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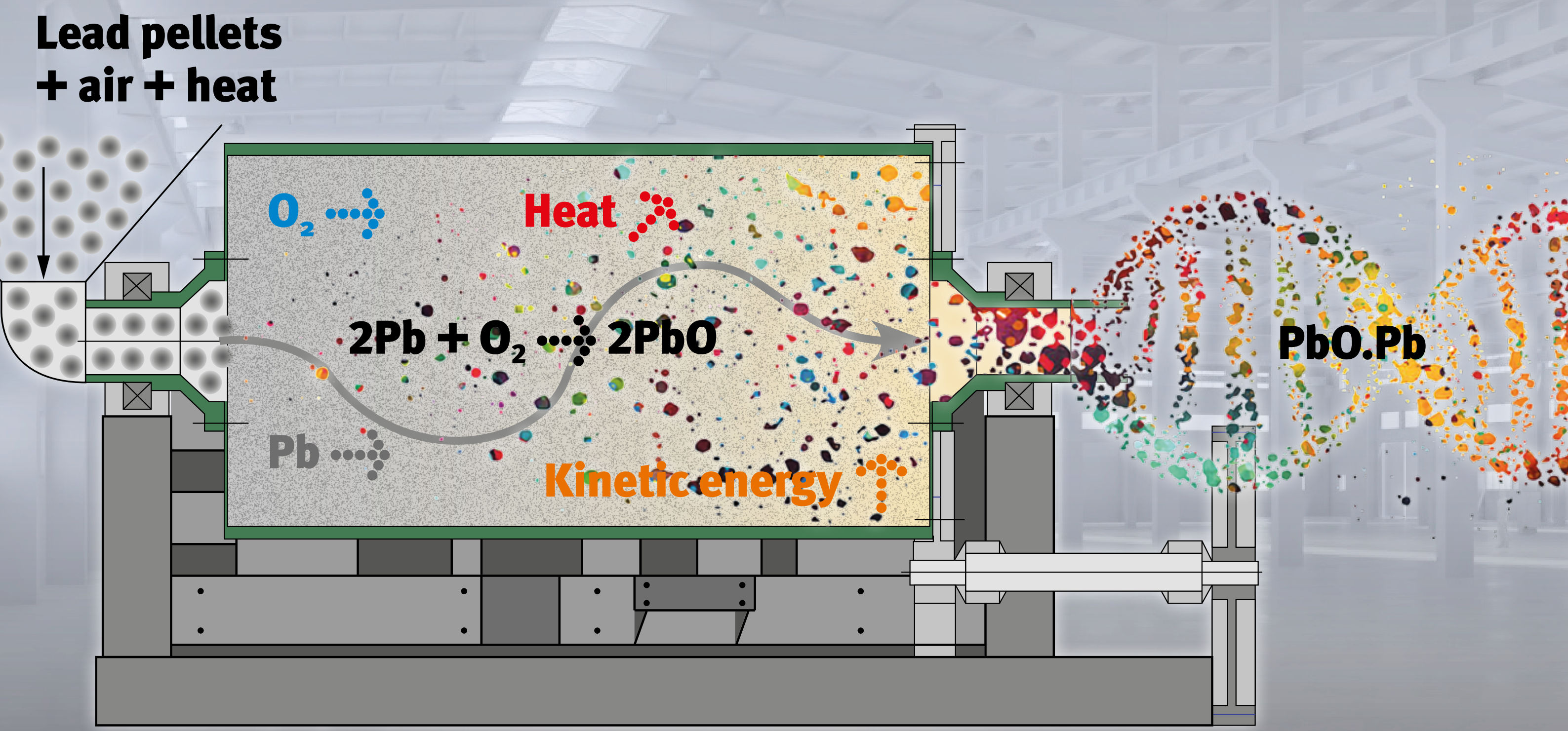
Operating in a parallel charging universe

Charging multiple strings of batteries connected in parallel



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When batteries chill out

As temperatures reduce everything moves more slowly, including the chemical reactions necessary for batteries to charge and discharge. As ions slow down more energy is required to get them moving again. *BEST*'s technical editor, Dr Mike McDonagh, takes a look at the effect of low temperature on lead-acid battery operation and charging and explains how to compensate for changes in operating temperature.

