1.7 Charging Methods

In brief, charging is the process of supplying direct current to the battery so as to convert it back into a chemical state at high energy level, capable of delivering electric power.
There are a variety of charging methods which can be used to charge sealed lead-acid batteries. From the view point of controlling the charging process, these methods can be classified into some basic categories: **constant-voltage, constant-current, tapered-current** and **combination charge systems.** (There are some other special methods used to control the charge by detecting internal pressure or battery temperature.)
The above types (with the exception of the special methods) are discussed here: 〔a summary chart appears in **section 1.6.1**〕

1.7.1 Constant Current Charging

Constant current charging is one of the most well-known methods.
The advantage of constant current charging is the ease of determining the amount of capacity (amp hrs) supplied during charging; and there is no need for temperature compensation which is required in constant voltage systems.
On the other hand, the required charging time should be strictly adhered to, especially at high currents, which provides a full charge in a short period. On high-rate charge, the battery voltage rises excessively and the water decomposes, accompanying heat generation at the final stage of charge. This can damage a battery.
The constant current method, however, may be satisfactory when the charge rate can be kept at a relatively low rate and charging time is not critical.
Because of self-discharge, batteries require a refreshing charge from time to time during storage. A constant current charge may be used as a refreshing charge when many batteries are charged at one time, as this method will easily determine the amount of charge returned to the battery. **Batteries, which have been left on the shelf under the same known condition, shall be recharged approximately 120 percent of the lost capacity (Ah), as estimated from the data shown in Fig 7.**
If storage conditions such as temperature and time are known, but different for each battery, the charging amount shall be based on the worst storage condition or the largest lost capacity. For longest life, it is not recommended to repeatedly use constant current charging for refreshing the batteries.
It is also important to minimize the need to repeat the refreshing charge, by always keeping the batteries under a well-controlled stock rotation plan. ***Storing at lower temperature is the key to battery shelf life. If stored at a high temperature, batteries will require frequent refreshing charges.***

1.7.2 Constant Voltage Charging

It is very often necessary to restore batteries to a fully charged condition in as short a time period as practical. In doing this, much care must be exercised not to exceed specified charge rates or charge voltages as the battery is approaching a fully charged condition.
A constant voltage charger can accomplish this type of charging. Ideally such a charger should have very stable output voltage and high current capacity, as extremely large currents are allowed to flow at the initial stage of charge, where the battery voltage is low. This type of charger, however, is not practical because the requirement of a high current capacity or a negligible small impedance for the power transformer, results in high cost and a large and heavy charger. Undesirable heat generation inside the battery cells, caused by initial high current, should also be taken into consideration.
In general, a commonly utilized constant voltage charger has a device to limit initial current. This current limitation can be accomplished by a constant-current regulator, a properly designed output voltage from the power transformer, or by designing the overall impedance of the circuit (for example by using a current regulating resistor). A constant voltage charger will perform effectively for charging in a short time, as during the final stage of charge the current automatically decreases, and the water decomposition will be minimized.

1.7.3 Tapered Current Charging

This is a simple and relatively inexpensive method. The circuit requires a power transformer, rectifiers and a suitable resistance for limiting current. In this system, the charging current drops gradually as the charging proceeds. If the impedance of the circuit is low, a step current slope can be obtained. This type for charge is generally considered to be unsuitable for charging sealed lead-acid batteries because the charging current will vary with fluctuation of line voltage as well as changes in battery voltage.
These effects, however, can be minimized by using a power transformer with a secondary voltage which is considerably higher than the battery voltage and a suitably high resistance in the circuit for current limiting. This type of charger will perform similar to a constant current charger, and can be utilized instead of a constant current charger for industrial uses; not only for recharging many batteries at one time, but also as a trickle charging system.

1.7.4 Combination Charging (Two-step)

A combination charging employs two types of charging. It's called a "Two-rate" or "Two-step" charging. A variety of couples can be made, such as constant-current/constant current, constant-voltage/constant-current and so on. In general the first step uses a quick or fast charge mode, and the second uses a low charge current. The switching from the first step to the second can be carried out by many different methods; battery voltage sensing, a time control, charge current sensing etc. **Some of these typical charging patterns are shown in Figure 12.**

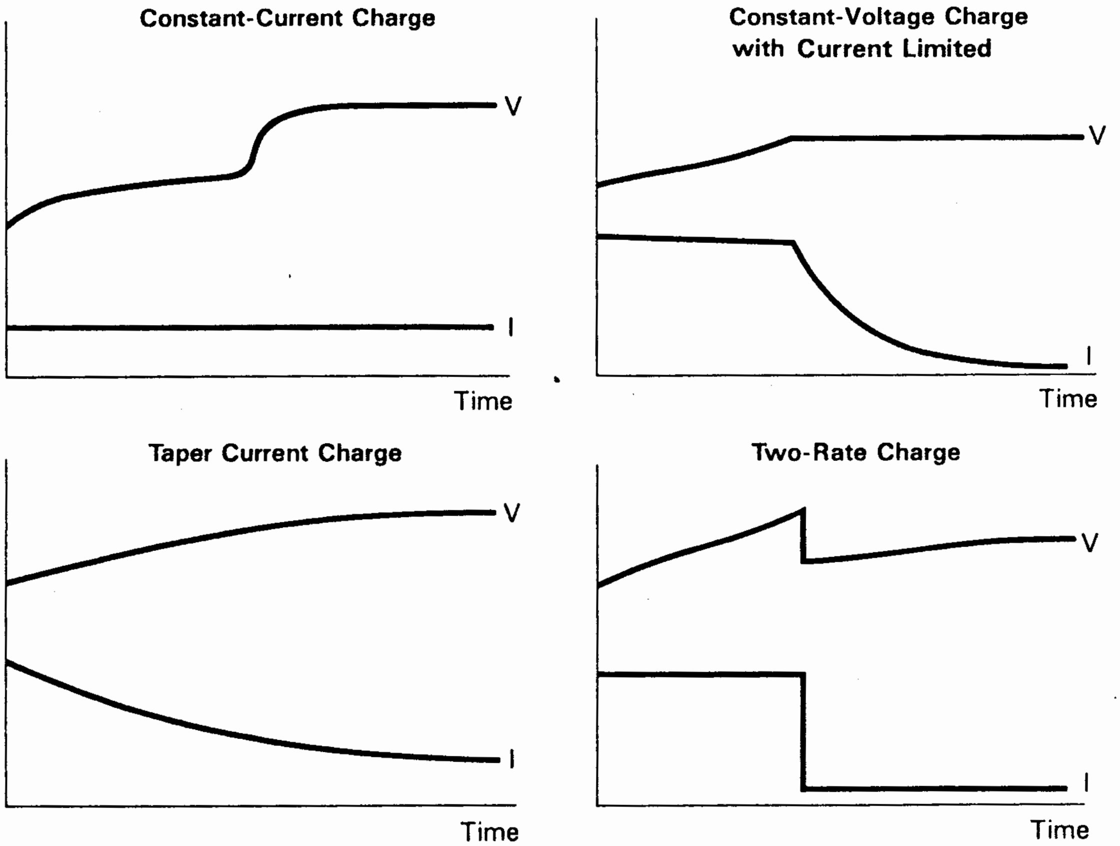


Figure 12
Typical Charging Patterns

1.7.5 Charging Application Notes

All of the charging methods discussed above are commonly used with satisfactory results. Applications of sealed lead-acid batteries can be classified roughly into two types; cyclic operation and standby service, and must be charged accordingly.

1.7.5.1 Cyclic Operation

Cyclic applications generally require a short time charge and protection against excessive charges and discharges, because the battery may be operated under unfavorable conditions by inexperienced users.
The most important requirements in a constant voltage charge technique are to hold the output voltage at the specified level at the final stage of charge, and to suppress the initial current below the designated maximum value as follows;

Constant Voltage Charge:
Initial current: 0.4 C* or less
Regulated voltage: 7.3 to 7.5V/per 6V battery
(Note) * C means the nominal capacity.
The regulated voltages are at a temperature of 68°F (20°C)

For a 12V- or a 24V-battery, the regulated voltage (above) shall be multiplied by 2 or respectively.
If the battery will be charged in a wide range of

ambients, **it is desirable for the charger to be temperature-compensated as shown in Figure 13.**

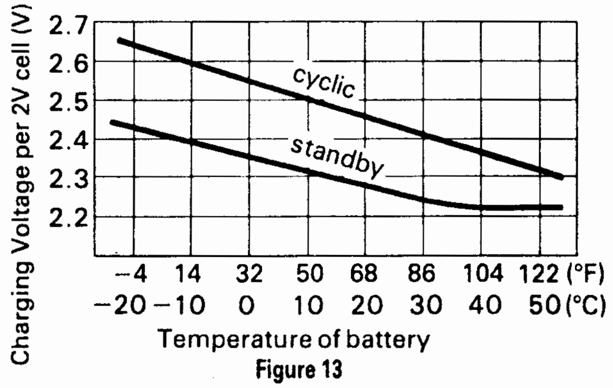


Figure 13

Recommended Temperature-Compensation for Voltage Regulation at the End of Charge

Without temperature compensation, the charge might be excessive in a high ambient area, insufficient in a low ambient area, resulting in cycle life patterns as illustrated in Figure 14.

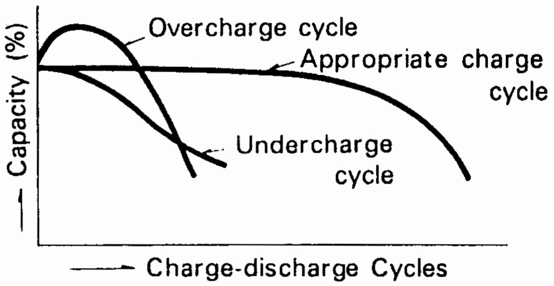


Figure 14

Cycle Life Patterns Resulting from Various Charging Conditions.

1.7.5.2 Standby/Backup Charging

LCR batteries (unless otherwise noted) can be utilized in standby applications, where they normally are kept in fully charged condition, and serve as a power supply to the load only when AC power fails. There are two modes of charging standby applications; trickle- and float-charge.

1.7.5.2.(a) Trickle Charge

This is a system in which AC power is normally supplied or operating the equipment, while charging the batteries which are not connected to the load. If AC power fails, a relay circuit connects the batteries to the load and battery power is supplied.

