A Guide To Lead-Acid Batteries

Structure and Operation

Most lead-acid batteries are constructed with the positive electrode (the anode) made from a lead-antimony alloy with lead (IV) oxide pressed into it, although batteries designed for maximum life use a lead-calcium alloy. The negative electrode (the cathode) is made from pure lead and both electrodes are immersed in sulphuric acid.

When the battery is discharged water is produced, diluting the acid and reducing its specific gravity. On charging sulphuric acid is produced and the specific gravity of the electrolyte increases. The specific gravity can be measured using a hydrometer and will have a value of about 1.250 for a charged cell and 1.17 for a discharged cell, although these values will vary depending on the make of battery. The specific gravity also depends on the battery temperature and the above values or for a battery at 15°C.

Specific gravity is defined as:

$$\text{Specific Gravity} = \frac{\text{mass of a specific volume of electrolyte}}{\text{mass of the same volume of pure water}}$$

The chemical reactions that occur during charging and discharging are summarised in figures 1 and 2.

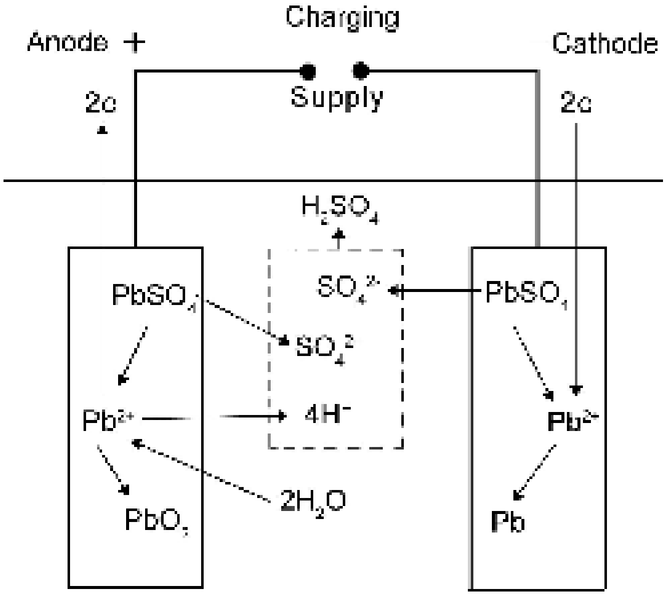

Figure 1: Charging. Lead (IV) oxide is formed at the anode, pure lead is formed at the cathode and sulphuric acid is liberated into the electrolyte causing the specific gravity to increase.

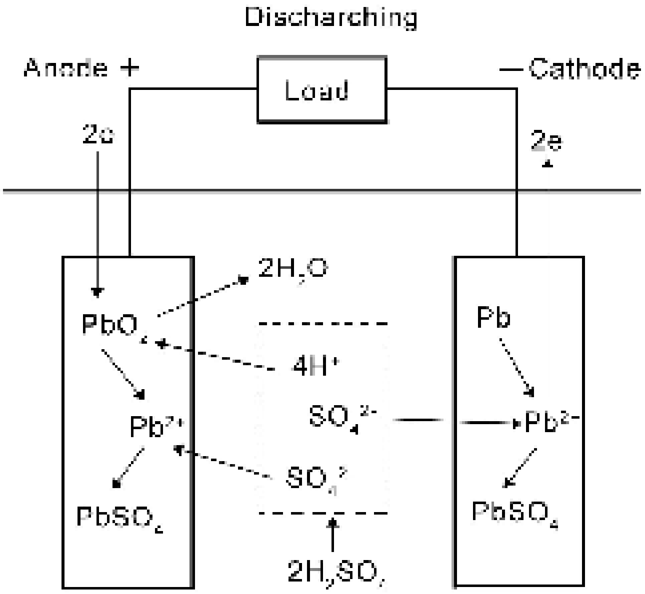

Figure 2: Discharging. Lead sulphate is formed at both electrodes and sulphuric acid is removed from the electrolyte causing the specific gravity to reduce.

If lead-acid batteries are over discharged or left standing in the discharged state for prolonged periods hardened lead sulphate coats the electrodes and will not be removed during recharging. Such build-ups reduce the efficiency and life of batteries. Over charging can cause electrolyte to escape as gases.