Most battery users are fully aware of the dangers of operating lead-acid batteries at high temperatures. Most are also acutely aware that batteries fail to provide cranking power during cold weather. Both of these conditions will lead to early battery failure. However, it is fair to say that very few end users are aware of the full implications of using batteries at low temperatures.

Failure to meet duty cycles plus early end of life failure due to partial-state-of-charge (PSoC) effects are just some of the consequences. This article demonstrates how a lead-acid battery can be unknowingly used and abused simply by not recognising the need for temperature compensations in the charging and discharging of a battery during cold weather periods.

As a ready guide, the problems associated with cold temperature operation for lead-acid batteries can be listed as follows:

- Increase of the on-charge battery voltage.
  The colder the battery on charge, the higher the internal resistance. This raises the on-charge voltage, which can fool automatic and 'intelligent' chargers into accepting a battery as fully charged when it is not

- This reduces the amount of charged active material in the plates. At low temperatures the state-of-charge (SoC) of the battery, based on the measured voltage, will indicate that the battery has a high state of charge. However, the lack of active material means that the usable capacity available (i.e. the % of charge), is less than would be expected from the battery voltage

- The types of charging: CV, CC, CC/CV, pulse etc. will all be affected as described above, by the higher on charge voltage

- It is important to accurately compensate for the higher on-charge voltages for different types of charging. This is particularly important to ascertain the battery's SoC and to set correct voltage cut-off points for different charging stages

- Understanding the theoretical basis for voltage change with temperature is important in order to be able to predict the voltage compensation values *(see below)*

- As a guide, the temperature compensation is between 3.5 and 4mv per individual cell for every degree change in temperature. The exact value is dependent on the battery design. The factor is added to the voltage as the temperature drops, and deducted as the temperature rises. For a 12V battery this would mean 6 x 3.5mv = **0.021V** should be added for every 1°C drop in temperature as a minimum

- Incorrect charging voltage due to lack of temperature

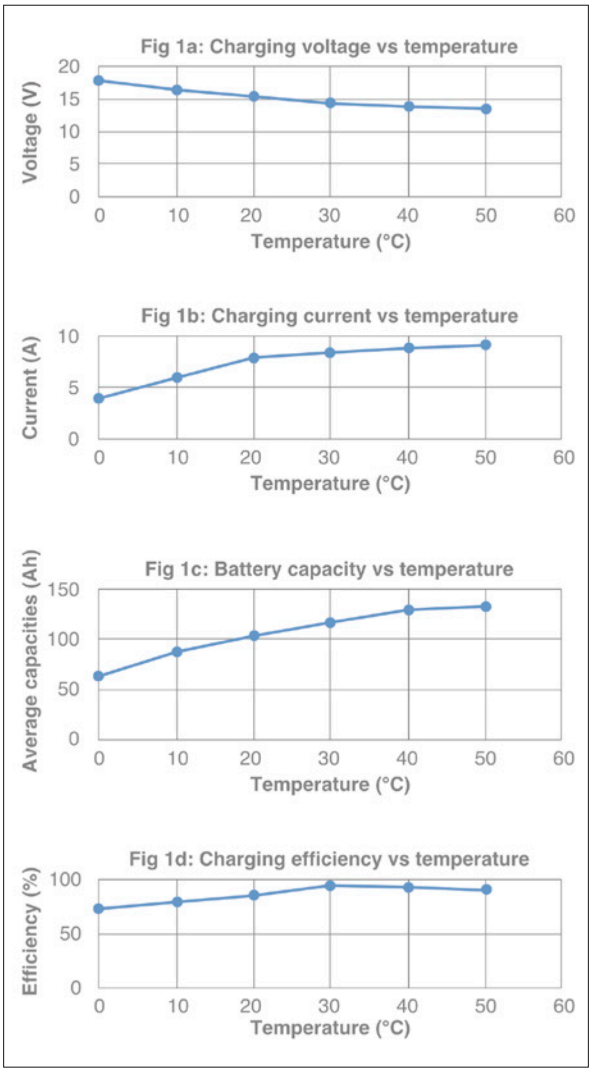
compensation has a deleterious effect on a battery's performance and life. A battery's life can be shortened by undercharging as easily as it is by overcharging. Undercharging, due to lack of low temperature voltage compensation, leads to low specific gravity (SG) of the electrolyte in a battery.
The SG in a discharged battery is higher at low temperatures than it would be under standard operating conditions. This is due to the normal SG variation with temperature of any liquid. Because of this, the normal discharge control using a cut off voltage will believe the battery is in a higher state of charge than it really is. It will then continue to discharge the active material beyond its design limits and create more lead sulphate in the plates than is the case at standard temperatures.
When this is combined with the above effects of a higher on-charge voltage, the overall consequence is an over-discharged battery operating in a partial state of charge. The repercussions from these twin ills have been described in earlier versions of *BESTmag*. However, the net result is that the plates become heavily sulphated and can kill a lead-acid battery in just a couple of months.