Trickle charging is generally considered to compensate for selfdischarge by continuously charging the battery at a low constant current to keep it fully charged. A constant voltage charge can accomplish this objective.

The appropriate current rate for trickle charge is **0.002C to 0.005C. (C/500 to C/200)**

In applications where AC power failure occurs infrequently, and the discharge is very small, the battery will be restored to a fully charged condition in short time, even at such a low current rate. In the case of deep discharges, this method will take an extremely long time to charge the battery. **A two-rate charger, or a constant voltage charger, is recommend for solving the problem, because of their initial quick charge modes. A two-rate charger has a distinct advantage, as there is no need for temperature-compensation.**

A constant voltage charger requires some precautions as follows:

(1) In these applications, the batteries are subjected to constant charging so long as a voltage difference exists between the battery and charger voltages. The charger voltage, therefore, must be stabilized in a narrow range during trickle charge.

(2) **When using the battery in a wide range of ambients, the charger should be temperature-compensated, as the charge characteristics will be greatly affected by the ambient temperature. (See Figure 13).**

Typical data for trickle charge application is shown in Figure 15.

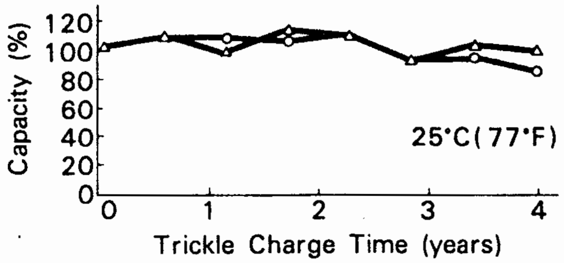


Figure 15 Trickle Charge Life

1.7.5.2.(b) Float Charge

This is a system in which the load and the battery are connected in parallel with the rectified power source.

This system requires only a constant voltage charger, in which the charge voltage is stabilized in a range of 6.8V to 6.9V per 6V battery, regardless of the power consumption by the load.

As the regulated voltage of a float charger is very close to the open circuit voltage of the battery, major fluctuations in the charge voltage may cause many small discharges of the battery while on float. In other words, the constant voltage charger should be designed for the maximum load, or the maximum load should be balanced within the stabilizing ability of the charger. Otherwise the life of the battery can not properly be estimated due to the irregular and complicated discharge patterns. In general, life in float service may be somewhat shorter than in trickle charge service.

1.7.5.3 Charger Design

1.7.5.3.(a) General Considerations

Battery life is affected not only by performance of the charger, but also by operating conditions. Charger, selection and design, therefore, must consider battery usage as well as charging characteristics. All charger designs use the same fundamental principles and require knowledge of the following basic parameters.

(1) the internal resistance of the batteries,
(2) the initial and final charge current and/or voltage value,
(3) the charges in battery voltage during the charging process,
(4) the required charging time,
(5) the effect of variable conditions such as ambient temperature and changes in voltage on the battery parameters,
(6) the maximum overall cost for the charger and batteries, and
(7) the expected battery life.

It should be noted that the resistances of lead wires and wire connections may be higher than the internal resistance of the battery.

1.7.5.3.(b) Unregulated Charger

This is one of the simplest chargers, and it is called a transformer type charger. This type of charger consists of a power transformer, diodes, and a resistive element for limiting current.

An elementary charging circuit is shown in **Figure 16** from which the following basic electrical relations are derived.

$$Edc = Eb + IR \qquad I = \frac{Edc - Eb}{R}$$

Where Edc is an impressed voltage from a direct current power source, Eb is battery voltage during charge, I is a charging current, and R is an overall impedance in the circuit (which consists of the internal battery resistance, rectifier dynamic resistance, current limiting resistance,and impedance of power transformer).

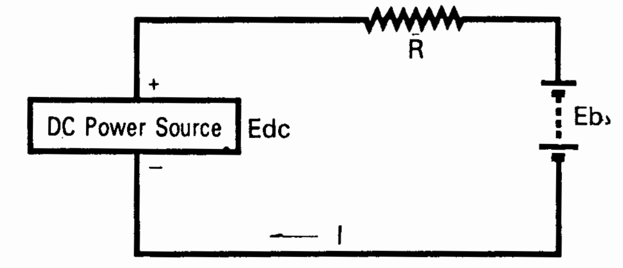


Figure 16
Elementary Charging Circuit

The DC voltage of the circuit decreases with increasing charge current due to the overall impedance. The V-I performance of the charger depends on the circuit resistance and the open the circuit voltage of the transformer. **Figure 17** shows three different V-I performances by chargers P-, Q- and R-. The circuits of P and Q have the same impedance, but different open circuit voltages. P- and R-circuits have the same open circuit voltage, but their impedances are different. The V-I relations of the battery at various states, from the discharged to the fully charged condition are also illustrated.

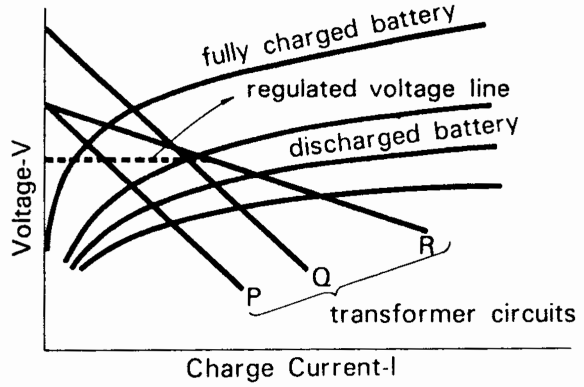


Figure 17
V-I Relations of Chargers and Battery at various states of charge

These three chargers having different V-I characteristics, will provide different charging performances as shown by solid lines in **Figure 18.**

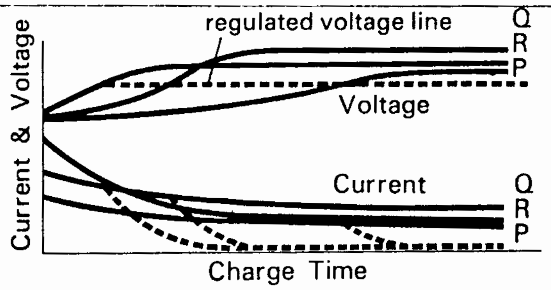
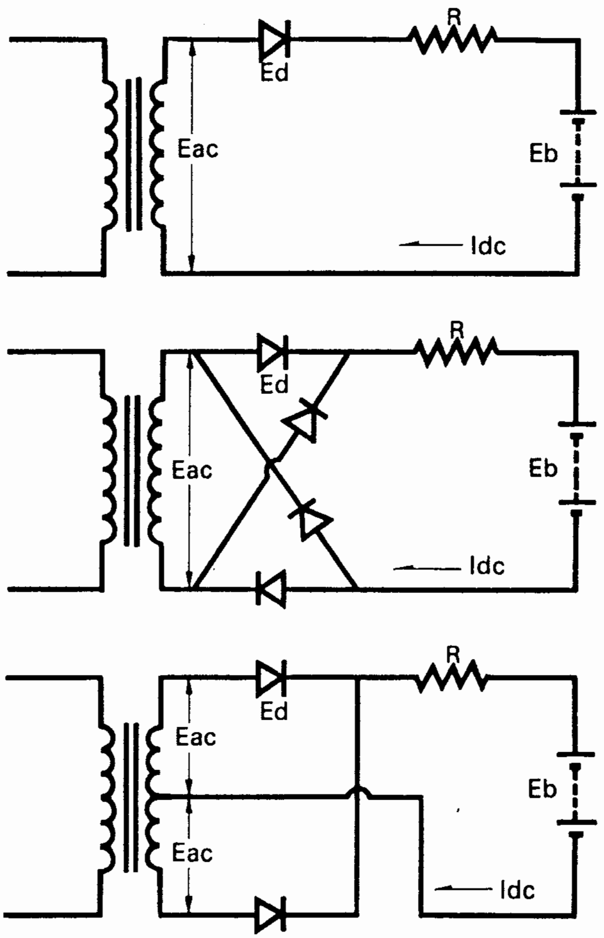


Figure 18
Charge Performances of P-, Q- and R- chargers having different V-I characteristics

The difference in V-I characteristics of the chargers results in different final steady state on charge voltages. However, if these circuits are connected to the batteries through a voltage regulating device, charge performance curves will reach the same final state. This constant voltage charger will be discussed in the next section. The single phase charging circuits and design equations are shown in **Figure 19.**



HALF-WAVE

$Eac = K_1 (Eb + Ed) + K_2 Idc \cdot R$

$Irms = K_3 \; Idc \sqrt{2}$

FULL-WAVE, BRIDGE

$Eac = K_1 (Eb + Ed) + \frac{K_2}{2} Idc \cdot R$

$Irms = K_3 \, Idc$

FULL-WAVE, CENTER TAP

$Eac = K_1 (Eb + Ed) + \frac{K_2}{2} Idc \cdot R$

$Irms = K_3 \, Idc$

Figure 19
Single Phase- Unregulated Charging Circuits and Design Equations

The symbols in **Figure 19** are as follows:

Eac = Open circuit rms source (secondary) voltage
Eb = Battery voltage during overcharge
Ed = Rectifier forward threshold voltage
Idc = Average overcharge current
R = Total circuit resistance
K_1 = DC voltage equation factor (taken from Figure 20)
K_2 = DC current equation factor (taken from Figure 20)
K_3 = Current form factor (taken from Figure 20)

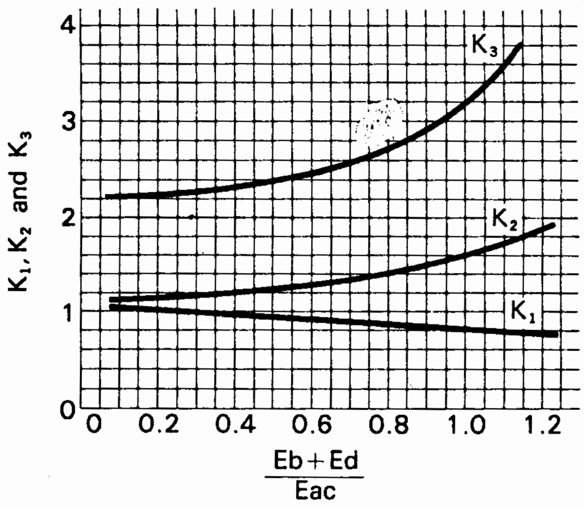


Figure 20
Design Equation Factors for Transformer Type Chargers

Charge currents at the 1-hour rate or less are commonly used in this type of charging system. Although the battery voltage during overcharge (Eb) varies with the charge rate and temperature, a value of 2.8 volts per cell is used with a satisfactory result for charger design calculations.

