

Power Supply Concepts for Driverless Industrial Trucks

P. PREUSS

3.1 THE IMPORTANCE OF DRIVERLESS INDUSTRIAL TRUCKS

Although relatively unknown some years ago, driverless industrial trucks have come to occupy an important position within the framework of highly organized systems of driverless transport (DTS). The essential factors contributing to this fact are without doubt on the one hand the increased need for automation in industry, and on the other hand the high degree of flexibility afforded by these appliances. The overall view of these appliances ([Figure 3.1](#)) clearly shows that driverless industrial trucks (DIT) may as a whole be divided into three categories.

The majority of these installations will be found in the automotive industry, which requires a wide variety of applications specific to driverless trucks. In this context, considerable importance will be attached to the third generation of driverless transport systems used, for example, to create the link between individual pieces of manufacturing equipment or assembly workplaces. This task may be designated “product engineering transport” and represents the second transport assignment after “works transport” to be mastered successfully by driverless industrial trucks. A third transport assignment, “transport between factories”, has so far been little investigated, but is becoming more and more the subject of discussion.

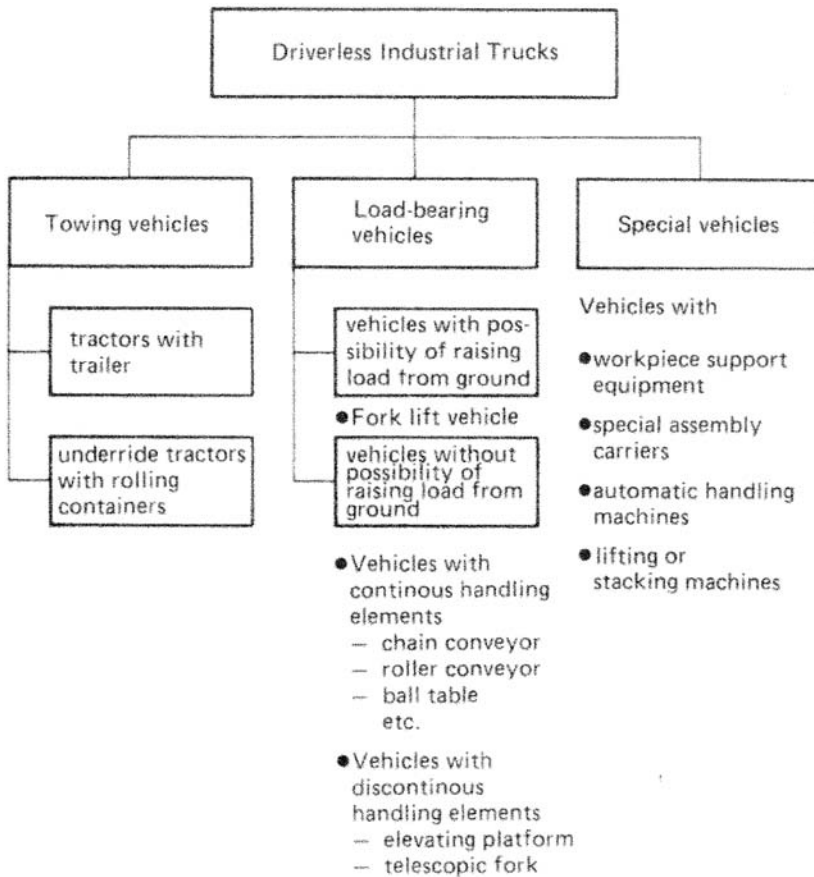


Figure 3.1 Structural family tree of driverless industrial trucks.

3.2 LOAD PLACED ON TRACTION BATTERIES BY DRIVERLESS INDUSTRIAL TRUCKS

Traction batteries are of central importance as suppliers of power. Together with the stationary charging set, or under certain circumstances the charging set located “on board”, and the principles of charging of the system employed, drive batteries comprise the power supply. Experience has shown that the demands made on the battery differ from system to system. It is therefore not possible to refer to “the DIT battery”, but widely differing systems of batteries are required to cover the range of applications lying between the two extremes (Figures 3.2a and b) of (a) capacitive operation and (b) cyclic operation.

A few explanations are given below on these two modes of operation.

- Capacitive operation signifies that the total, or practically total, useful battery capacity is consumed in the course of one discharge period, and then of necessity restored by being fully charged. Batteries in conventional

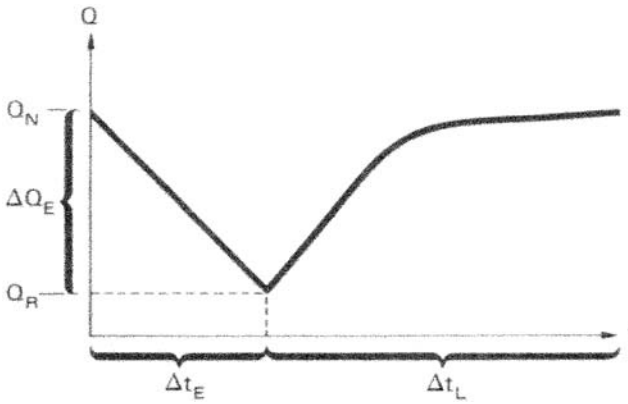


Figure 3.2a Capacitive operation.

industrial trucks have always been run in this way; the discharge time is here, for example, an 8-hour shift.