Types of Lead-Acid Battery

- *Starting Batteries* – Used to start and run engines they can deliver a very large current so a very short time, discharging by about 2-5%. If deep cycled these batteries quickly degenerate and will fail after 30-150 cycles but should last for a very long time when used correctly.
- *Deep Cycle Batteries* – Used to store electricity in autonomous power systems (e.g. solar, mini-

hydro), for emergency back-up and electric vehicles. These batteries are designed to discharge by as much as 80% of their capacity over thousands of charging and discharging cycles. True deep cycle batteries have solid lead plates however many batteries that do not have solid plates are called semi-deep cycle.
- Marine Batteries – Usually a hybrid battery that falls between deep cycle and starting batteries although some are true deep cycle batteries. hybrid batteries should not be discharged by over 50%.

Types of Deep Cycle Battery

- *Flooded* – These batteries have a conventional liquid electrolyte. Standard types have removable caps so that the electrolyte can be diluted and the specific gravity measured, such batteries are supplied dry and you add distilled water. Standard flooded batteries are cheap and if they are kept topped up they are not overly sensitive to high charging voltages. Sealed batteries are supplied pre-flooded and have fixed valves to allow gases to vent during use however, they will still leak if inverted and the electrolyte can not be replenished so that over charging will cause damage.
- Gelled Electrolyte – The electrolyte is a jelly and so will not leak. The electrolyte can not be diluted so that over charging must be avoided and these batteries may only last for 2 or 3 years in hot climates although with good care they can last for 5 years.
- *Absorbed Glass Mat (AGM) Batteries* – The electrolyte is held between the plates absorbed in a fine boron-silicate mat. Like gelled electrolyte batteries they will not leak acid but they can withstand more careless treatment and are less sensitive to over charging since they are designed to retain vented gases. AGM batteries can also stand for 30 days in a totally discharged state and still be recharged successfully. The major drawback to these batteries is that they cost between 2 or 3 times as much as flooded batteries.

Internal Resistance

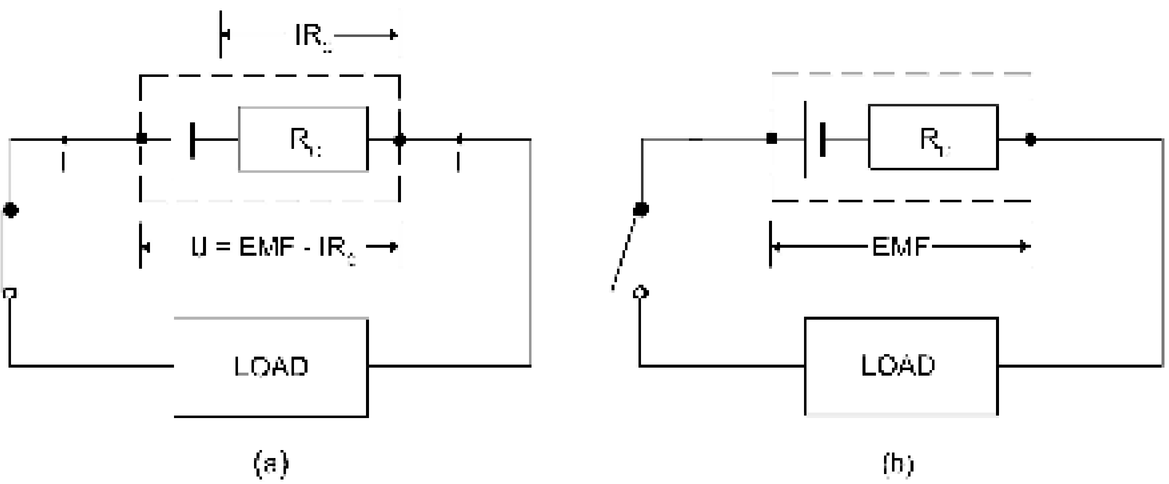

Figure 3: The internal resistance of a battery and the voltage measure across the terminals: (a) current flowing through a load; (b) no current flowing.

