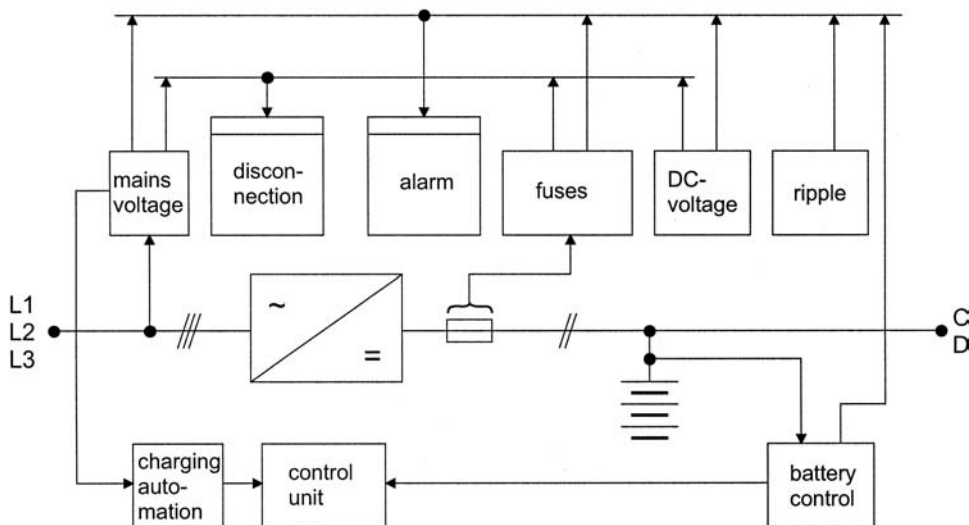


Figure 13.12 Surveying equipment and additional devices.

13.6.1 Mains Surveillance

Whenever the mains voltage lies outside of a certain tolerance or one phase fails, faultless function of the charger is no longer guaranteed.

Mains undervoltage or phase failure is followed by switch-off of the charging device and monitoring of the irregularity.

Mains overvoltage is also followed by switch-off of the charging device and monitoring of the irregularity.

If the voltage returns to normal values, the charging device is automatically reactivated.

13.6.2 DC Voltage Surveillance

An increase or decrease of the DC voltage outside of tolerance limits must be prevented for protection of the consumers attached and for satisfactory charging of the battery.

Overvoltage results from a fault at the charger. Undervoltage may be a result of mains failure or faulty functions of the charger. Overload of the charger can also be the reason, because the DC voltage decreases as the current limitation comes into effect.

During single charging operation DC overvoltage is followed by switch-off of the charging device and monitoring of the irregularity, and DC undervoltage is followed by (in the case of low DC voltage) monitoring of the irregularity.

When for redundancy purposes two or more chargers are attached to one power rail, the faulty device must be distinguishable in case of failure. In order to distinguish the faulty device the charger output current may be checked.

During parallel charging operation DC overvoltage is followed by switch-off of the faulty charger and monitoring of the irregularity; and DC undervoltage is followed by switch-off of the faulty charger and monitoring of the irregularity.

13.6.3 Surveillance of the DC Voltage Waviness

A fault in the converter or a failure of the smoothing filters may increase the AC voltage share at the DC side to a magnitude harmful to the consumer or the connected battery. It is therefore necessary to control the waviness of the DC voltage.

Upon notice the irregularity is monitored

13.6.4 Fuse Surveillance

Triggering a fuse may be the result of old age, overstress, or short circuit. This event is followed by switch-off of the charger and monitoring of the irregularity.

13.6.5 Automated Charging

Lead-acid cells and NiCd cells are often recharged after mains failure with an increased voltage value of 2.3–2.4 V/cell (for Pb) and 1.6 V/cell (for NiCd). Changeover to a higher voltage level is done manually or automatically. The automatic changeover is to float-charge operation after a given period of time.

13.6.6 State-of-Charge Surveillance

For fast and economical recharge, depending on the battery's state of charge, after mains failure and in order to utilize the battery's capacity optimally, continuous information on the state of charge and on the load is indispensable. Devices that register and process the different values of interest such as current, voltage, and temperature have been developed and tested.