The above comments are a brief summary of the trouble that can be caused by ignoring temperature compensation settings for both the charging and the over-discharge protection equipment. The rest of the article gives a more in-depth discussion of the mechanisms of this phenomenon and the recommended remedies to prevent its occurrence.

Fig 1 shows the results of an investigation by the Department of Physics at the University of Garhwal in India. In this the researchers showed the effect of temperature on four key properties of lead-acid batteries. These were: charging voltage and current, capacity and battery round trip efficiency. From these results it is evident that a decrease in battery temperature had the following effects:

- An increase in charging voltage ***(Fig 1a)***
- A decrease in charging current ***(Fig 1b)***
- A decrease in capacity ***(Fig 1c)***
- A decrease in charge efficiency ***(Fig 1d)***

Fig 1: Effect of temperature on battery performance.



These curves can be explained by looking at the electrochemistry of the lead-acid battery (LAB). A LAB is part electronic and part electrochemical. Its total voltage is made up of two major components: the metallic conducting parts, grids, plate straps and take-offs, and the semi-conducting electrolyte. Collectively these two components are responsible for the total internal resistance or impedance of the battery.

The metallic part of the battery will follow Ohm's law, whilst the electrolyte will behave like a semi-conductor. Any temperature change will push the individual component's resistances in opposite directions. With higher temperatures, the metallic resistance will increase whereas the electrolyte resistance will decrease due to better ionic mobility. With lower temperatures, the opposite will occur. The exact contribution from each of these components will depend on the material balance. Fortunately, most lead-acid batteries have a fairly standardised structure and therefore roughly similar response to temperature variations. The overwhelming contribution is made by the electrolyte. ***Fig 2*** shows a typical LAB's resistance variation with operating temperature. It is a linear relationship and can be calculated for a particular battery from the following relationship, known as the Nernst Equation:

$$E = E^0 - [2.303 \times RT/nF] \times \{\log[a_{products} / a_{reactants}]\}$$

Where:

E^0 is the potential at standard conditions of temperature and concentration.

E represents changes in the EMF of products and reactants in non-standard states.

R is the gas constant (8.314 J/deg.mole).

T is the absolute temperature.

n is the valency of the reaction

F is faraday's constant

$a_{products}$ **and** $a_{reactants}$ are the activities (effective concentrations) of products and reactants, respectively.

Using the well-known lead-acid double sulphate reaction:

Discharged *Charged*

$$2PbSO_4 + 2H_2O \leftrightarrow PbO_2 + Pb + 2H_2SO_4$$

Using this in the charging direction to substitute into the Nernst equation:

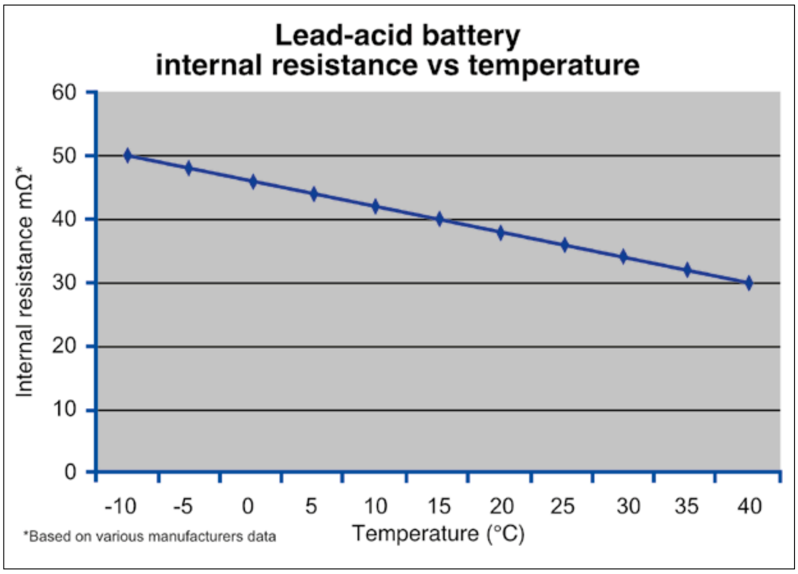


Fig 2 :

$$E = E^0 - [2.303\ RT / nF] \times \{[aPbO_2 * aPb * aH_2SO_4] / \log[aPbSO_4 * aH_2O]\}$$

Where **a** represents the activities of the reactants and the products of the cell, defined as an effective concentration.

Since $aPbSO_4 = 1, aH_2O = 1, aPbO_2 = 1, aPb = 1$ (activity of a solid and water), all this boils down to:

$$E = E^0 - K*T \times \log a_{H2SO4}.$$

Where $K = 2.303*R/F$

In essence this shows how the EMF (voltage of a cell) is dependent on the temperature and concentration of sulphuric acid. The higher the temperature, the lower the EMF. Activity **a** (concentration) can be calculated from the specific gravity of the electrolyte. However, the voltage variation due to temperature will depend mostly on the battery's internal resistance. Taking a simplified ohm's law relationship for a standard 12V lead-acid battery:

Battery rest voltage = **Vr = 12.80V**

Battery internal resistance = **Ri**

On charge condition:
When a current, Ic is applied, there is an added voltage:
Ic x Ri = Vc

According to ***Fig 2*** the IR difference between +30°C and -5°C is 10mΩ this gives a voltage difference on a 20A charge of 20 x 0.01 = + 0.2V.

Discharge condition:
When a current, Id is applied, it has a negative value:
-Id x Ri = -Vd

According to ***Fig 2*** the IR difference between +30°C and -5°C is 10mΩ this gives a voltage difference on a 20A discharge charge of 20 x 0.01 = -0.2V.
The higher internal resistance, creating a higher voltage on charge, has the opposite effect on discharge, causing the battery to have a lower voltage.

A primary consideration for a

battery operation is the charging method. It is vital to understand the dependence of correct charging on accurately knowing and interpreting a lead-acid battery's voltage response to a current input. The voltage of a battery on charge is a crucial measurement. It is an indication of the state of charge and the nature of the chemical reactions that are occurring. The two main reactions are the conversion of the active material on charge and discharge.

$$2PbSO_4 + 2H_2O = Pb + PbO_2 + 2H_2SO_4$$

The standard double sulphate reaction for lead-acid batteries describes the chemical conversions of the electrode materials under charging and discharging conditions.