Batteries transfer energy to electrons so that they 'flow' around a circuit, the Electro Motive Force (EMF) is the total amount of energy per coulomb of charge that a battery can supply and is measured in volts. The EMF of a lead-acid cell is provided by that chemical reactions described above (figures 1 and 2) and can be seen as the maximum possible voltage across the cell's terminals (the open circuit voltage). The path taken when current passes through the lead-acid cell will have resistance . This internal resistance depends on the cell's design, construction, age and condition. On discharge this internal resistance (R_C) causes the voltage measured across the cell's terminals to be less than the EMF (E) of the cell (the voltage drop = I x R_C, figure 3a). Thus when a current (I) flows the terminal voltage (U) is given by:

$$U = E - IR_C$$

Example

A cell has an internal resistance of 0.02Ω and an EMF of 2.2V. what is its terminal potential difference if it delivers (a) 1A, (b) 10A and (c) 50A?

(a) $U = E - IR_C = 2.2\ (1 \times 0.02) = 2.18V$

(b) $U = E - IR_C = 2.2\ (10 \times 0.02) = 2V$

(c) $U = E - IR_C = 2.2\ (50 \times 0.02) = 1.2V$

Note that if a high resistance voltage meter is used to measure the voltage across a battery's terminals it will register the batteries EMF; as long as there is no current flowing through a load from the battery (figure 3b). If the terminal voltage is measure when a current is flowing through a load from the battery, the meter will register the EMF minus the voltage drop across the internal resistance (figure 3a).

When charging a cell the voltage applied across the terminals must be great enough to push the desired current against the cell's EMF. Therefore the effective voltage across the internal resistance is the difference between the terminal voltage (in this case applied to the cell) and the the cells EMF. Therefore the current that flows is given by:

$$I = \frac{U - E}{R_C}$$

and:

$$U = E + IR_C$$

Example

A cell with an EMF of 2V and an internal resistance of 0.08Ω is to be charged at 5A. What terminal voltage must be applied?

$$U = E + IR = 2 + (5 \times 0.08) = 2.4V$$

Cell and Battery Voltage

A well maintained cell should have a cell EMF of about 2.2V falling to about 2V when fully discharged. Once the internal resistance has been taken into account the terminal voltage (the potential difference across the cell terminals) of each cell will be about 2.1V, but this value will drop depending on how much current is being drawn. Six cells in series make up a twelve volt battery which when fully charged will have a terminal voltage of 12.6 to 12.8V. The EMF of lead-acid cells is dependent on chemistry although the actual terminal voltage differs depending on the battery design, this must be taken into account when using a voltmeter to determining the batteries state of charge.

Battery Capacity

The capacity of a battery is usually expressed as a number of ampere-hours (Ah). One ampere-hour is the amount charge delivered when a current of one ampere is delivered for one hour. Since the capacity of lead-acid batteries depend on the rate at which they are discharged a discharge rate is also quoted. For example a battery with a 300Ah capacity when discharged over 10 hours (10 hour rate) can give (300÷10) 30A continuously however, it may only have a 250Ah capacity when discharged at the 5 hour rate which will occur if (250÷5) 50A are continually draw from it (figure 4). In short the more slowly you discharge a battery the greater its capacity, deep-cycle battery capacities are normally quoted for the

20 hour rate. Figure 4 shows a typical battery capacity versus discharge rate graph.

Capacities are sometimes expressed in terms of kilowatt-hours (kWh) which can be calculated from the ampere-hour rate using the following equation:

$$\mathrm{kWh} = \frac{\mathrm{Ah} \times \text{battery volatge}}{1000}$$

Therefore a 12V battery with a capacity of 300Ah at the 10 hour rate will have a capacity of (12x300/1000) 3.6kWh.

The Ampere-hour is a measure of the amount of charge that a battery can deliver: one ampere is a flow of charge at the rate of one coulomb per second, therefore a number of amperes multiplied by a time (i.e. hours) gives us a quantity of charge. Similarly, the watt-hour is a measure of the amount of energy that a battery can deliver: one watt is the supply of energy at the rate of one joule per second, therefore a number of watts multiplied by a time gives us a quantity of energy.