A smaller ratio of (Eb + Ed) to Eac requires higher resistance for current limiting, which results in higher power losses. However, this may minimize charge current changes with line voltage fluctuations. The ratio is commonly chosen to be between 0.4 and 0.7.

The rectifier voltage drop (Ed) depends on diode materials and circuit types, as shown in the following Table 2.

Table 2 Rectifier voltage drops (Ed)

Type of circuit	Materials Silicon
Half-wave	0.8V
Full-wave, Center tap	0.8V
Full-wave, Bridge	1.6V

Peak inverse voltage (PIV) applied to the diode is the sum of the AC peak voltage ($\sqrt{2}$ Eac) and the battery voltage (Eb) for half-wave and, full-wave bridge type rectifications, or $2\sqrt{2}$ Eac for full-wave center tap.

Half-wave rectification is more economical than full-wave, if the product of Irms and Eac is small. Otherwise it is advisable to shift to full-wave rectification.

1.7.5.3.(c) Constant Voltage Charger

A constant vorage charger is a system in which a voltage regulating device is put between the transformer circuit and the batteries, as shown in **Figure 21.**

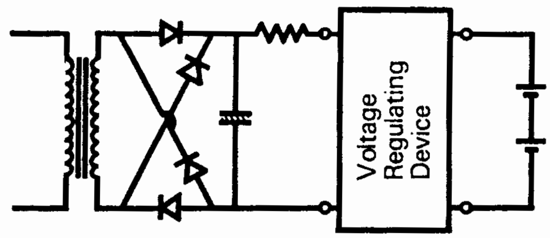


Figure 21
Charging Circuit with Voltage Regulation

The transformer circuit used in a constant voltage charger is generally required to have full-wave rectification, because of the relatively high DC current required.

The voltage regulating device includes a power transistor or thyristor to be connected in series with the batteries. Therefore, Ed in the design equations should include the voltage drop which a transistor or thyristor produces (0.8 or 1.1 volts, respectively).

Practical transformer design can be satisfied with the following rough calculation: the required rms secondary voltage of the transformer, supplying the desired initial current, is 3.5 to 4 volts in excess of the nominal voltage of the batteries. For example: to design a charger with an initial current of 1.0 ampere for a 12 volt battery, the transformer is required to have a secondary voltage of 15.5 (=12+3.5) volts when loaded at 1.0 ampere.

The voltage regulating device has a voltage detecting circuit which may allow a small current leakage from the batteries when AC line fails; and a diode for preventing reverse current flow may be put between the regulating device and the batteries, if necessary. In this case, however. the voltage drop caused by this diode should be included in the total diode voltage drop Ed. (It should be noted that the regulating device maintains a total potential equal to this diode plus the batteries, but does not apply a constant voltage to the batteries.)

In order to get a smooth current a filter capacitor is usually utilized. A big capacitance results in a large, well-smoothed current. But too big a capacitance may shorten life of the capacitor.

Characteristics of semi-conductors such as transistors diodes and Zener diodes, are all affected by temperature. Some have negative coefficients, and others positive ones. It is important to select semiconductors, and combine them, so that the voltage regulating device will have a temperature coefficient conforming to the battery characteristics.

SECTION V
METHODS OF CHARGING

FUNDAMENTAL PRINCIPLES

In order to recharge a storage battery after discharge, it is necessary to pass direct current through the cells in the proper direction (opposite to that of discharge) for a time sufficient to equal the ampere hours discharged, plus a small excess to make up for losses. This excess amount may vary from 5 to 20 per cent, depending upon the previous discharge, rate of discharge, age of battery, temperature, etc.

Proper charging simply means recharging sufficiently without excessive gassing, overcharging or overheating of the battery. In general, any charging rate is permissible which does not produce excessive gassing or a cell temperature exceeding 110°F (43°C).

CONDITIONS

The type of battery, service conditions, time available for charging, and the variation in battery voltages (number of cells) when charged in multiple, will determine which of the four following methods is best adapted to the solution of any particular problem. In charging lead acid batteries, the "finishing rate" of the charge is of the utmost importance and must not exceed the battery manufacturer's published values. Normally, lead acid batteries are recharged in eight hours based on normal discharged condition. However, batteries can be recharged over longer periods if time permits.

Before discussing various methods of charge, first review the volt-ampere characteristic of the lead acid battery during charge at various amounts of discharge. Figure 42 shows that a well discharged battery will absorb high charge rates at a relatively low battery voltage. It also shows that as the charge progresses, the voltage at end of charge is considerably greater than the voltage at the beginning of charge.

On this curve we have indicated ampere rates up to 40 per 100 ampere hour capacity. This means up to eight times finishing rate. This is a very high charge rate and is never used in normal charging but we have carried this curve to this high value to illustrate how much the voltage varies between rates at various percentages of charge. With modern charging equipment properly adjusted, the normal start charge rate to a completely discharged battery is in the area of 3-1/4 times finishing rate which usually is between 16.5 and 22.5 amperes on this curve.

Note the slight increase in voltage, even over this wide range of ampere rates between a 100% discharged battery and when 10% of the charge has been given to it.

An analysis of this curve will explain why, with modified constant voltage and taper charge, we have high charge

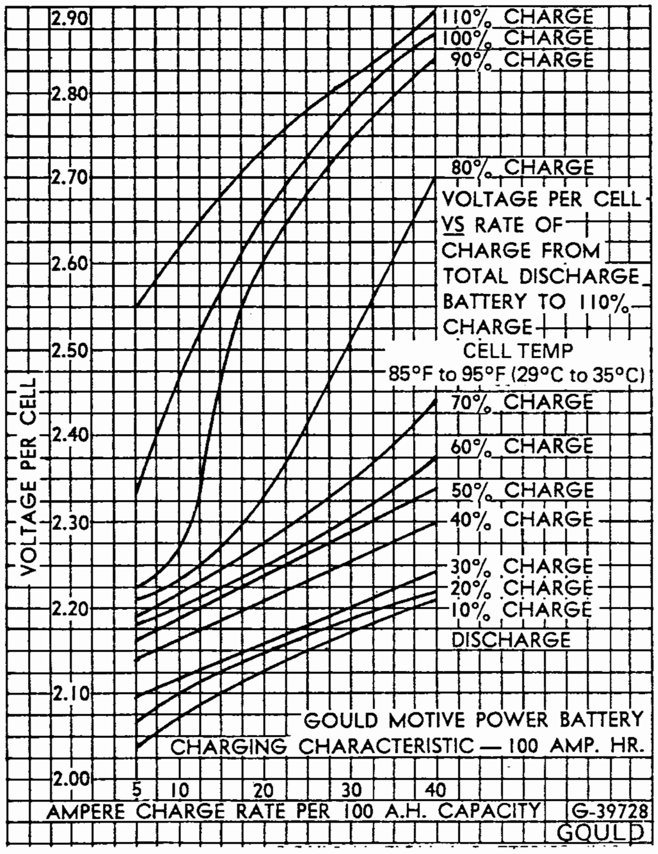


Figure 42. Charge Rate Characteristics

rates during the early part of a charge to a well-discharged battery and low end-of-charge rates when the battery is practically charged and yet no adjustment was made to the equipment during the charge.

This curve is not to be used for checking equipment. It is only for general information of battery volt-ampere characteristics.

METHODS OF CHARGING

MODIFIED CONSTANT POTENTIAL METHOD

In this method, the direct current voltage is maintained within a constant ± 3% of the rated voltage or 2.63 volts per each cell of the battery if an 8 hour recharge is required.

Figure 43 illustrates the relationship of volts per cell versus available time for recharge. Note for an 8 hour charge, 2.63 volts per cell is required of the power source; while for a 16 hour recharge, 3.27 volts per cell would be required. By the same comparison, on an 8 hour recharge 22-1/2 copy under figure 43 to be set smaller

(1) Hours Available for Recharge	(2) Bus Volts per Cell	(3) Resistance Values Per Cell: Normal "Tap"	(4) Resistance Values Per Cell: Max. to Provide	(5) Ampere Rates Per 100 A. H.: Start of Charge	(6) Ampere Rates Per 100 A. H.: Resistor Capacity
7.0	2.60	0.016	0.027	27.5	32.5
7.5	2.61	0.018	0.029	25.5	30.0
8.0	2.63	0.022	0.031	22.5	26.0
8.5	2.65	0.026	0.035	20.0	23.0
9.0	2.67	0.030	0.039	18.5	21.0
9.5	2.69	0.034	0.043	17.0	19.5
10.0	2.72	0.040	0.049	15.5	17.5
12.0	2.84	0.064	0.073	12.0	13.5
14.0	3.00	0.096	0.105	10.0	11.0
16.0	3.27	0.150	0.160	8.5	9.0

Design constants based on 100 ampere hour cell capacity. For cells of other capacity, external resistance per cell will be inversely proportional and ampere values directly proportional to the capacity. Cell resistance values correspond to electrolyte temperature 77°F (25°C).

Figure 43. Modified Constant Voltage Charging Design Constants

amperes per hundred ampere hours at start of charge is required; where the 16 hour recharge requires only 8.5 amperes per hundred ampere hours. The modified constant potential method of charge is illustrated in figure 44. Note in figure 43 that a charging resistor of sufficient current carrying capacity and resistive value may be selected to provide the proper start and finish rates of the battery.

The charging current, when using this method, will automatically be reduced as the charge progresses, to the ultimate finish rate of the battery.

When charging batteries in multiple from either a constant voltage source derived from a motor generator or rectifier, the modified constant potential method of charge is most acceptable, since the charge current inherently tapers during the charge, reducing the possibilities of severe overcharge.

The primary disadvantage of this method of charge is the loss in watts created by the necessity of ballast resistance. Furthermore, hot batteries will be charged excessively because the battery voltage will be depressed as the battery temperature increases which prevents the normal tapering of the charge current.