13.7 HARMONIC OSCILLATIONS AND REACTIVE POWER

Converters take out a non-sine-shaped current from the three-phase supply. It is composed of a fundamental oscillation at mains frequency and several harmonic oscillations whose frequencies are integer value multiples of the mains frequency. These harmonic oscillations can be viewed by approximation as impressed current that are enforced on the three-phase supply. Harmonic voltages are encountered at mains impedances, which are superposed on the mains fundamental oscillation and therefore distort the mains voltage.

Whenever the harmonic currents exceed a certain value, generally resonances and therefore disturbances in the power supply system are encountered.

Through closely analyzing the converter currents and employing exact countermeasures it is possible to reduce the mains disturbances to a large extent. Therefore it is possible to operate large converters in the mains.

As battery chargers mostly have a low power consumption compared to the overall power consumption of the plant, they can be operated without difficulties. It is however indispensable to reduce these harmonic currents to a minimum for large stationary plants or on a large-scale employment of on-board chargers in electric vehicles.

A fully controlled three-phase bridge circuit and a primary-chopped switch mode power supply shall be viewed more closely in the following:

13.7.1 Three-Phase Bridge Circuit

The three-phase bridge circuit draws a square-wave current under ideal conditions from the mains (Figure 13.13). Harmonic oscillations of the ordinal $v = p(k \pm 1)$ are encountered ($p = \text{pulse number } (p = 6)$; $k = 1, 2, 3, \dots$). The amplitudes of the harmonic currents are inversely proportional to their ordinal number:

$$I(v) = \frac{1}{v} I_{(1)}$$

The most significant harmonics are the 5th, 7th, 11th, and 13th as the amplitudes of higher frequencies are very small.

Harmonic oscillations can be reduced by employing a higher number of pulses of the converter or application of filter circuits.

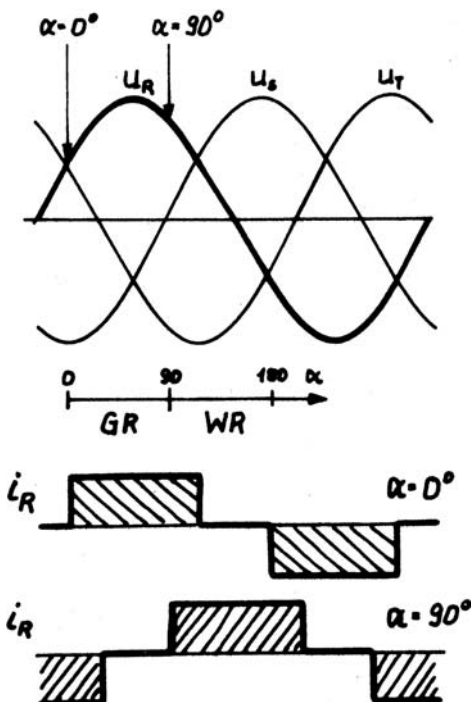


Figure 13.13 Mains current of a three-phase bridge circuit.

For a converter with a pulse number of 12, for instance, the 5th and 7th harmonic disappears. In many cases, however, the filtering circuits are the more economical solution (Figure 13.14). Filtering circuits are series resonance circuits with their frequencies adjusted exactly to those of the harmonic oscillation currents to be eliminated. Therefore they represent very low impedance for these harmonic oscillations and prevent their flowing into the power supply system.

Filtering circuits are mostly employed for the 5th, 7th, 11th, and 13th harmonic. In many cases, however, a filtering circuit for the 5th harmonic is sufficient.

A controlled bridge circuit most of all draws, apart from the distorted current, an induced reactive power from the mains, which, depending on the trigger delay angle, is greatest for 90 degrees (Figure 13.13). As filter circuits are always capacitors for fundamental oscillations, they automatically compensate part of the fundamental oscillation reactive power.

13.7.2 Primary-Chopped Switching Power Supply

Battery chargers with primary-chopped switching power supplies redress the mains voltage by means of an uncontrolled bridge circuit. The mains current only is conducted when the rectified mains voltage is at that time higher than the voltage at the capacitor C1 (Figure 13.9). Only peak currents with a large harmonic oscillation component where the 3rd harmonic is emphasized are drawn from the mains (Figure 13.15).