The capacities of lead-acid batteries are very dependent on the temperature at which the battery is operating. The Capacity is normally quoted for a temperature of 25°C however, the capacity will reduce by about 50% at -25°C and will increase to about 10% at 45°C (figure 5).

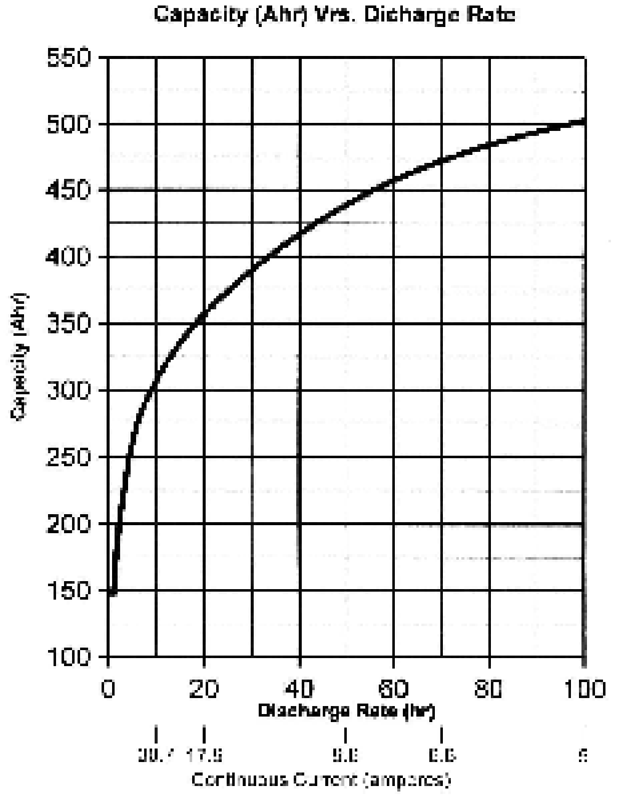

Figure 4: The battery capacity vrs. discharge rate graph for a Surrette Series 500 battery. The continuous current at various rates are also shown.

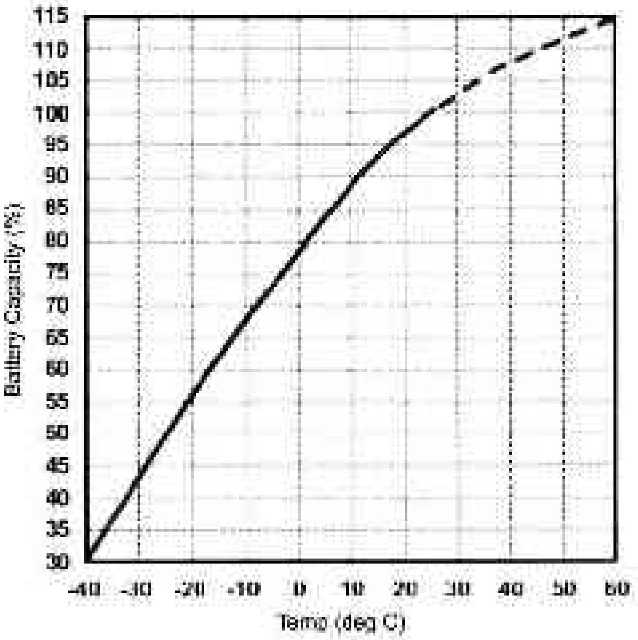

Figure 5: Battery capacity vrs. operating temperature graph.

Battery Life

In a small autonomous power system (i.e. one without a mains grid connection) the batteries will be continually charged and discharged. The life span of a deep-cycle battery is normally quoted in the number of cycles that it can be expected to perform, a cycle being a discharge followed by recharging. Deep cycle batteries should not be discharged by more than 60% of their capacity and the less you regularly discharge a battery the longer it will last. A battery in daily use and discharged by no more than 40% of its capacity should last for more than 3000 cycles and may not need replacing for up to 12 years. A battery that is frequently heavily discharged may last no longer than 2 years.

Figure 6 shows the variation in battery life with the depth to which it is discharged.