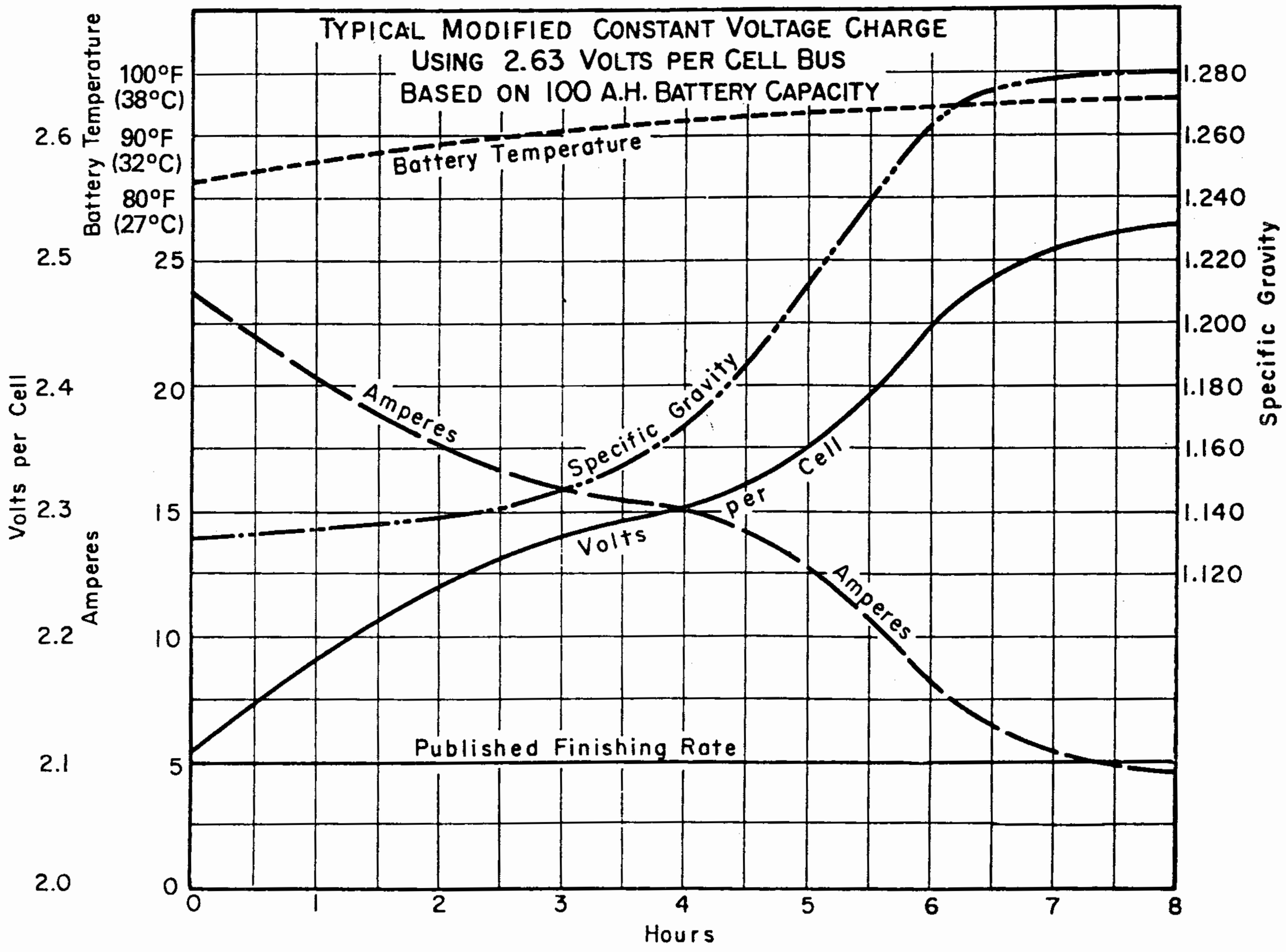


Figure 44. Typical Modified Constant Voltage Charge

To calculate the kilowatt requirements for motor generators to charge batteries in multiple from a fixed voltage bus in 8 hours would be as follows:

$$KW = \frac{A.H. \times 0.225 \times \text{no. cells} \times 2.63 \times 0.8 \times \text{no. circuits}}{1000}$$

Example: To charge four (4) 18 cell 500 ampere hour batteries:

$$\frac{500 \times 0.225 \times 18 \times 2.63 \times 0.8 \times 4}{1000} = 17\ KW$$

In figure 44 note the relationship of charge amperes to volts per cell. At the start of charge, we have approximately 22-1/2 amperes per hundred ampere hours at 2.135 volts per cell. At the end of charge, we have 5 amperes per hundred ampere hours and 2.52 volts per cell. These curves are typical of a modified constant potential method of charge.

TAPER METHOD

This method can apply to either generator or rectifier type equipment and can be considered a variation of the modified constant potential method of charge. It is employed only where one battery of a certain type and number of cells is to be charged. There are shunt wound motor generators so designed that their volt-ampere characteristics correspond to the modified constant potential type charge.

This is also true in the case of the controlled rectifier where the volt-ampere characteristic of the rectifier is designed to recharge the battery safely in a manner similar to the drooping voltage method of motor generators. In either case, no resistance is placed in series with the battery and the generator or rectifier is designed to provide the correct charge rate for the battery. Start of charge rates for lead acid batteries should be approximately four to five times the finish rate specified by the battery manufacturer. The rate in amperes will depend on the type of cell and the number of plates in the battery. The taper method of charge is not suitable for charging several batteries in parallel.

In order to meet the requirements of charging a single battery from a motor generator set, the following design perameters must be met:

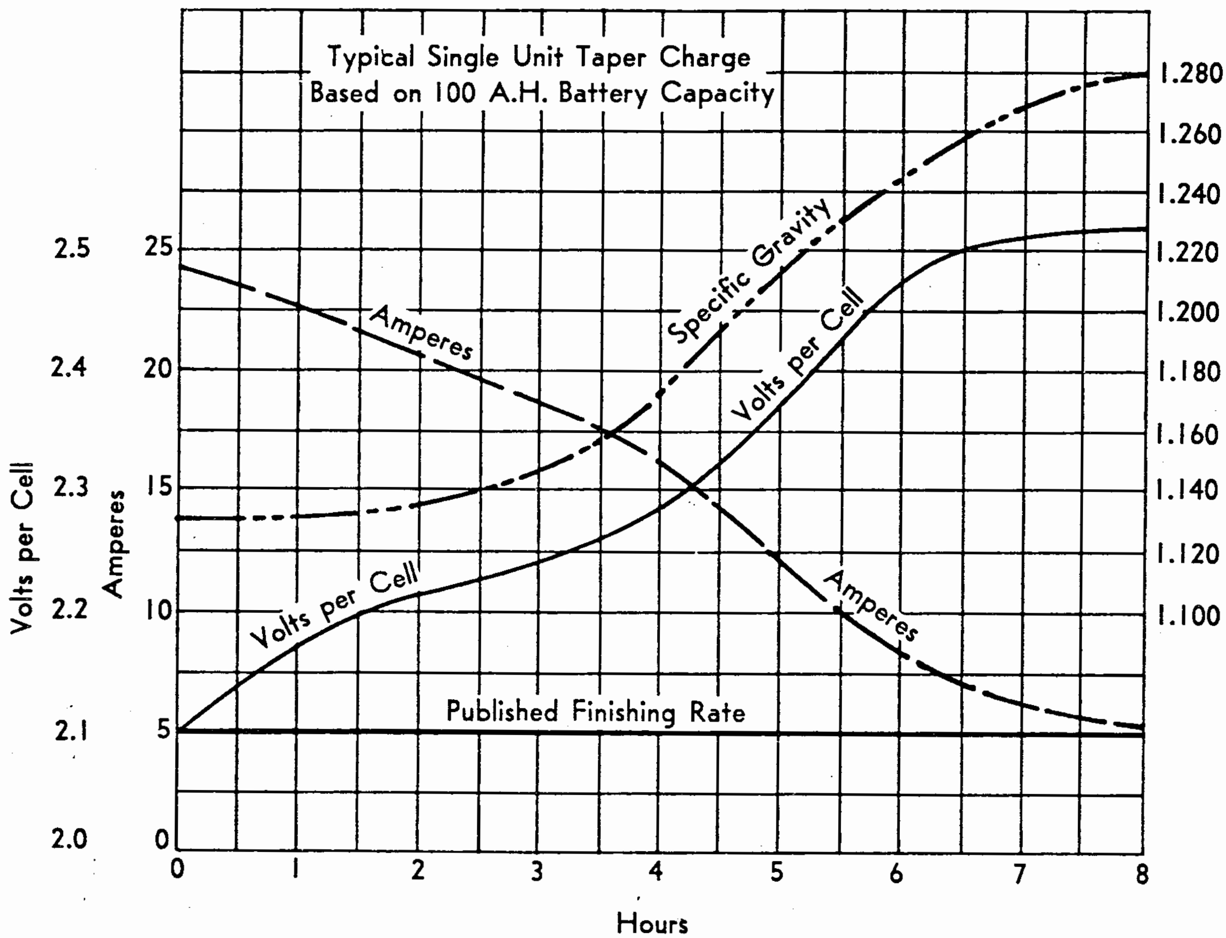


Figure 45. Typical Single Unit Taper Charge

The nominal voltage of the generator should be approximately 2.25 volts per cell. The generator should be so designed that at the start of charge, the generator voltage should droop to about 2.135 volts per cell. As the charge progresses, the voltage should rise in proportion to the increase of counter e. m. f. voltage of the battery being charged. At the end of 8 hours, the charging current should be approximately 5 amperes per hundred ampere hours and the voltage of the generator should rise to 2.52 volts per cell.

Figure 45 illustrates a charging curve produced by a single circuit motor generator having inherent taper characteristics.

TWO-RATE METHOD

Where the charging voltage available equals or exceeds 2.7 volts per cell, two-rate charging is necessary. Two definite resistor values are selected. One resistor is calculated, based on the output voltage of the power source, to provide the proper "start" of charge in amperes. The second resistor is selected with sufficient capacity in amperes and resistance, and is placed in series with the "start" resistor so that when it is switched into the circuit the two resistors will provide the proper "finish rate."

The "charge rate" (or when the charge rate resistor is incorporated into the circuit) will usually occur at the gassing point of the battery. Which is when the average cell voltage of the battery reaches 2.37 volts per cell.

Figure 46 illustrates the charge curve characteristic when utilizing the two-rate method of charge. Note that when the battery reaches the gassing point, there is a sharp decrease in charging current.