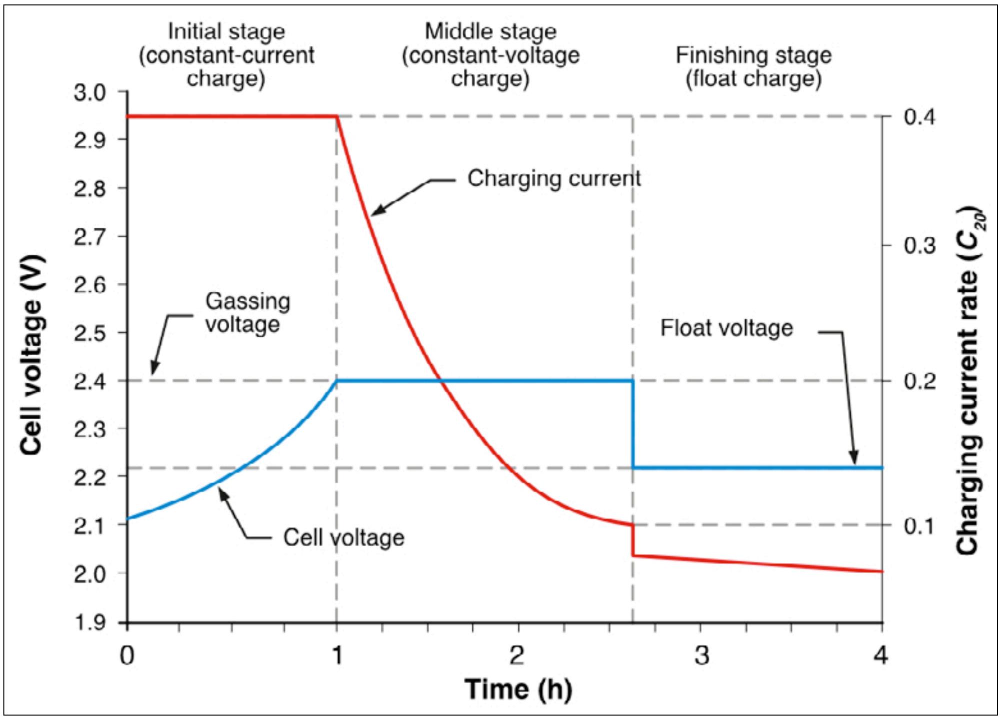
Ensuring high conversion rates of these active materials enables a battery to maintain its required output capacity during its duty cycle. Unless the battery voltage on charge is correctly recognised then undercharging or overcharging is possible. If frequent undercharging occurs, maintaining the correct electrolyte density to prevent PSoC deterioration due to plate sulphation becomes more difficult.

> **"The main message is quite simple: batteries are just as badly affected by the cold as they are by the heat"**

The use of battery voltage to trigger different stages in a charging regime is a critical part of the process. There are several basic methods for the charging of lead-acid batteries. The chosen method depends on the application and the type of battery being charged. ***Fig 3*** is a typical LAB charging regime in common use. In this method, the voltage is a key indicator to signal a switch from one mode to another, e.g. from bulk to float charge. For this reason, the voltage settings on the charger are of paramount importance in order to ensure optimum charging level and optimum charging efficiency. Unfortunately, these voltage points are not fixed; they are substantially affected by the battery temperature.

Because of this, it is important that temperature correction factors are used to adjust battery chargers to take into account temperature variations. Battery manufacturers generally have recommended voltage compensations for their batteries' operations. Usually, these are between -3 and -4 mv per °C. On average there is a variation of 3.5 mv per °C for a single lead-acid cell. It demonstrates that a 12V battery on charge at 14.4V at 5°C would have an on-charge voltage of 13.77 volts (0.105 x 6) at 30°C. In other words, a voltage-controlled charger, without temperature compensation, at this temperature, would switch from bulk mode charging to the gassing phase, earlier than it would at 30°C. With less time in bulk charging and at a lower current, the battery will be undercharged. This will result in the charger supplying fewer ampere-hours than is required to completely recharge the battery. This situation could result in the undercharging of a battery by around 20%. For this

Fig 3: Common voltage-controlled charging method



reason, manufacturers usually supply charts of temperature adjustment for the charging voltage. In some cases, chargers have automatic or manual temperature controls.

Charging current and charging efficiency are also affected. ***Fig 1b/d*** shows that the lower the temperature the lower the on-charge current that the battery will absorb. Likewise, the charging efficiency is also reduced.

Added to the charging voltage variation is the inherent lower capacity of a battery with temperature reduction. ***Fig 4*** shows how a lead-acid battery's run time will be reduced as its temperature falls. Identification of the cut-off point in a battery's discharge regime is critical in order to prevent over discharge. This will effectively reduce the amount of energy available from the battery. Lower discharge voltages for the same current will result in battery powered equipment shutting down earlier. Because battery capacity is lower and recharge capability is less, this invariably results in significant undercharging. This contributes to both a failure to perform, and also to battery death brought on by PSoC effects resulting from extended undercharging.

The same chemical mechanisms causing an increase a LAB's IR when chilled, are also at play in reducing its capacity. The reasons are due to the mobility of ions in a solution, as described by the Arhenius equation:

$$K = A\ e^{-Ea/RT}$$

Taking logs:

$$\log K = \log A - Ea/2.303RT$$

Where,

K - Reaction rate;

A - Rate constant;

Ea - Activation Energy;

R - Molar gas constant, and

T - Temperature.