- Cyclic operation means that under certain circumstances only a very small portion of the battery's capacity is consumed during one discharge period (discharge cycle) and is immediately recharged (charge or boost charge cycle). Discharge and charge cycles can easily have the order of magnitude of only minutes or even seconds. Plants operating three shifts and weekend shifts are no rarity, so that full charging of batteries is not possible, at least not at acceptable intervals. The battery capacity will first fall under these application conditions, and then even out at a certain capacitance level after a calculable number of cycles, on account of the boost charge cycles. Such application conditions pose specific problems, to which further reference will be made below.

Purely cyclic operation is only run as an exception with conventional industrial trucks. Elements of this mode of operation can nevertheless be found in the form of

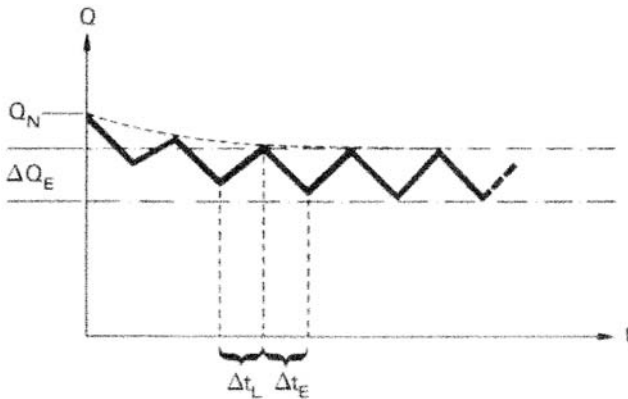


Figure 3.2b Cyclic operation.

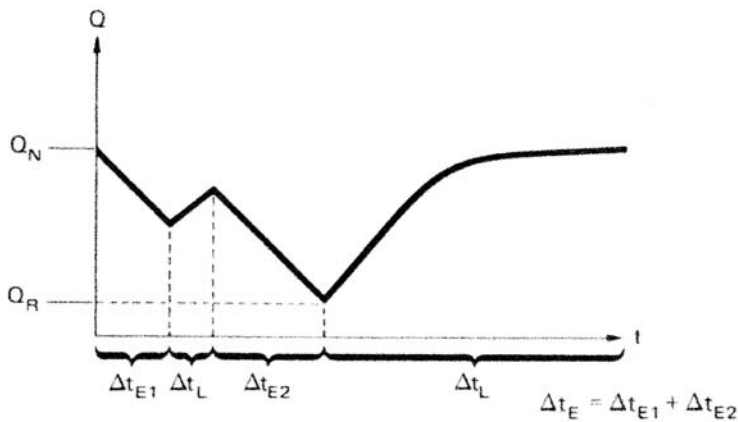


Figure 3.2c Capacitive operation with boost charge.

boost charges during rest periods, aimed at extending full capacity and thus increasing the period of use (Figure 3.2c). This combination of elements from capacitive and cyclic operation may be designated a mixed mode of operation.

Knowledge of the load placed on batteries in the course of the discharge phase will generally not suffice even in capacitive operation for the development of a reliable, functional power concept. The intervals between applications dictated by the sequence control system, which forms the basis for the plan of charging, have a decisive influence, particularly in the case of cyclic operation. Furthermore, attention must be paid to further basic application parameters. The more data known on the application of the batteries, the more reliable it is to specify the power concept.

3.3 TRACTION BATTERIES FOR DRIVERLESS INDUSTRIAL TRUCKS

In contrast to the sector of conventional trucks, practically all systems of batteries, which have proved successful in practice, are used in driverless industrial trucks. In addition to the lead-acid batteries (LAB) common in the sector of conventional industrial trucks nickel/cadmium batteries (NCB) have taken over quite a considerable slot in the market in the DIT sector, on account of their particular properties.

3.4 OPTIMIZATION OF TEMPERATURE

The plant operator expects from a concept of power supply that it will fulfill the following requirements:

1. It must guarantee readiness for use by the driverless industrial trucks at all times within the understanding of the system of sequence planning.
2. The point at which the battery requires renewing should be as late as possible, but should be recognized as early as possible.
3. It should be predominantly independent of any external supervision.

4. Operating costs should be at a minimum.

Requirements 1–3 naturally provide the prerequisite for 4.

3.4.1 Considerations on Battery Dimensioning

A concept of power supply can always be made on the basis of an efficient description of a battery's application. However, to fulfill the above-mentioned requirements, it is advisable to plan the battery dimensions based on principles which may be described as optimizing temperature factors. This method departs from the premise that any battery, which is not subject to impermissible heating under prescribed load, is bound to exhibit the necessary efficiency and service life, i.e. to have the desired operating reliability. The temperature of the electrolyte would ideally display a constant value, merely being dependent on the ambient temperature in the driverless industrial truck, which is itself only subject to minor fluctuations. The temperature of the electrolyte would in this way be directly related to normal ambient temperature. If this were to fall drastically in winter, additional measures would of course have to be taken to raise the temperature of the electrolyte.