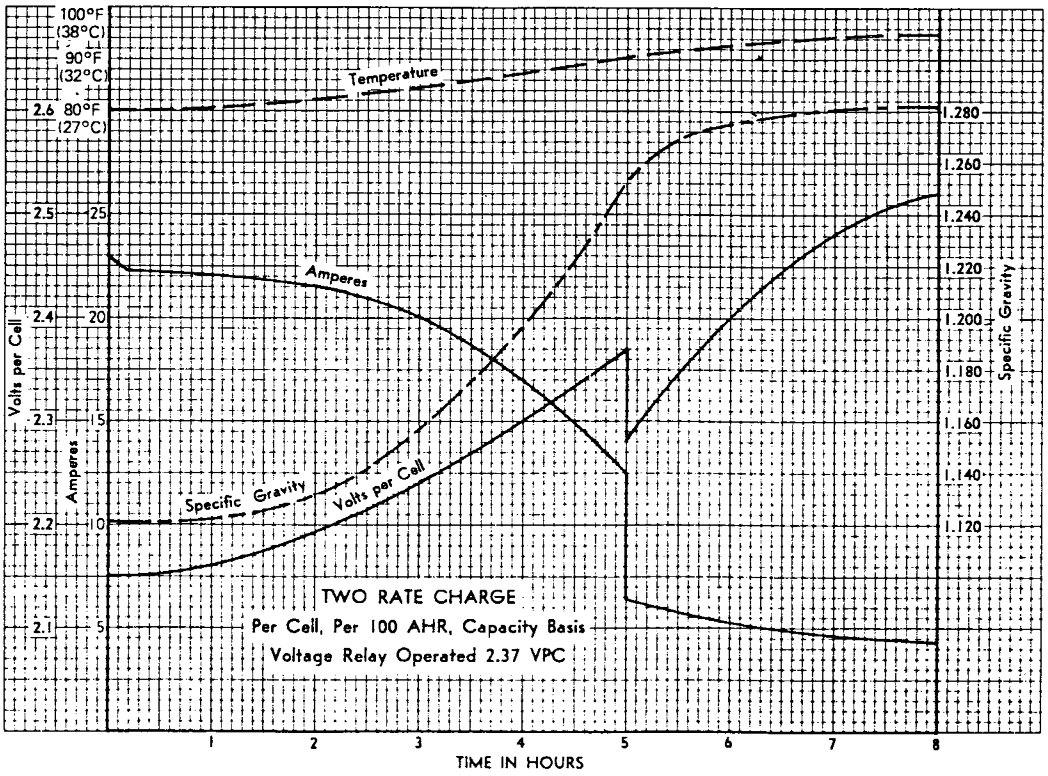


Figure 46. Two-Rate Charge

SOLID STATE CHARGE SYSTEM

"Solid State Charge System" implies a system which does not incorporate any mechanical means for the control of charger output current or voltage. Since the charging system depends on the battery back voltage which is sensed by the control unit (a solid state system), the sensing device is independent of any mechanical means. The mechanically operated chargers offer at best a two step function whereas the "Solid State Charge System" permits much finer regulation of the charger functions, as can be seen from figure 47.

Figure 47.

The solid state control provides a constant current for about 80% of the recharge and then changes to a constant voltage control mode so that only the necessary amount of charge is provided. A special feature of such system is the low trickle rate established when the battery has been fully charged. This does not only maintain the battery fully charged but also provides an equalizing charge for a battery over weekends without any extra effort of control necessary.

Since the solid state control provides for a constant current over 80% of the charge period required, it offers special savings in the peak power demand because a 36% lower charge rate for a given battery needs to be provided.

Typically a charge rate of 16.5A/100AH battery capacity is required for the solid state controlled charger, whereas most other systems require 22.5A/100AH starting rate.

A further benefit arises with the use of solid state controlled chargers; they are virtually maintenance free, since they contain no moving parts like fans, relays, mechanical timers, etc.

However, while all charge systems function well and prevent overcharging of batteries when the batteries being charged are healthy and at normal operating temperature, this is no longer true when defective cells occur, the battery ages, or operates at excessive temperatures.

For such reasons chargers are available, which incorporate a second completely independent control function, so that overcharging of other than perfect batteries is safely prevented. This independent control supervises the charge programme on a time basis and reduces the high charge rate at 80% of the charge period to the finish rate. At 100% of the charge, the rate is reduced to the trickle rate of approximately 1.5A/100AH which remains constant until the battery is disconnected.

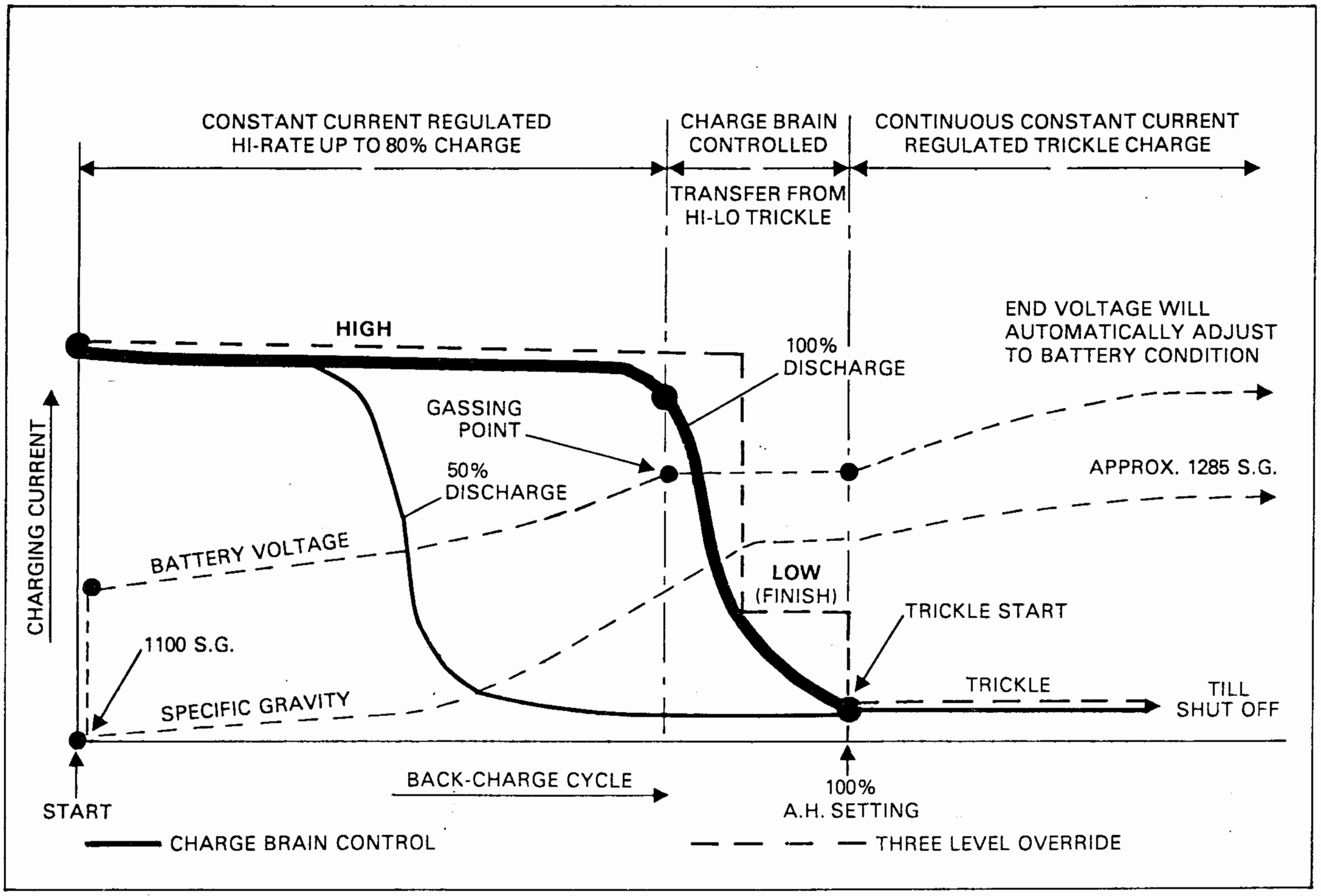


Figure 47. Solid State Charger Performance

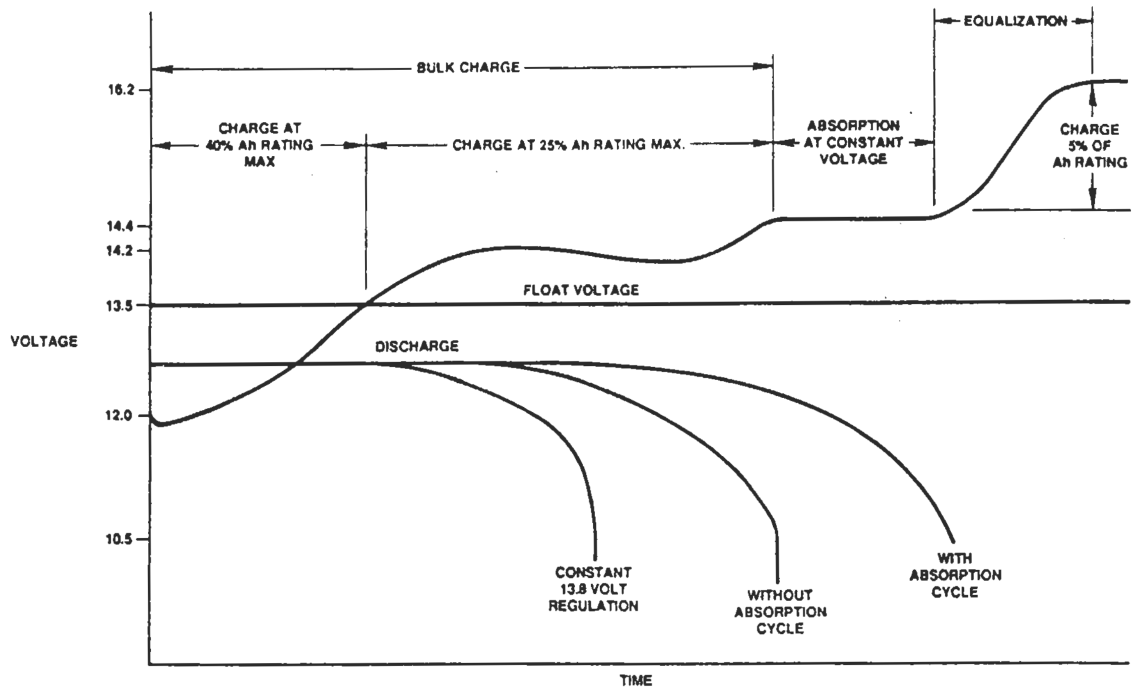


FIGURE 102. THE FOUR CHARGE CYCLES

Application Note 102: The Four Cycles required to Charge a Battery.