From the logarithmic derivation it is more obvious that a lower temperature means that reaction rates slow down. In short, everything moves more slowly at lower temperatures, including the ions involved in the chemical reactions at the electrode interfaces. This means more energy is needed for the reactions to progress. Additionally, the more sluggish ionic movement in the acid solution, results in a lower charge carrying capacity, i.e. a lower coulombic transfer rate on discharge.

Other consequences arising from low temperature operation, include reduction in both on-charge gas evolution and battery capacity.

The gas evolution reactions can be summarised as:

Positive

$$PbSO_4 + 2H_2O \leftrightarrow H_2SO_4 + PbO_2 + 2SO_4^{\ 2-} + 2H^+ + 2e^-$$

$$2H_2O \leftrightarrow O_2 + 2H^+ + 2e^-$$

Negative

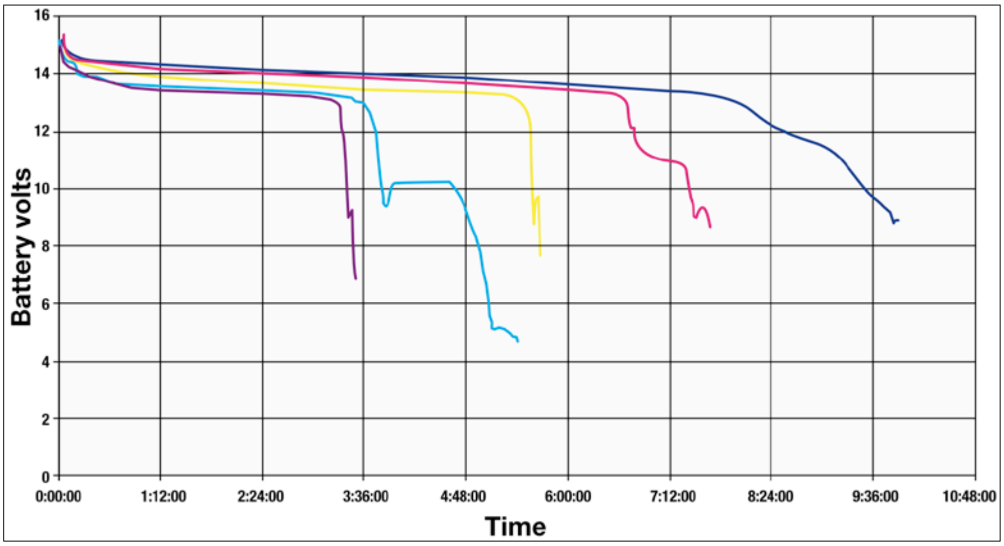
$$PbSO_4 + 2H^+ + 2e^- \leftrightarrow Pb + H_2SO_4$$

$$2H^+ + 2e^- \leftrightarrow 2H_2$$

Whilst water loss is more of a problem with higher temperatures, insufficient gassing due to charging at low temperatures may result in inadequate electrolyte stirring. This in turn can promote stratification with subsequent damage to active material and capacity loss.

From everything discussed so far, the main message is quite simple: batteries are just as badly affected by the cold as they are by the heat.

Fig 4: Effects of temperature on discharge duration of SLA batteries



Failure mechanisms maybe different but they are just as damaging as those created by higher temperatures. Operating lead-acid batteries at low temperatures, without temperature compensation will have damaging consequences for both the application and the battery. These are principally:

- Inability to perform duty cycle due to lower capacity
- Incomplete battery recharging due to raising of the on-charge voltage
- Irreversible battery damage due to PSoC cycling resulting from inadequate battery recharging
- Low cycle efficiency due to higher internal resistance

All of this adds up to underperforming batteries that fail early and require replacement. The other important point is that the failure to meet the required duty cycle due to low capacity and inadequate recharge capability can occur in a few days. This does of course depend on the frequency of use. However, in many outdoor applications, where there is a daily charge and discharge regime, then this is highly likely. And we are not talking about sub zero temperatures, in the example mentioned earlier, it is only a 20°C difference between the rated 25°C for the charger, and an actual 5°C in operation.