3.4.2 Estimating Battery Load Rating

Heating of the battery system presented in Figures 3.3 and 3.4 with the same capacity and under equal load differs considerably during the charge and discharge phase due

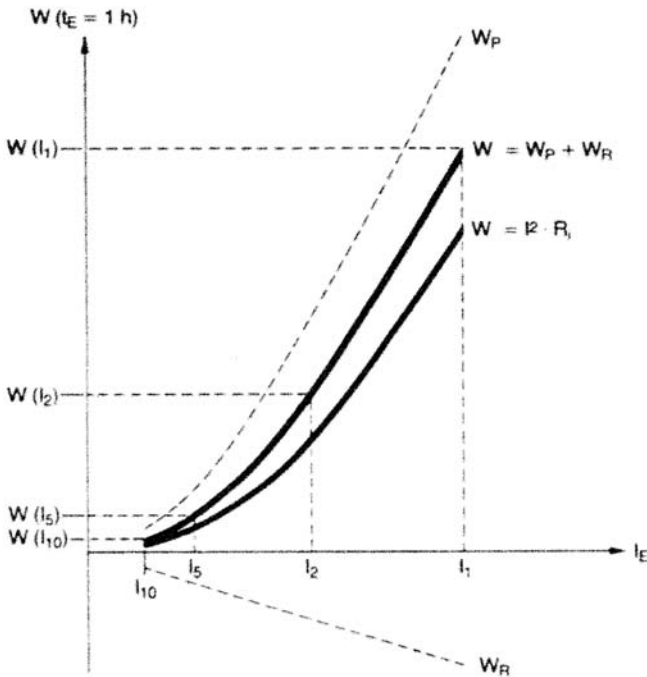
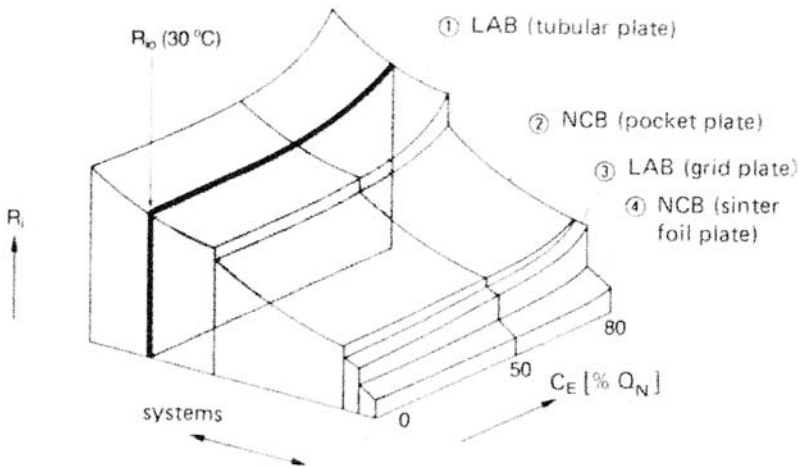


Figure 3.3 Depiction of thermal energy generated in 1 h in a tubular plate battery with different discharge currents.

a) $R_i = f(\text{System, series, level of discharge})$



b) $R_i(\text{TPB}) = f(T_{el}, \text{level of discharge})$

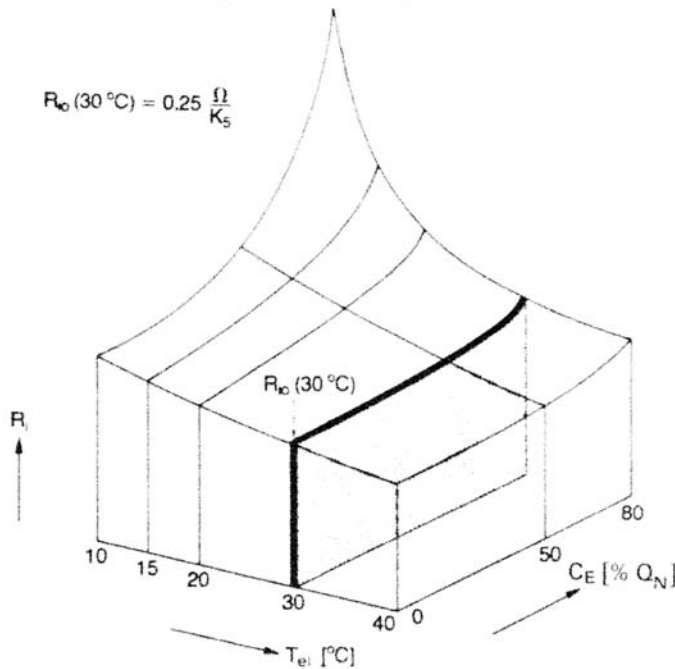


Figure 3.4 Internal resistance in the different battery systems, quality curves.

to the different systems employed (electrochemistry/design). This can be seen clearly by comparing the respective reaction and polarization heat component, which always exists. Determining the thermal differences by way of the electric heat generated at the internal battery resistance by the effective current value is only a

rough form of estimation, and can also only be conducted during the discharge phase. Figure 3.3 shows the difference from the actual heat generated using a tubular plate battery as an example. Calculation by way of electric heat fails completely for the charge phase. Nevertheless, it is possible to estimate the load rating of a battery system with the aid of internal resistance. Figure 3.4 shows the curves for internal resistance in different battery systems at normal temperature, and the dependence on temperature of internal resistance in a tubular plate battery. Based on this estimation, and supported by results achieved in practice, Table 3.1 contains permissible load ratings for uninterrupted cyclic operation. Extreme plant conditions, which tend to be the exception in practice, always require an accurate calculation to be made of the rise and fall in temperature, particularly during charge phases.