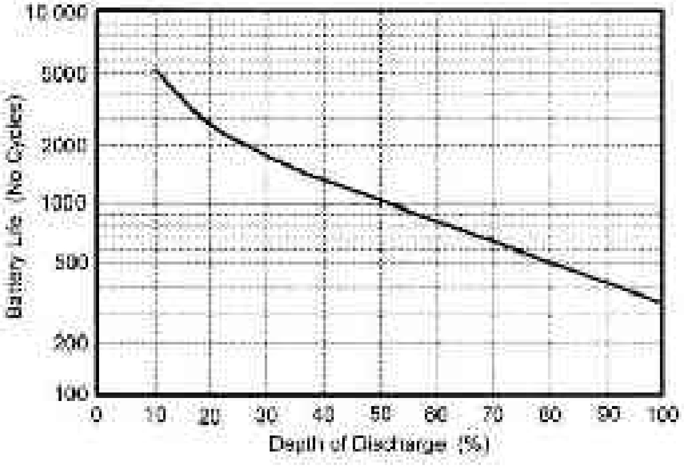

Figure 6: The effect of discharge rate on battery life.

Charge State

There are two main methods for determining the state of charge for lead-acid batteries:

- *Terminal Voltage* - The open circuit voltage (no current flowing) of a fully charged cell depends on its type but will be 2.1V to 2.3V (12.6V to 13.8V for a 12V battery). If the voltage is measured with the charging current flowing it will be increased by the voltage drop across the internal resistance. If discharging the measured voltage will drop due to the internal resistance of the cell. Table 1 gives the approximate battery and cell voltages for various states of charge.
- *Specific Gravity* – This is the recommended method if the battery is not sealed and a hydrometer can get into the battery. For a flood-type battery in good condition the specific gravity should vary in the region of 1.25 for a fully charged battery to 1.17 for a fully discharged battery. These figures vary slightly depending on the battery type and the temperature: 0.0007 should be added to these values for each degree above 15°C. Table 2 gives the specific gravity values for several lead-acid batteries.

State of Charge (approx.)	*12 Volt Battery*	*Volts per Cell*
100%	12.70	2.12
90%	12.50	2.08
80%	12.42	2.07
70%	12.32	2.05
60%	12.20	2.03
50%	12.06	2.01
40%	11.90	1.98
30%	11.75	1.96
20%	11.58	1.93
10%	11.31	1.89
0	10.50	1.75

Table 1: The approximate battery and cell voltages for various states of charge.

State of Charge (approx)	***Apex***		***Suncycle***		***PVStar***	
	SG*	OCV**	SG*	OCV**	SG*	OCV**
100%	1.277	2.12	1.240	2.0866	1.225	2.0950
90%	1.258	2.10	1.230	2.077	1.216	2.0775
80%	1.238	2.08	1.220	2.067	1.207	2.0600
70%	1.217	2.06	1.210	2.058	1.198	2.0425
60%	1.195	2.04	1.200	2.048	1.189	2.0250
50%	1.172	2.02	1.190	2.040	1.179	2.0075
40%	1.148	2.00	1.180	2.031	1.171	1.9900
30%	1.124	1.98	1.170	2.022	1.163	1.9725
20%	1.098	1.95	1.160	2.013	1.153	1.9550
10%	1.073	1.93	1.150	2.005	1.145	1.9375
0	1.048	1.91	1.140	1.996	1.135	1.9200

Table 2: The approximate **s**pecific gravity values for several lead-acid batteries in various states of charge.
* SG = specific gravity at 25°C.
** OCV open circuit voltage per 2V cell.

Charging

The charging voltage must be higher than the battery voltage for current to flow into the battery. There are two basic ways to charge a lead-acid battery from an uninterrupted supply (e.g. mains or a generator):

- *Constant-voltage charge* – A constant voltage is applied across the battery terminals. As the voltage of the battery increases the charging current tapers off. This method requires simple equipment but it not recommended.
- *Constant-current charge* – An adjustable voltage source or a variable resistor maintains a constant current flows into the battery. Thus requires a sophisticated charge controller.