A performance charging system treats the battery to at least three distinct cycles. In technical parlance, the three are known as bulk charge, absorption, and float. For ultimate performance, a fourth, 'equalization' cycle should be applied periodically.

The four cycles are shown in Figure 102. As shown, bulk charge cycle covers initial charging until the battery voltage reaches the vigorous gassing point at about 14.4 Volts. The voltage should then be held constant at 14.4 until the charge current through the battery declines to about 5% of the Amp-Hour Rating of the battery. This portion of the cycle is called the absorption cycle.

Following the absorption cycle, the battery is usually placed on a maintenance 'float' voltage. This is a voltage high enough to keep the battery charged, but low enough to prevent continuous charge current. A typical float voltage falls in the range of 13.5 to 13.65 Volts.

Periodically, an equalization cycle should be applied to conventional liquid electrolyte batteries. The equalization process breaks up sulfate crystals which are a by-product of normal discharge. As shown in Figure 102, equalization starts where absorption leaves off. To properly equalize a battery, use a constant current equal to 5% of the Amp-Hour rating of the battery. Apply this current for 3 to 4 hours or until the battery voltage tops out at 16.2 Volts.

All the voltage values given are for liquid electrolyte, lead-acid batteries at 77 degrees Fahrenheit. Immobilized electrolyte batteries charge at different voltages, and do not require equalization. For a full description of proper charging and temperature correction, refer to our book 'Living on 12 Volts with Ample Power.'

Designing battery chargers

Difficult-to-find design curves and an inexpensive over-charging protection circuit

by Thomas Roddam

Have you ever seen a simple account of how to design a battery charger? It was with some surprise that I realised recently that I could not recall any description at all of the design characteristics of a transformer-rectifier system for pumping energy into a battery. Yet we are all using batteries nowadays. In my earliest days there was a simple procedure: you seized the leather strap, and headed for the local bicycle shop. Later there was the great array of cells in a battery room: two lots at 13 volts and two at 24 volts. Fred, in permanent attendance, living in a permanent sulphuric atmosphere, spent all his day charging and discharging 'his' batteries. Now we have float operation and if we are very rich, sensors for cell temperature, electrolyte specific gravity, the F.T. index, and a small computer to decide just what current to deliver.

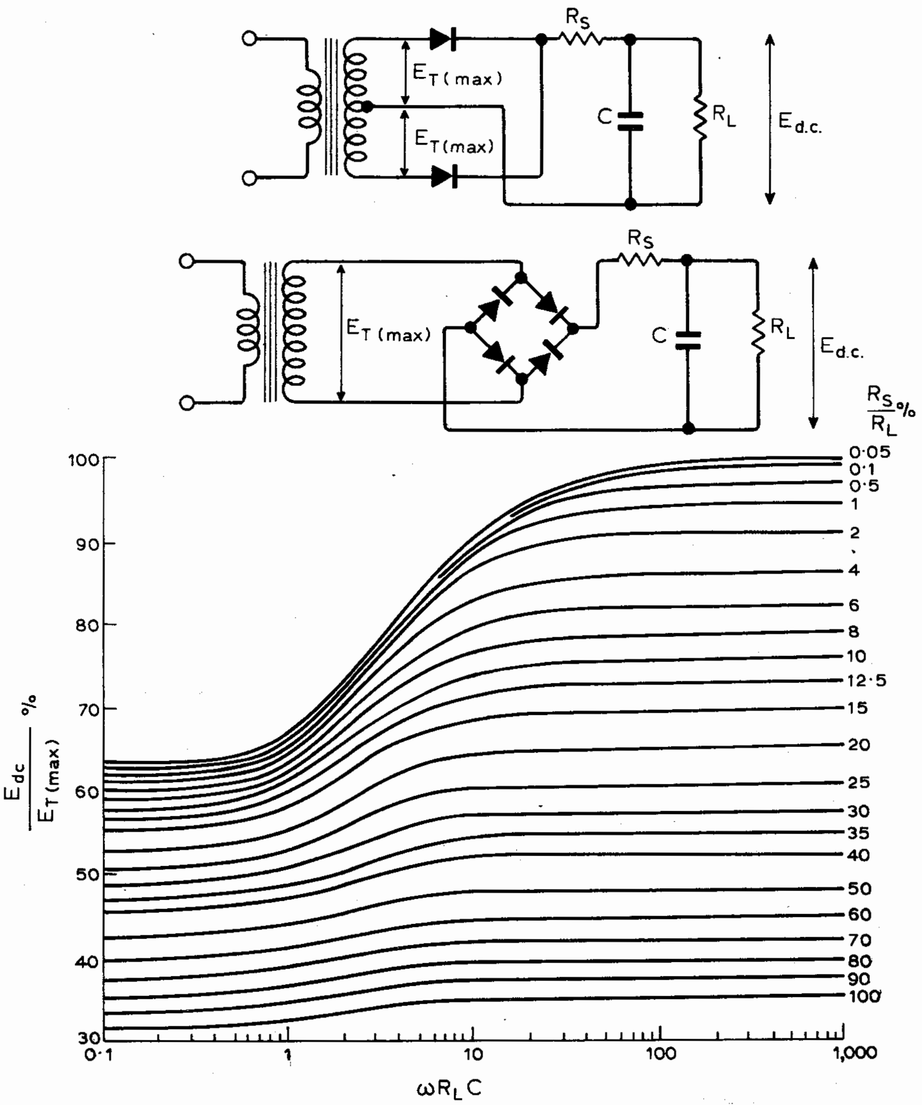
I just want to charge my batteries, though I may add a cut-off device. How do I choose the transformer and the rectifier. The essential conditions really boil down to the following. If the mains voltage is high, and the battery voltage is low we must not overheat the transformer or overload the rectifiers. I assume we are not in a mad panic to get the battery charged again, so that we are well below the safe charging current of the battery. If the mains voltage is low and the battery is not particularly low we want to go on feeding energy into the battery.

There is a G.E. application report which can be used to guide the designer, although I found, when I tried to use the equations provided, that I fell rather quickly into confusion. The alternative method which I have now adopted involves some guess and try, but does provide a very simple approach. The starting point is a very useful set of curves for the design of rectifier circuits with capacitor input filter which are out of print in the original publication and which are reproduced in Fig. 1.

To use these curves we consider what happens when we charge a battery. The charging current is, or so the meter says, a direct current, while the terminal voltage remains nearly constant. This is very much the behaviour of a parallel capacitance and resistance. The only difference is that instead of thinking of a load current we must now think of a charging current. The battery capacitance is very large, so that we can replot the ratio curves as a single graph for ωCR large, with simply output voltage as a function of the ratio of source resistance to load resistance. This is what we have in Fig. 2.

Let us assume that we are dealing with a nominal 24-volt battery, with 12 cells. The float level of this battery will in practice be 2.25 volts per cell, giving 27 volts. The reason for operating at 2.25 volts per cell is that this is the point at which we have the maximum energy storage combined with the longest possible life. When a battery has been used it is not uncommon to boost it up

Fig. 1. $E_{dc}/E_{T(max)}$ % as a function of $\omega R_L C$ for full-wave circuits. C in farads and R_L in ohms, $\omega = 2\pi f$.



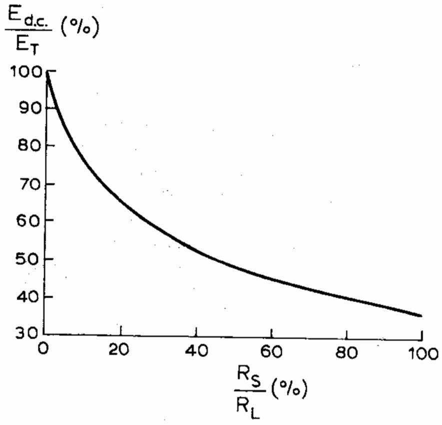


Fig. 2. Characteristics of full-wave rectifier for ωCR large, as is the case in battery charging.

to 2.6 to 2.7 volts per cell. I am not sure why, but it may be to make sure that all the cells are fully charged. This can bring us to a terrifying 32.4 volts, when lamps and transistors start to pop. Actually, the terminal voltage falls back once the charging current is cut.

Let us allow a meagre 1.2 volts drop in the rectifier bridge and our extreme condition corresponds to a direct voltage of 33.6. For the purpose of this analysis I shall assume that on a day when the mains input is 6% low it will take forever to reach 2.7V per cell. I shall therefore have $I_{load}=0$, so that $R_{load}\rightarrow\infty$ and $R_S/R_L=0$. For a peak voltage E_T of 33.6 we must have $E_{rms}=23.8$V. This, however, is for a low mains input, and the nominal value must be 6% higher, or 25.3V r.m.s. We have thus defined the turns ratio of the input transformer.

When the mains are 6% high we shall get $E_{rms}=26.8$V, and $E_T=37.8$V. Now we must subtract, say, 1.3V for the rectifiers, and we have an effective E_T of 36.5 volts.

It must be accepted that if you are sharing a battery, the other users will run it down to 1.8 volts per cell. When at last you can switch on the charger the terminal voltage will be only 21.6 volts. Sooner or later this condition coincides with the high mains input and we must consider the condition where $E_{dc}/E_T=21.6/36.5$, which is pretty close to 60%.

This max-min-max-min rate gives us our entry point to Fig. 2. We find that we must have a value of $R_S/R_L=27\%$. Let us say that to save money, not time, we have a nominal charge rate of 6 amps. For this current, and 24 volts, the value of R_L is 4 ohms. Immediately we see that we must make R_S 1 ohm. This includes the resistance of the transformer secondary and the primary resistance as seen at the secondary. Usually we can simply take twice the secondary winding resistance as a reasonable approximation. The transformer is, roughly, a 150W size, and will certainly not have 36 watts of copper loss: a physical resistor will be needed.