3.5 THE CHOICE OF BATTERY

Apart from the specific load rating, there are a number of further parameters or relationships which require attention when developing a suitable concept of power supply. Although these are in fact self-evident, they will be repeated here for the purposes of completeness.

3.5.1 Maximum Permissible Capacity

The differing application requirements make necessary different levels of capacity between two charge cycles or phases, which need to be transformed into the nominal capacity, following the principles of temperature optimization, and including the specific system load ratings and any necessary temperature corrections. Examination of the capacity available in practice can thus, under certain circumstances, already lead to the choice of a particular system. Table 3.2 contains typical permissible

Table 3.1 Uninterrupted cyclic operation: maximal effective values for discharge/charge current.

Battery system	I_{Emax}	$I_{\text{Lmax}}^{\text{a}}$ in	
		ZL	VL
<i>LAB</i> with			
– tubular plates	I_5	$I_5 / \text{—}$	I_5
– grid plates	$1.5 \times I_5$	$I_5 / \text{—}$	I_5
<i>NCB</i> with			
– pocket plates	$1.5 \times I_5$	$1.5 \times I_5 / \text{—}$	—
– sintered plates	$5 \times I_5$	$10 \times I_5 / 15 \times I_5$	—

ZL = Boost charge (minute/second range).
VL = Full charge (t_L (LAB) = 7–8 h).
^aI_{L_{max}} is not always possible, as in certain circumstances, and depending on the system, limitations to charging efficiency exist which evidence themselves in a shortened current flow time.

maximum levels of capacity. These show that there is no alternative to the tubular plate battery for medium to high capacitive loading.

3.5.2 Maximum Permissible Temperature in Battery Systems

A further selection criterion is provided by the different limit temperatures in the electrolyte, as is also depicted in Table 3.2. The use of a particular battery system becomes questionable when the ambient temperature approaches its maximum permissible temperature. Nickel/cadmium batteries have a significantly lower limit temperature than lead-acid batteries. The systems thus dictate that lead-acid batteries should exclusively be used when the ambient temperature exceeds 35 °C to 40 °C. In the case of extreme ambient temperatures, however, a renewal of batteries should also be planned for, in order not to jeopardize the long service life typical of the system, even when using tubular plate batteries.

3.5.3 Charging Requirements

The electrochemical processes occurring in the course of charging and discharging lead batteries with aqueous electrolytes lead, in time (particularly in high cells), to the well-known phenomenon of acid layer formation, unless measures are taken at regular intervals to counteract this development. These measures are necessary, as the formation of acid layers has a number of consequences, which lead to a reduction in capacity and service life of the battery. In practice, this means utilizing the convection arising in the course of full or equalizing charging by the controlled generation of hydrogen in the negative electrode, which can be relied on to equalize the specific gravity of the acid. In the case of cyclic operation, however, it is well known that the energy balance can be maintained by short boosting charges, which do not lead to any notable hydrogen evolution in aqueous electrolytes. This is also desirable in view of minimizing the amount of water used. Lead-acid batteries with aqueous electrolytes can therefore only be used if the opportunity exists, at least at acceptable intervals, of giving equalizing charges or of renewing the battery. If these conditions do not exist, a decision must be taken in favor of the nickel/cadmium battery, where the problem of electrolyte layer formation is known not to exist.

Table 3.2 Battery system limit capacity/limit temperatures.

Battery system	C_{limit} Ah (five hours)	Of which max. useful	T_{limit} °C
<i>LAB</i> with			
– tubular plates	1,400	80% C_{limit}	55
– grid plates	160	80% C_{limit}	55
<i>NCB</i> with			
– pocket plates	250	100% C_{limit}	45
– sintered plates	200	100% C_{limit}	40

3.6 DEVELOPMENT OF A CONCEPT OF POWER SUPPLY

The efficiency of any power supply concept depends greatly on the amount of relevant data available on its application. The more detailed the description of its application is, the more reliably the solution produced will be able to fulfill all requirements.

3.6.1 Nature and Scope of Application Data

Two examples of applications will show which data are required in order to develop an appropriate concept for power supply. Figure 3.5a shows the capacitive application of a high-lift truck over two shifts on 5 days (Monday to Friday). The necessary scope of data is small. It is sufficient to describe one shift, represented in a considerably simplified manner, by summarizing application times and rest periods. This shift represents the smallest, regularly repeated application period, referred to as cyclic element (CE). The description of application only indicates how often this CE is repeated per day (2 x), and how often this definition of the working day is repeated per week (5 x). The third shift is available each day for charging, the weekend is excluded for charging.

The example for cyclic operation (Figure 3.5b) appears somewhat more complicated, but is based on the interlinking of described data. As is shown, more complex sequences can also be recorded using minimum data. The depiction is again of the cyclic element (a sequence of discharge and charge cycles) which, repeated 10 times and completed by an additional charge phase, corresponds to one shift in the example. After being repeated twice, this is followed by a rest period, without the possibility of recharging. This description of the working day is then repeated regularly (7 x) for each day of the week.

These examples, which are admittedly shown in a simplified form, are intended to indicate which information is essential for producing the power supply concept:

- Different effective discharge current values.
- Actual flow times.
- Closed-circuit current required.