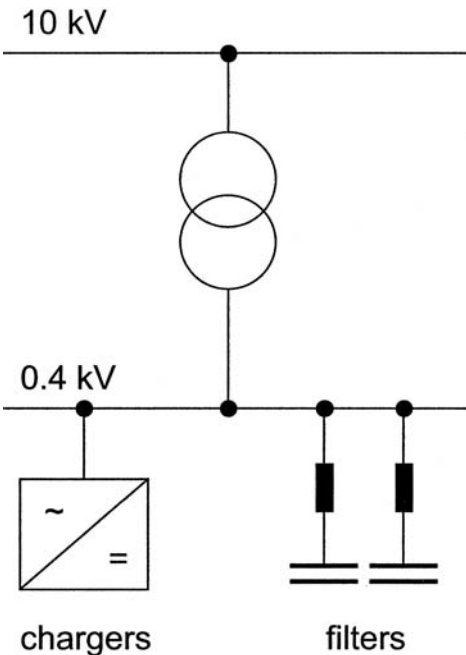


Figure 13.14 Compensation with filter circuits.

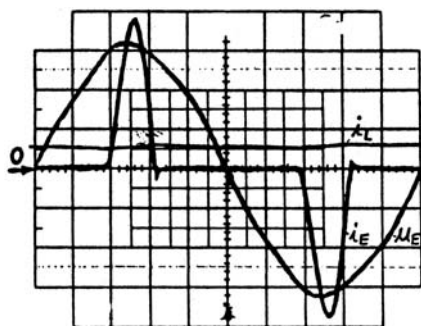


Figure 13.15 Mains current of primary-chopped switching power supplies.

An accumulation of devices of this kind will therefore always be problematic. It shall be mentioned at this point that for the application of chopped devices special measures for radio interference suppression must be taken.

This makes power supply circuits that draw harmonic currents from the mains indispensable, and therefore these devices are being developed and are undergoing testing. Their construction demands more technical expenditure than the devices employed at this time, making them more expensive. Their introduction to the market is largely dependent on the demands of the electric power supplying companies.

13.8 INVERTERS FOR ASCERTAINED POWER SUPPLY OF THREE-PHASE CONSUMERS

Power supply for three-phase consumers is presently mostly ascertained by systems consisting of rectifiers, batteries, and inverters. Controlled chargers with an IU characteristic are employed for rectifiers. They take over power supply for the inverters in normal operation and ascertain charging and float charging of the battery that takes over power supply in case of mains failure. The inverter changes the DC voltage to an AC voltage that is largely independent of fluctuations of the DC voltage or loads.

13.8.1 Inverters with Double-Phase Bridge Circuits

Self-commutating converters with regulative voltages are employed for inverters (Figure 13.16). During ignition of the valves V1 and V3 a positive voltage lies between the transformer terminals 1 and 2, whereas when the valves V2 and V4 are ignited, a negative voltage is encountered here. The “valves” each consist of a main thyristor and a clearing device with a reset thyristor; therefore an offset mode or a conducting mode can be controlled by the according enabling impulses.

Amplitude of the output voltage is controlled by means of pulse-width modulation. A harmonic or square-wave reference voltage with the same basic oscillation frequency as that of the output voltage and variable amplitude is sampled by a delta voltage of pulse frequency and constant amplitude (Figure 13.17).