From uninterrupted power supplies lead-acid batteries are normally recharged using the constant-current technique; the manufacturer's data should be checked to find an appropriate charging rate. A common rule of thumb used to calculate a suitable charging current is that it should be one tenth of the ampere-hour capacity at the 10 hour rate; i.e. 6A for a 60Ah battery at the 10 hour rate. Another estimation of a safe charging current is the “C/8” rate which is the capacity at the 20 hour rate divided by 8, although Trojan batteries recommend 10 to 13% of the 20 hour rate. Gelled cells should not be charged with more than the 5% of their Ah capacity. Note that you should take into account the ampere-hour capacity of the whole battery bank (see the 'Battery Bank' section below).

Trickle or Float Charge

Lead-acid batteries can be maintained over long periods of time by replacing charge lost via self discharge. To do this a continual trickle charge current is maintained across the battery terminals. Typically the current is very small, being the value in milliamperes which equals the ampere-hour capacity (at the 10 hour rate) for cells up to 100 Ah i.e. 60mA for a 60Ah battery. For batteries above 100Ah the following equation can be used:

$$\text{Trickle Charge Current in milliamperes} = [70 + (3 \times 10\ \text{hour capacity})]$$

The voltage maintained across the battery during trickle charging should not be higher than about 2.25V per cell (13.5V for a 12V battery). Self-discharge will be reduced by keeping the batteries clean and free of dust, particularly between the terminals.

Solar Chargers

When lead-acid batteries are charged from a variable source, such as PV panels, three charging stages are normally provided by the charge controller:

- *Bulk Charge* – Current is sent to the batteries of the maximum safe rate they will accept until their voltage rises to about 80 to 90% of their fully charged value. The bulk charging voltage is typically about 14.8V but may be as high as 15.5V for a 12V system, this may vary so that the maximum possible current in maintained. Gel batteries often have lower recommended voltages in the region of 13.8 to 14.1V.
- *Absorption Charge* – The voltage remains constant, typically about 14.2V for a 12V system (depending on temperature) and the current tapers off as the battery reaches 100% charge.
- *Trickle or Float Charge* – For a 12V battery bank a voltage of about of about 12.8 to 13.2V is maintained across the batteries to keep them in good condition.

Some charge controllers have pulse width modulation (PWM) which can be used to provide the last bit of charge and maintain a trickle charge. Rather than letting the current taper off a larger current is pulsed into the battery, the length of the pulses reduces as less charge is required.

Equalisation Charging (vented liquid electrolyte batteries only)

For a bank of batteries to work efficiently they should all have the same voltage at any given time, similarly for a single multi-cell battery all of the cells should have the same voltage at any given time. However, due to slight irregularities from battery to battery constant charging and discharging leads to an imbalance in the specific gravity of individual battery cells. Also, during use the electrolyte may become stratified so that the electrolyte is more concentrated at the bottom of the cell than the top.

These problems can be rectified by applying an equalisation charge that will return all of the cells to the same voltage and eliminate irregularities in the electrolyte concentration. The voltage used during a equalisation charge is normally 1V higher than the bulk charge voltage for 12V systems and 2V higher for 24V systems, although this may be significantly higher at cooler temperatures.

Equalisation charges are normally necessary about once every month for batteries in frequent use and is most effective on fully charged batteries. The equalisation voltage is normally maintained for about two hours. After equalisation the batteries should be checked to see if they need topping up with distilled water since electrolyte may be lost as gas during this process.

Battery Efficiency

Due to internal resistance and the fact that the charging voltage is greater than the discharge voltage, the energy returned by the battery upon discharge will be less than the energy used for recharging. Typically a lead-acid battery will be 80 to 90% efficient when considering ampere-hours (i.e. charge transferring efficiency). This figure assumes that the charging and discharging voltages are the same since:

$$\text{ampere - hour efficiency} = \frac{\text{discharged Ah} \times 100\%}{\text{charging Ah}}$$

Capacities are quoted in terms of the number of ampere-hours that a full battery can discharge, but this will only be about 80% of the ampere-hours needed to completely recharge the same battery from empty. The charging voltage is the sum of the cell EMF and the internal voltage drop (due to internal resistance) whereas the discharge terminal voltage is their difference. A truer method is to calculate an energy efficiency for a battery using watt-hours:

$$\text{watt} - \text{hour efficiency} = \frac{\text{discharged watt - hours} \times 100\%}{\text{charging watt} - \text{hours}}$$

The watt-hour efficiency is typically 65% for a lead-acid battery. Ampere-hour efficiencies are still useful for solar power sizing calculations since these often use ampere-hours when sizing the panel array needed to charge the battery bank but be careful.