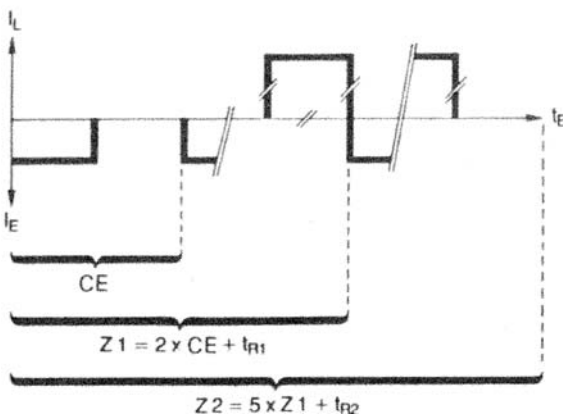


Figure 3.5a Capacitive application.

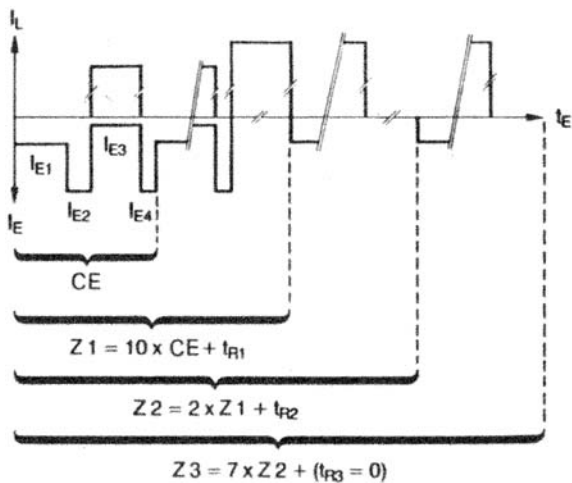


Figure 3.5b Cyclic operation.

- Rest periods, which can be used for charging (boost charge/full charge) and those which are pure rest periods without the possibility of charging.

These data must be further supplemented by the following application parameters:

- Ambient temperature range.
- Minimum permissive discharge voltage.

Details on battery renewal, maximum weight, and volume would further complete the collection of application data, rendering it sufficient. There would now be no hindrance to determining the power supply concept, even if application conditions were to become more complicated (Figure 3.5c).

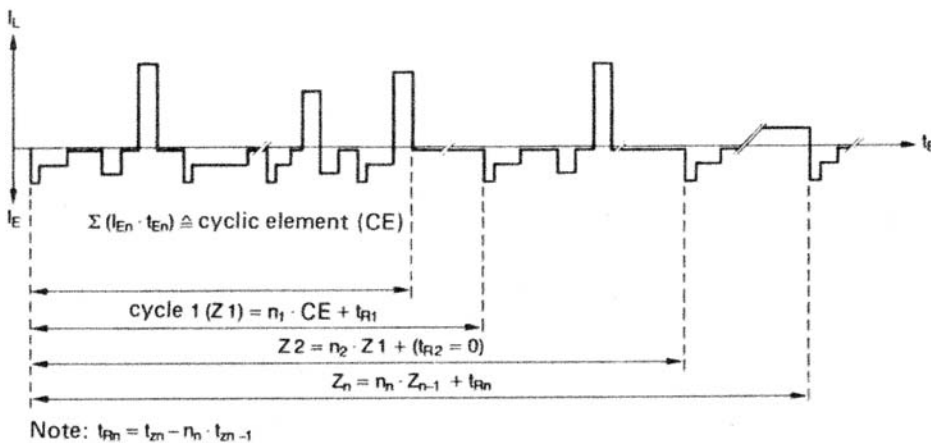


Figure 3.5c Cyclic operation: general example.

3.6.2 Processing and Transformation of Application Data

In view of the fact that an arbitrary number of different plans for use are feasible in installations with driverless industrial trucks (practice), it is not possible to postulate an easy system for determining the components in producing the power supply concepts. The reason for this lies in the at times widely differing properties (Figure 3.6) displayed by the various battery systems, which also have a great influence on charging technology. It is possible, however, to specify the steps, which actually need to be taken every time. These refer to the smallest, regularly repeated interval between applications, which at the same time contain the total feasible boost charge capacity, i.e. do not necessarily coincide with the cyclic element. The calculations are all based on simple mathematical relationships.

3.6.2.1. Determining the Capacity Required $Q_{\Delta E}$ in the Interval Between Applications Δt_E

Capacity generally corresponds to the product of current time:

$$Q = \int_{t_0}^{t_0+T} i \, dt$$

With respect to an interval between applications with many current flow phases of different strengths, as will always be the case in problems of drive (acceleration phase, steady-state phase), this equation can be converted into

$$\Delta Q_E = \Delta Q_{E1} + \Delta Q_{E2} + \cdots + \Delta Q_{En}$$

By inserting individual currents and current flow times, this gives us

$$\Delta Q_E = i_{E1} \cdot \Delta t_{E1} + i_{E2} \cdot \Delta t_{E2} + \cdots + i_{En} \Delta t_{En}$$