We do not know if this design is even roughly right, however. Let us go to design centre conditions. We shall then have a nominal 23.5V r.m.s., giving $E_T=33.2$, from which we take off 1.2V (the exact figure is chosen to get round numbers) to get $E_T(\max)=32$V. The battery voltage is assumed to be at the 2.25 volts per cell level, or 27V so that $E_{dc}/E_T=85\%$. Returning to Fig. 2, we find $R_S/R_L=4\%$, to that R_L must be about 25 ohms. At the float level, then, the charging current is only a little more than 1 amp. We probably need to change something. What has happened is that we have been overcautious with our boost condition, but I shall stick with this transformer for a moment longer.

I do not work with a simple float system, because it is really too noisy and although it does not affect the way my equipment works, it gives a fuzzy trace on the oscilloscope. Now a battery which is roughly 20 to 80% fully charged is operating fairly close to 2 volts per cell. Under these conditions, when the battery is being topped up at lunchtime, for example, $E_{dc}/E_T=24/32=75\%$. This means that $R_S/R_L=10\%$. If we take a desirable charging current as 4 amps, this will make $R_L=6$ ohms, and so $R_S=0.6$ ohms. My guess for the effective copper loss resistance of the transformer is 0.2 to 0.3 ohms. We then have the possibility of putting in an external resistor to give the extra 0.3 to 0.4 ohms, with an additional 0.4 ohms which is switched into circuit to limit the current under flat battery conditions. We could have changed the resistance to suit 2.25 volts per cell, but then we should have needed to check the 2.0V condition. However, let us see what happens at 2.25 volts per cell with 0.6 ohms. We have $R_S/R_L=4\%$, so that R_L must be 15 ohms. The charging current has fallen from 4 to 1.8 amps. At a rough guess, I should say this was about the right size of float unit for a system in which the load varied from, say, 1 to 3 amps.

It is quite easy to work out the charging current at various values of E_{dc}, an invented regulation characteristic for the charger. If the current is found to be excessive, a new value of R_S must be used, and we can choose to switch this into circuit. There are advantages in putting this resistance on the primary side. In our example the transformer will be roughly 10:1 for 240 volts working. It is much easier to find a 33-ohm resistor than a 0.33-ohm unit. At 6 amps the dissipation will be about 12 watts. An inductor, in the a.c. part of the circuit, can be used. A 1mH inductor will give 0.3 ohms effective impedance at 50Hz, and will reduce the amount of heat generated – at a price.

Rectifier circuits

A figure for rectifiers in the ordinary power supply is shown as Fig. 3. Again we just use the right-hand edge of this set of curves. We had a condition of 6 amps average with $R_S/R_L=27\%$, and 4 amps average with $R_S/R_L=10\%$. For use in Fig. 3 we need to take $R_S/2R_L$, because the rectifier is full-wave, and so we have either $(2.1\times6)/2$ or $(2.5\times4)/2$ as our criterion. It boils down to a rectifier r.m.s. current of 6 amps as our design figure. The reverse peak voltage follows the usual rule of being either E_T or $2E_T$ but everyone is conservative

Fig. 3. The ratio r.m.s. rectifier current/average current per rectifier plotted against $n\omega R_LC$. C in farads, R_L in ohms. n = 1 for half-wave, n = 2 for full-wave and n = 0.5 for voltage doubler.

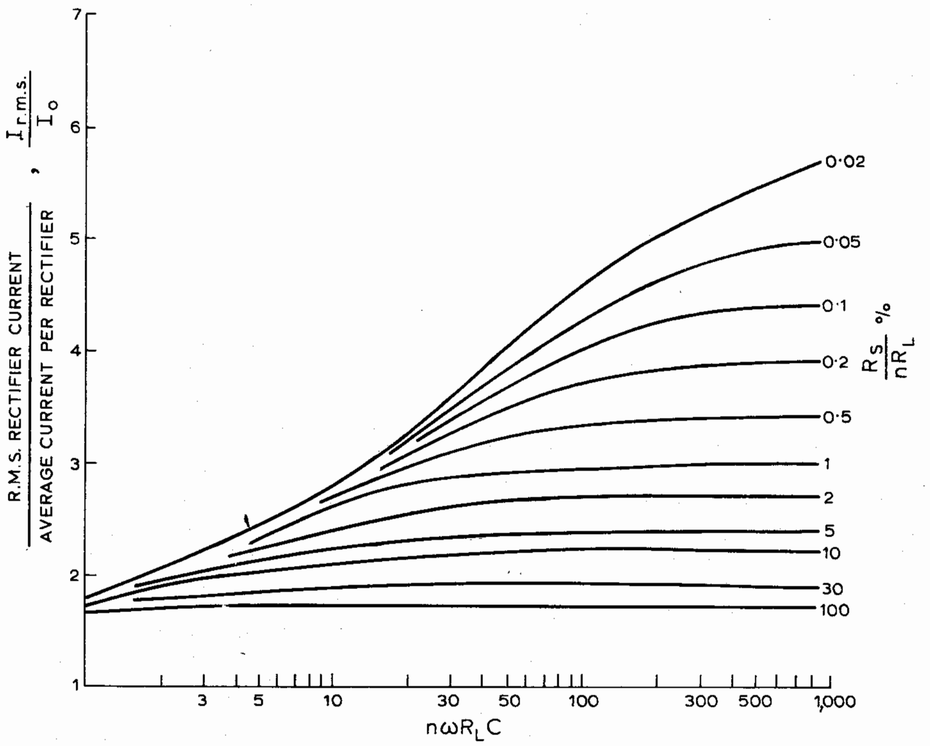
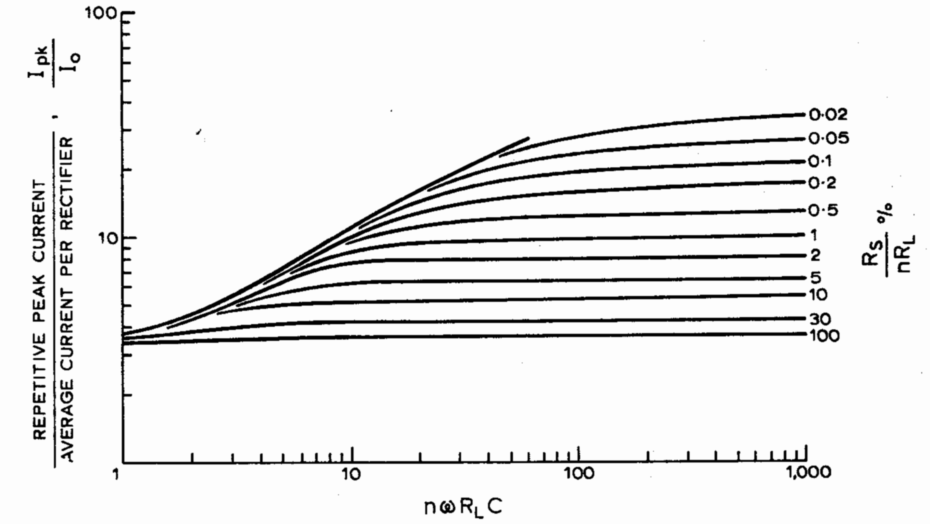


Fig. 4. The ratio repetitive peak current/average current per rectifier, plotted against $n\omega R_L C$. C in farads and R_L in ohms, $\omega = 2\pi f$ and f is line frequency. n = 1 for half-wave, n = 2 for full-wave and n = 0.5 for voltage-doubler.



when it comes to the choice of rectifier and step-down circuits are notoriously sensitive to mains spikes.

It is useful to check the rectifier peak circuit, using Fig. 4. There is no single inrush problem with a battery, as it is a charged capacitor when it starts. Under running conditions we shall get a ratio of I_{pk}/I_o of about 6.5 or a current of about 13A. The rectifier designer has usually taken this into account, but this figure enables us to guess an order of magnitude for the ripple voltage. A battery will have an internal resistance in the region of 10 milliohms, though it is not easy to get more than a rough number. But 10 milliohms will give 0.13 volts peak-to-peak ripple on the battery. It is a spiky ripple, as the peak-to-average current ratio indicates and is acoustically more of a nuisance than the numerical value indicates.

The use of half-wave rectification for battery charging was quite common at one time. Whether this was simply an economy measure in the days when copper was cheap and rectifiers were expensive, or whether it was the result of a mildly magical belief that the battery needed 15 milliseconds rest after a 5 millisecond current injection it is hard to know. Half-wave circuits have been used recently with thyristor controllers and it is useful to have on record the essential design curves, even if only to use them for their original purpose. Fig. 5 is the half-wave version of Fig. 1 and, as before, we can construct Fig. 6 to cover the very-large-capacitor or battery application. The regulation is seen to be even worse than the regulation of the full-wave system. The curves for the rectifier requirements are applicable to both modes of operation, so that we have a complete basis for the design of the half-wave system.

Information about the transformer, and all those odd factors which appear as utilisation factors, can be found in any reference book and in a good many rectifier catalogues. It is hardly necessary to repeat them here. One detail is worth mentioning, however, because it does sometimes get designers confused. If we use a half-wave rectifier we naturally have current flowing in the transformer secondary only for, say, the positive half-cycles. This means that a meter will show d.c. flowing through the winding. We all know that if you have d.c. in an iron-cored coil you will probably need to provide an air gap in the core. The unwary designer thinks of his transformer secondary as an inductor carrying d.c. and arrives at an unnecessarily large structure. The conditions in the core are set by the applied voltage: the flux density is the time integral of the voltage, with turns and area as factors, and the voltage is symmetrical. The use of half-wave rectification does not produce any flux offset under any normal operating conditions. The high I_{rms}/I_{dc} ratio makes the transformer pretty inefficient anyway, but there is no advantage in making it even worse.