Example

A discharged 12V battery is charged for 10 hours at 12A, the average charging terminal voltage being 15V. When connected to a load current of 10A for 9 hours at an average terminal voltage of 12V the battery is discharged.

$$\text{ampere - hour efficiency} = \frac{10 \times 9 \times 100\%}{10 \times 12} = 75\%$$

$$\text{watt} - \text{hour efficiency} = \frac{10 \times 9 \times 12 \times 100\%}{10 \times 12 \times 15} = 60\%$$

Note that because of the internal resistance of the battery the efficiency will depend on the charging and discharging rate.

Battery Banks

Battery banks in small power systems normally have nominal voltages of either 12V or 24V however, lead acid batteries are available from 4V up to 24V. Batteries can be combined in series (figure 7a) so that their voltages are added together: two 12V batteries in series will provide 24V. Although voltages are added the same current will flow though each battery, so that two identical batteries 12V in series supplying 5A to a load each supply 5A: therefore the Ah capacity of two identical batteries in series is the same as one battery on its own. The total internal resistance of batteries in series will equal the internal resistances (R_C) of the individual batteries added together.

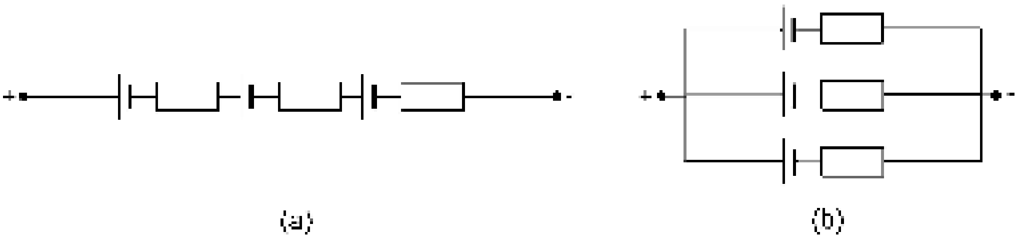

Figure 7: (a) 3 batteries and their internal resistances in series; (b) 3 batteries and their internal resistances in parallel.

Example

(a) A 12V battery with an internal resistance of 0.3Ω is connected to a load with a resistance of 4Ω.What Current will flow?

$$I = \frac{E}{R + R_C} = \frac{12}{4 + 0.3} = 2.8A$$

(b) What current will flow in the same load if the current is supplied by two similar 12V batteries connected in series?

$$I = \frac{E}{R + \text{Total } R_C} = \frac{12}{4 + (2 \times 0.3)} = 5.2\text{A}$$

When batteries are connected in parallel (figure 7b) they all operate at the same voltage and only identical batteries should every be connected in parallel. With this arrangement the total current being provided is split equally between the batteries so that two 12V batteries supplying 5A contribute 2.5A each, therefore the total capacity of these two batteries is twice the capacity of one battery supplying 2.5A (which in turn will be greater than the capacity of one battery supplying 5A). The internal resistances must be summed as if they are resistors in parallel; that is that the reciprocal of the total resistance equals the sum of the reciprocals of each resistor.

Example
From the previous example:
(c) If three of the same 12V batteries are connected in parallel to the 4Ω what current flows?