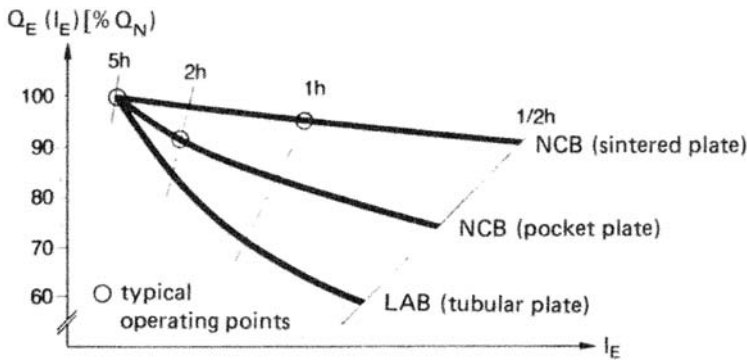


Figure 3.6 Differences in capacity for different battery systems with same hourly measurement, $T_{el} = T_N$.

which can be condensed into

$$\Delta Q_E = \sum_{n=1}^k i_{En} \Delta t_{En}$$

3.6.2.2. Determining the Effective Discharge Current Value I_E in the Interval Between Applications Δt_E

The effective value of the discharge current can be calculated by using the following formula:

$$I_E = \sqrt{1/T \int_0^T i_{E2}^2 dt}$$

Note: This actually comprises the root mean square value. As this is important for the heat generated in one pulse sequence, it is called the effective value. In the same way as we determined the capacity required, the formula may be quoted as follows:

$$I_E = \sqrt{1/\Delta t_E (i_{E1}^2 \Delta t_{E1} + i_{E2}^2 \Delta t_{E2} + \dots + i_{En}^2 \Delta t_{En})}$$

where

$$\Delta t_E = \sum_{n=1}^k \Delta t_{En}$$

3.6.2.3. Determining the Charging Set Nominal Current

Including a safety factor S , which mainly compensates for aging of the batteries and other imponderables which will always be present in a system concept, the charging current in steady-state condition can be determined by using the following formula:

$$I_L = S \frac{\Delta Q_E}{\Delta t_L}$$

where

$$\Delta t_L = \sum_{m=1} \Delta t_{Lm}$$

3.6.2.4. Determining Nominal Capacity

Experience has shown that this subject causes the most discussions. What needs to be considered in determining nominal capacity?

1. *Load rating specific to the system.* The different load rating of the various battery systems has been given in approximation in [Table 3.1](#) for three-shift operation. The hypothetical capacity must first be determined with the aid of the permissible discharge current. This is subsequently checked using the permissible charge current. Not only the permissible effective values, but also the peak values must be observed.

2. *Dependence on temperature.* This must be considered if the temperature probably to be reached by the electrolyte is to lie clearly below the nominal temperature specific to the system. The capacity chosen should then be corrected on the basis of

$$Q_N = k \, Q_N$$

k corresponds to a correction factor including the temperature dependence of battery capacity as shown in Figure 3.7a.

3. *The lower voltage limit.* Voltage should not be allowed to fall below the minimum of U_{Bmin} at any time during the interval between applications discussed here. In addition, attention must be paid to the dependence of discharge voltage on discharge current, discharge level, and of course electrolyte temperature, as shown in Figures 3.7b and 3.10. It goes without saying that the hypothetical value must be

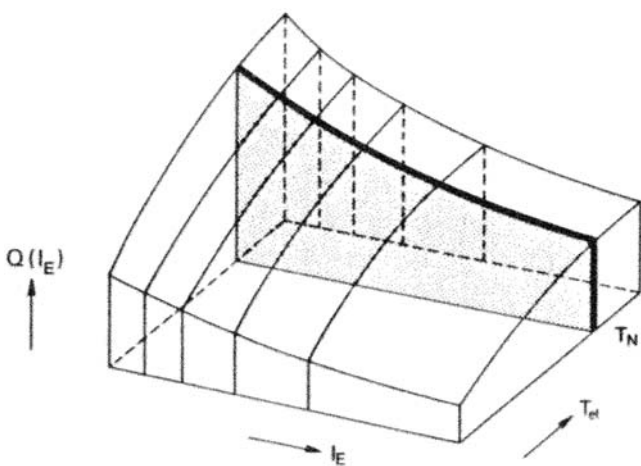


Figure 3.7a Temperature dependence of capacity: example of LAB with tubular plates.

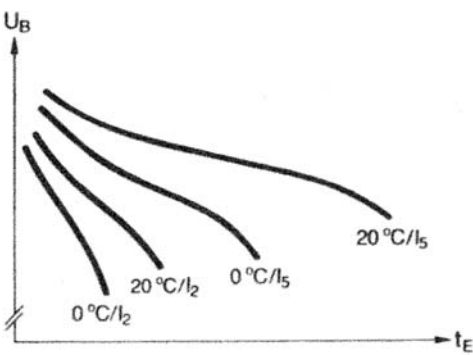


Figure 3.7b Temperature dependence of battery voltage: example of NCB with pocket plates at temperatures of 0 °C, 20 °C, and I_2 , I_5 .

greater than C_E calculated under 1. The typical values in cyclic operation lie between (a) $\Delta Q_E = 10\%Q_N$ depending on the battery system, length of cycle and element, and level of charging current and (b) $\Delta Q_E = 30\%C_N$. This will assure a high system reliability and service life.

Note: Service life refers here to a time interval in absolute time units (e.g. years).