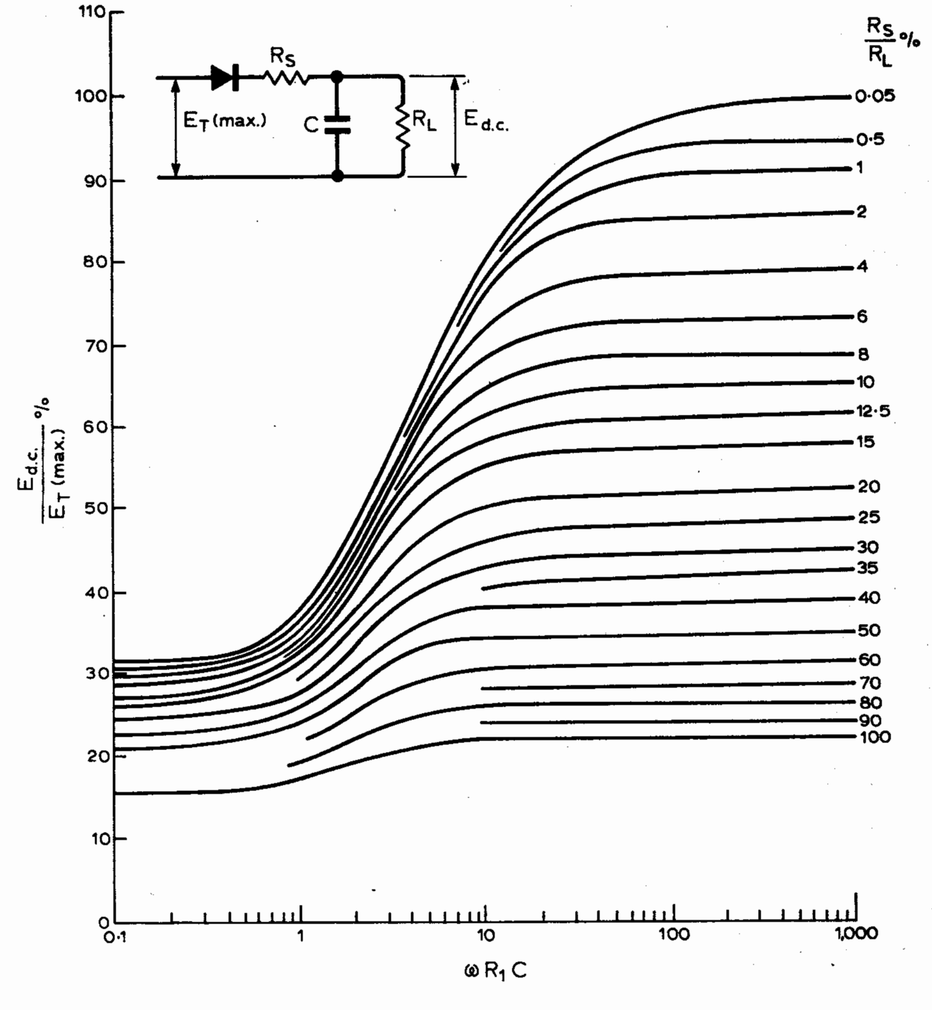


Fig. 5. $E_{dc}/E_{T(max)}$% as a function of $\omega R_L C$ for half-wave circuits. C in farads, and R_L in ohms, $\omega = 2\pi f$.

The full-wave rectifier circuit was designed as an example to show the use of the design curves and with the criterion that it should just haul the battery up to the 'boost' voltage, combined with a maximum current at the start of charge, we found that the charging current fell smartly as charging progressed. We should call this 'taper charging' if we wanted to sell a cheap charger with this performance, and would point out the essential safety of the drooping current characteristic. Some users, however, do not want to wait forever, to get a really full charge into the battery.

Examination of Fig. 2 shows that the curve is pretty close to

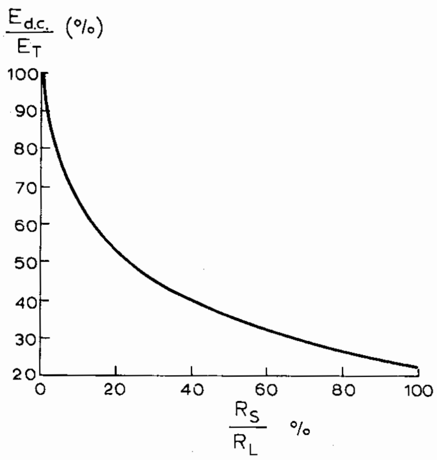


Fig. 6. Characteristics of half-wave rectifier for ωCR large.

$$\frac{E_{dc}}{E_T} = \frac{R_L}{R_L + 2R_S}.$$

Let us choose to have 6 amps charging at 21.6 volts, which makes R_L 3.6, and 4 amps charging at 27 volts, the normal float level, which makes R_L 6.7. We can then write

$$\frac{E_T}{21.6} = \frac{3.6 + 2R_S}{3.6}$$

and
$$\frac{E_T}{27} = \frac{6.7 + 2R_S}{6.7}.$$

It is a quick step to get $E_T = 37.2$ volts and R_S = 1.3 ohms.

We can, if we wish, construct a full regulation characteristic, but the resistor is now going to be rated at, in practical terms, 48 watts. This charger, left on indefinitely, will try to bring the battery up to just over 3 volts per cell.

Over-charging protection

It is not expensive to provide some protection against over-charging. The cost starts to rise if we write a very tight specification. At one time the method was to use a voltage-sensitive trip circuit, but it is probably cheaper to use solid-state switching, and we can make the system fully automatic. This means that it will be permanently connected to the battery. The disadvantage is battery noise, but in many applications the equipment must be designed to put up with this, anyway.

The circuit is shown in Fig. 7. Ignore D_2 and R_4, which are simply there to provide 50 to 100 mA trickle into a charged, idle battery, and possibly some lamps. The main charging path is through the thyristor Th_1. If Th_2 is not conducting, Th_1 will start to conduct as soon as point P rises enough above the battery voltage to get triggering current through R_1 and D_1. For a BTY79, which can be obtained easily, and which will carry the 6 amps of d.c., we might make R_1 100 ohms, and D_1 a small half-amp rectifier diode.

As soon as the voltage at P reaches about 3 to 4 volts above the battery voltage the thyristor triggers and current flows into the battery.

Now let us operate Th_2. The cathode of Th_1 is at not less than 21.6 volts, while P will peak up to 37.2 + 6%, say 40 volts under worst mains conditions. We can make $R_2 = R_1$, and the gate of Th_1 will only be 20 volts above the negative line, so that Th_1 will not trigger. The current through $R_1 + R_2$ will be, at its peak, 40/200, or 200 mA, which makes Th_2 a small device and R_1 and R_2 conveniently 3-watt resistors. A suitable cheap device (£0.50) for Th_2 is the BTX18, which needs up to 5mA to trigger it, and which may trigger at anything from 0.5 to 2 volts. The trigger current is provided by the capacitor, C, which is only needed to be, say, a 5-volt unit and can be 10 to 100μF. Resistor R_3 is needed to let C leak away, and 1000 ohms is as good a value as any.

The choice of P_1, the resistor in series with it, and the zener diode are pretty arbitrary. For a 24-volt battery it seems reasonable to choose a 10 or 12V zener diode. Value of P_1 is conveniently 1000 ohms, and the series resistor should be worked out so that the slider of the potentiometer is fairly near the top. Indeed, it is probably better to use a 500 or 200-ohm potentiometer and put resistors both above and below it, to limit the range of adjustment.

There are three phases of the control operation. If the battery is low, Th_1 fires but Th_2 does not. As the critical region is approached, after Th_1 has fired, the ripple voltage across the battery will be enough to tip Th_2 on, although as Th_1 has already fired this does not matter. When the battery voltage is high enough for the necessary few milliamps to be flowing through the zener diode, Th_2 will fire as soon as its anode volts permit. This is before Th_1 has reached the trigger point, and the firing of Th_2 cuts off the trigger supply to the gate of Th_1. Charging, except through D_2 and R_4, stops.

The circuit can be set up fairly quickly if a large capacitor and, say, a 6-ohm resistor are used in place of the battery. The low current through the zener diode and the range of values for the trigger conditions of Th_2 make it impossible to calculate the exact setting. In practice a unit of this kind will have a transition region of about half a volt, which is good enough for general applications. The use of an operational amplifier or comparator, in a control section of the style shown in Fig. 8, will give a very high precision, but such precision is meaningless when the ripple voltage is greater than the setting accuracy.

Perhaps the only justifiable improvement is to go the whole hog. The equipment is supplied from a stabilised power supply and the battery is merely a stand-by system. The problem we have considered is basically different from, and simpler than, this. The design curves are the necessary aids to its construction.

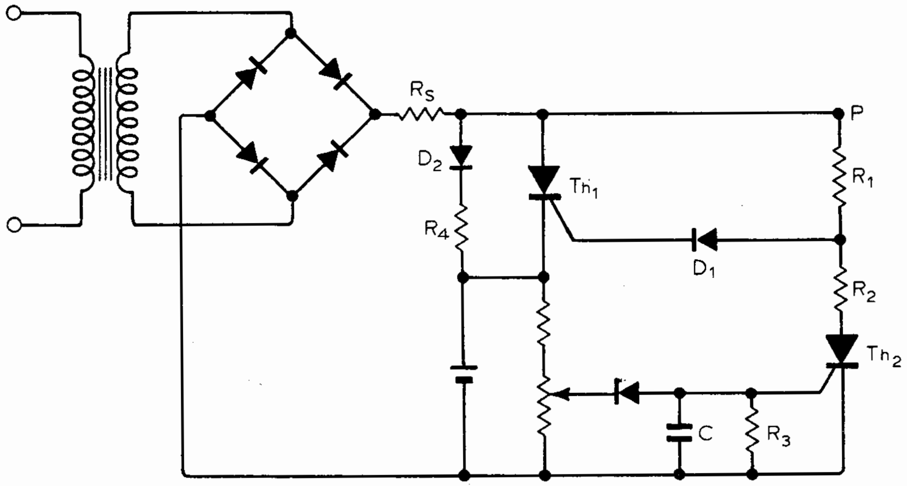


Fig. 7. Automatic charger control. Circuit can be simply set up by using a large capacitor and suitable resistor in place of battery.

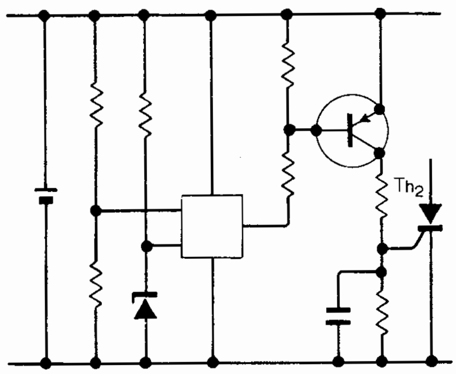


Fig. 8. Use of precision control section is only meaningful if ripple voltage is less than required setting accuracy.