Total internal resistance: $\frac{1}{\text{Total } R_C} = \frac{1}{3} \times 3 = 10\Omega$ Total $R_C = 0.01\Omega$

Therefore: $I = \frac{E}{R + \text{Total } R_C} = \frac{12}{4 + 0.01} = 3.0\text{A}$

Battery banks may be constructed from several strings of batteries in series connected in parallel (figure 8); note that all of the batteries must be identical and of course all of the series strings must contain the same number of batteries. The EMF of such a bank is equal to the number of batteries in series multiplied by the battery EMF, the Ah capacity is equal to the capacity of one battery (at the appropriate rate) multiplied by the number of string in parallel and the total internal resistance is given by:

$$\frac{R_C \times \text{number of batteries in a string}}{\text{number of strings in parallel}}$$

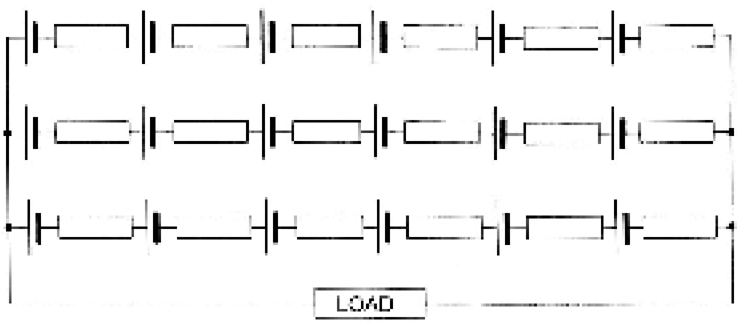

Figure 8: Batteries and their internal resistances in a bank containing 3 strings of 6 batteries each.

Example
Continuing the previous example:
(d) If a battery bank consists of three strings of two batteries each what current will flow?

The EMF of the battery bank is: $2 \times 12 = 24\text{V}$

The total internal resistance is: $\frac{2 \times 0.3}{3} = 0.2\Omega$

Therefore: $I = \frac{E}{R + \text{Total } R_C} = \frac{24}{4 + 0.2} = 5.7\text{A}$

Note that this is about the same current that is supplied by two batteries in series however, since there are three strings in parallel so the bank will be able to supply this current for more than three times as long (more than three times because the discharge rate has reduced). If the batteries have a capacity of 50Ah each at the 20 hour rate the bank will have a capacity of (3 x 50) 150 meaning that it can supply 7.5A for 20 hours, therefore it could supply 5.7A for slightly longer than 20 hours.

Care and Maintenance

Some Lead-acid batteries are designed to be maintenance free, such batteries are sealed and the electrolyte can not be topped up. Batteries that are sealed and not vented should not receive equalisation charges.

i. Batteries should not be left standing for any length of time, either charged or uncharged.
ii. Batteries supplied dry have a shelf life of about 2 to 3 years.
iii. Batteries should neither be over charged or discharged by more 60% of their capacity.
iv. Batteries in a bank should all be the same make and the same model. Once a battery bank has been operating for more than a few weeks, new batteries should not be added.
v. The electrolyte should be topped up regularly with distilled water. Refer to the manufactures literature to find the recommended specific gravity.
vi. Equalisation charges should be used about once a month for batteries that are regularly cycled.

Safety

Lead-acid batteries can be dangerous because they vent hydrogen and oxygen gas during operation. The following points should be remembered:

i. Keep the electrolyte in flooded cells at the correct level with distilled water, to make good losses due to evaporation and gassing.
ii. Use no materials or finishes which will be attacked by acid in the battery room. Spilled acid, and acid vapour given off during gassing, will quickly corrode most exposed metals other than lead. Use an asphalt floor where possible and coat wooden surfaces with anti-acid paint.
iii. Ventilate the battery room well, if necessary using corrosion-proofed fans.
iv. Do not allow a naked flame in the room; and prevent sparking by switching off a circuit before connecting and disconnecting. The gases present are explosive when in the correct proportions.
v. Mop up spilt acid immediately and wash with soda solution. Acid on clothing will quickly cause holes to appear.
vi. Do not allow acid to enter the eyes. If it does so, immediately lie down and run clean water over the eyes for as long as possible. Consult a doctor. Acid on the hands is not itself dangerous, but can easily be transferred to more vulnerable parts of the body.
vii. When mixing acid for the initial charge of new cells, always add acid to water, and not the reverse.
viii. Watch cell temperature, as excessive heat will damage lead-acid cells. Acid temperature should not exceed 36°C.
ix. Keep battery terminals clean and coated with petroleum jelly.
x. Remember that a short-circuit across the battery or cell terminals can result in very high currents which may result in fire or burns. Use only insulated tools and take great care not to allow terminals to connect together inadvertently.

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