3.6.3 Comparison of System

Assuming all battery systems to be possible, Figure 3.9 contains the result of a calculation on the basis of cyclic operation. Depending on the marginal conditions of their application, the example compares three possible systems. The tubular plate lead-acid battery exhibits by far the highest nominal capacity. The discharge range is then naturally lower (in relation to nominal capacity) than it is the case in the two nickel/cadmium batteries. All three variants in this hypothetical case are in the region of $U_B = 23.75$ V. The tubular plate LA battery has 12 cells, the pocket plate nickel/cadmium battery 20 cells, and the sintered nickel/cadmium battery 19 cells (Figure 3.8). The application corresponds to a two-shift operation.

3.7 CURRENT STATE OF CHARGING TECHNOLOGY

The charging sets in current use (milkers) are almost exclusively based on the known IU curve, with elements of the characteristic curve specific to the installation attached. Uncontrolled processes of charging are becoming rarer, and are mostly only used in smaller installations with purely capacitive use of batteries. The charging sets are predominantly of stationary design. Plans for producing on-board charging sets have so far remained the exception.

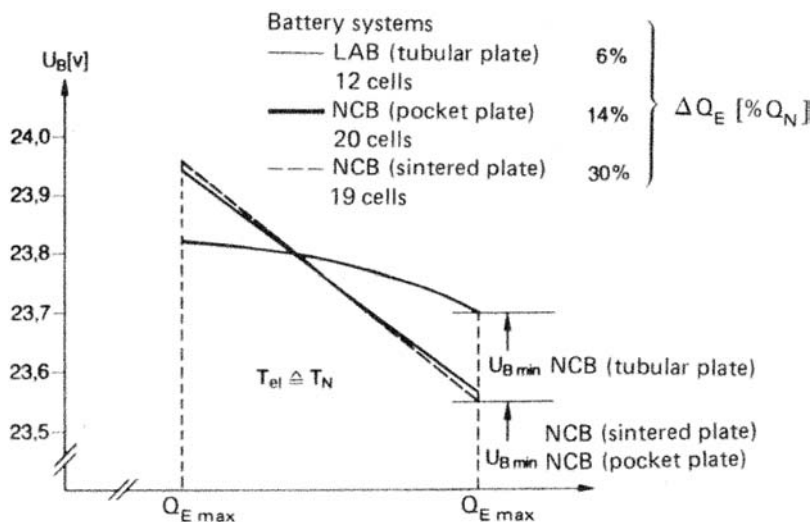


Figure 3.8 Voltage curves for different battery systems: example of cyclic operation/two-shift operation. (Depiction belongs to example for dimensioning.)

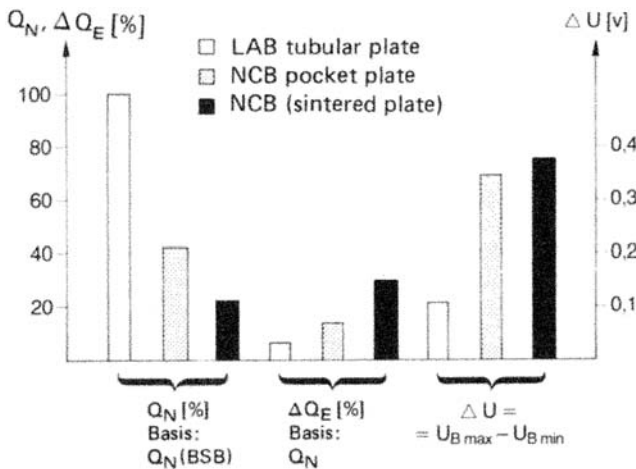


Figure 3.9 Comparison of system data for example of cyclic operation/shift application.

3.7.1 Methods of Control/Exchange of Information

Charging sets are generally actuated directly by the driverless industrial truck or by the sequence control system, i.e. they carry out instructions prompted by external control signals and at the same time supply information on the current state of charging (status signals).

The following functions have emerged as standard:

- Readiness on/off.
- Charging on/off.
- Include/exclude characteristic elements.

Execution of these functions can, for example, be initiated by jumps in potential ($OV \rightarrow U_S \rightarrow OV$).

Such digital status signals include

- Charging active.
- Current flow at high charging level OK.
- Characteristic curve identification.
- Collective fault warning (analysis of the type of fault is normally made by maintenance personnel) are supplied by the charging gear, e.g. indirectly by way of floating contacts.

3.7.2 Practical Example

Figure 3.10 depicts a basic method of charging which can in principle be used for all battery systems mentioned here and which permits both boost charges and full charges. The controller limit values I_{G1} = equipment nominal current, I_{G3} = recharge-recharging current; U_{G1} and U_{G2} should first be set, depending on the specific battery system I_{G1} and U_{G1} , together with I_{G2} , should also be treated as being independent of the actual installation. In certain circumstances, U_{G1} must be