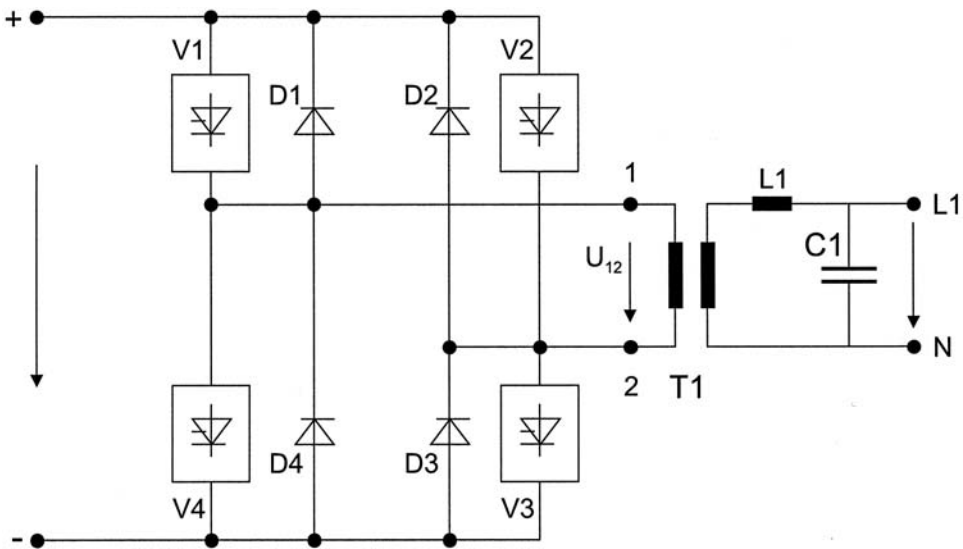


Figure 13.16 Inverter with double-phase bridge circuit.

The drive pulse for the thyristors is taken at the intersections, resulting in a pulsed output voltage. The load current can pass over the recovery diodes (D1-D4) during zero-voltage periods. In the case of the positive half-wave being blocked at valve V1, the current can flow over V3, D4, T1.

Transformer

The transformer T1 galvanically separates the battery and the consumer and can be additionally employed for voltage adaptation.

Output Filters L1, C1

A filter behind the transformer modifies the pulsed inverter output voltage into sine-shaped voltage. Less expensive low-pass filters (L1, C1) or band-pass filters can also be applied.

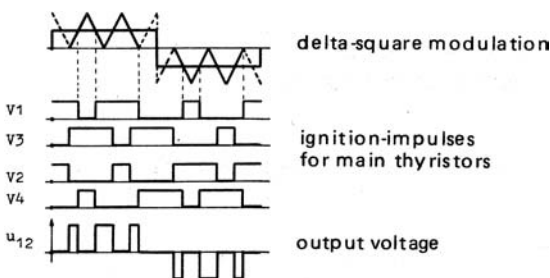


Figure 13.17 Voltage assembly by pulse-width modulation.

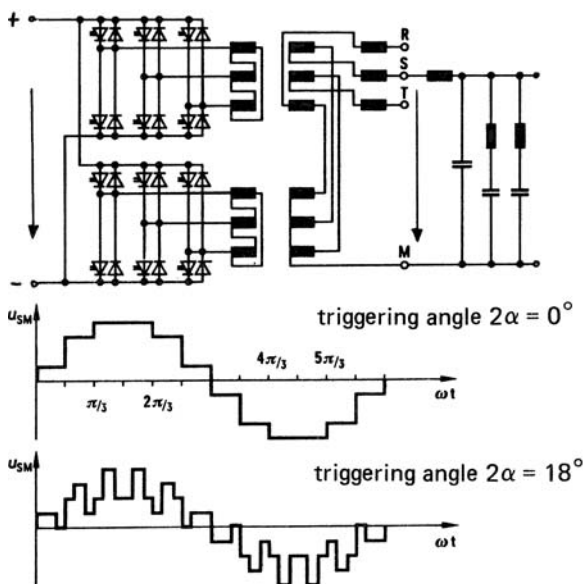


Figure 13.18 Twelve-pulse three-phase inverter. Circuit and flow of the unfiltered voltage.

13.8.2 Inverters with Three-Phase Bridge Circuits

Addition of a third strand to the single-phase inverter shown in [Figure 13.16](#) yields a six-pulse three-phase inverter. Figure 13.18 shows an inverter that consists of two three-phase six-pulse partial inverters that yields a 12-pulse output voltage. The main advantage is that the filters can be made much smaller. More dynamic voltage regulation is attained.

Recent developments in the field of power electronics and forced employment of microelectronics as well as continuous development of systems and circuitry techniques will allow the construction of devices that will have lower drop-out rates at lower overall dimensions and power losses.