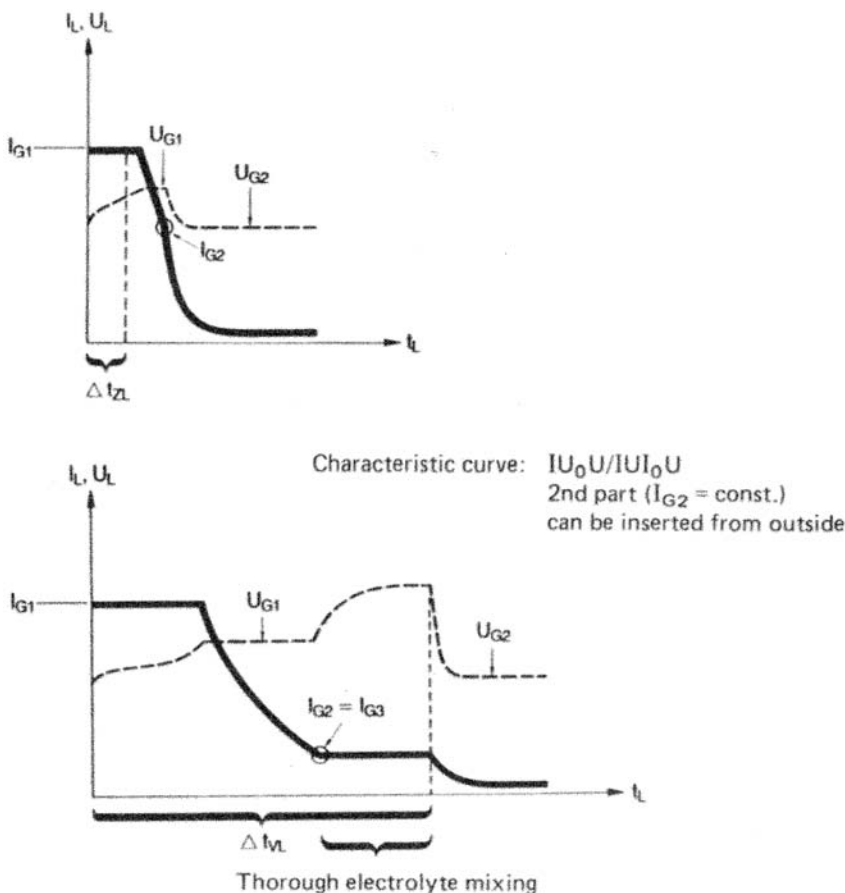


Figure 3.10 Basic charging process, suitable for boost/full charging of various battery systems.

corrected when starting up an installation, as the voltage losses during the high charging phase, especially at the contact points, are rarely known accurately. The level of I_{G1} is known to influence charging efficiency, and thus the balance of capacity in the first section of the charge curve ($I_{G1} = \text{const.}$). $t_{ZL\text{max}}$ should theoretically be at the end of the first section of the curve, as the charging energy supplied until this point would have been converted practically without loss into useful capacity. The curves in Figure 3.10 must naturally be seen as being dependent on temperature and aging, and the safety factor (S) introduced in the preceding section is thus justified.

3.8 SUMMARY AND OUTLOOK

The power storage unit on board a driverless industrial truck makes possible the required high level of mobility and even uninterrupted operation when combined

with a concept of charging adapted to application. Highly efficient, well-proven battery systems with long service lives have been in existence for a long time. Thousands of driverless industrial trucks are currently running on such systems, thus proving the reliability of correctly dimensioned power supply concepts. There is no competitive relationship between the different battery systems, when it is considered that each system has its technical logical and economical field of application. It is thus only possible to assess a particular system in conjunction with the conditions under which it is employed. The tubular plate lead-acid battery occupies a leading position for good reasons, particularly as single cells of the smallest design have since become available on the market.

The intelligence of driverless industrial trucks will increase. Further development aims are on the one hand at traveling without a guide wire, and on the other hand at taking over the function of battery monitoring. Figure 3.11 depicts how a charge/discharge monitoring system might be integrated into a driverless industrial truck. The monitoring software would receive information on the battery at any time by way of a suitable sensor system, and would rely on fundamental battery-oriented knowledge stored in a memory for evaluating this information. Temperature and load dependence could be recalled by a set of formula and control folders specific to the system, thus saving space. The first steps have already been taken in this direction. With the aid of this higher intelligence (with an understanding of the battery), it would be possible for future driverless industrial trucks to handle power storage units even more economically and to provide even clearer proof of the reliability of this power concept.

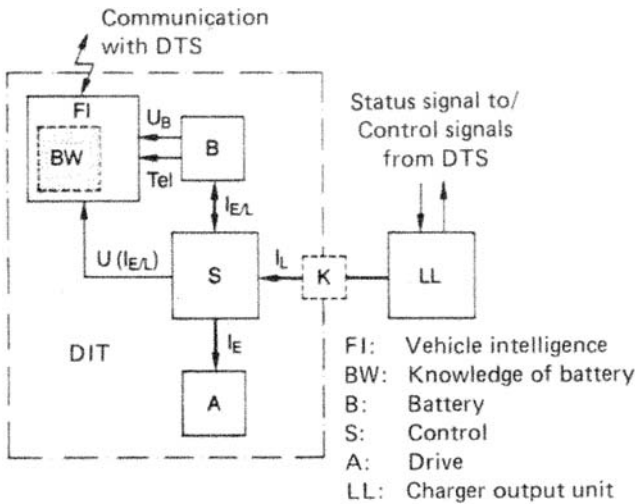


Figure 3.11 Battery monitoring by own DIT intelligence; depiction only takes into consideration information exchange between vehicle or DIT and power supply unit.