The message is clear, if you wish to have a fully functioning battery in an outdoor application, then a temperature compensated charging method is essential. This will avoid low battery performance and early battery failure. In almost every case it would be a false economy not to have this facility.

Operating in a parallel charging universe

Dr Mike McDonagh enters the battery-charging universe to examine what happens when charging multiple strings of batteries connected in parallel. Can you get something for free in this universe or are there hidden dangers lurking around the corner of convenience.

Whilst operating batteries in different configurations is a tried and tested practice, it is interesting to reflect on some of the common mistakes and misconceptions that are built into some companies' and individuals' working practices. Going back to the start of my working life (I hesitate to call it a career), I once asked a battery formation supervisor why he chose to operate so many circuits in parallel. His response was: "Because for every circuit charged you get another one charged for free."

It was not until I had to check a new UPS telecoms installation, using multiple series strings connected in parallel, that I understood his position ***(Fig 1)***. There were, in fact, six parallel strings connected to a single charger outlet. The reason for this was that the number of fairly small 12V batteries was limited by the charging voltage output of 100V. The maximum voltage was restricted for safety reasons; but the current output was 120 amps, giving a theoretical maximum of 20 amps per series string.

In effect, a fixed voltage would not restrict the number of strings you could connect in series; the limitation would be the magnitude of the current per string. With a float charge UPS application, you can easily accommodate a reduced current output. So, from a particular point of view, it was additional free charging space. In the case of increasing to a 10-series string output, the maximum current available per string would be 12 amps— more than enough for a float charge application with an occasional deep discharge. However, free charging space does not mean free-of-cost charging.

As explained above, the attraction of parallel charging is manifest. It can greatly increase the number of batteries charged from a single charger output. This saves on capital cost and potentially increases productivity. However, it should

Fig 1: UPS installation series parallel battery connections

also carry a warning label: "It's not that simple". Here are some of the potential consequences of parallel charging:

Charging series strings in parallel

- Current is diverted to those strings with a lower total resistance
- Lower resistance strings will get more Ah during charge than those with a higher resistance
- Those strings in a higher state of charge will discharge into those with a lower state of charge. This will slow down charging of the higher state-of-charge (SoC) strings
- In a series string, the lower voltage batteries or cells will not be charged to the same degree as the higher voltage ones, due to either their IR or their SoC
- The imbalance of Ah through parallel strings, or the voltage imbalance within these strings, will result in some batteries or cells being overcharged and others being undercharged, simultaneously in the same charging circuit
- Depending on the voltage settings on the charger, batteries or strings with a higher IR could be gassing, whilst the lower IR batteries are still converting AM from charging without gassing, despite the current being higher

Charging of single batteries in parallel

- Because batteries are single cells in series, this situation is similar to the parallel charging of strings of batteries
- Individual cells in a battery will be at different voltages as they will not have identical impedances. This means that some cells will be overcharged and some undercharged in voltage limited situations
- In the case of battery differences, the resistance of the connections and the cables between the batteries will add to the battery resistance. Differences in these connecting resistances will affect the voltage of the battery due to the current varying as a result of the total impedance of that parallel connection
- This can result in different voltages per battery despite their being connected in parallel. This will lead to undercharging of some batteries and overcharging of others

The following discussion provides the theoretical background and the practical experience that support the above statements. Firstly, understanding the basic principle of parallel series connection is straightforward. The principle is derived from Ohm's law.

For series connections

$\mathbf{V = I \times R}$

Current = **I** through each resistance and throughout the entire line

Total line resistance = $\mathbf{R_1 + R_2 + R_3}$

Total line voltage = $\mathbf{V_t = V_1 + V_2 + V_3 = IR_1 + IR_2 + IR_3}$

For series connections, the voltage is cumulative but the current is the same through each resistance.

For a parallel connected circuit

$\mathbf{V_t}$ is constant across each string

$\mathbf{i_t = i_1 + i_2 + i_3}$

$\mathbf{r_t = 1/r_1 + 1/r_2 + 1/r_3}$

$\mathbf{V_t = i_t \times r_t}$

In this case it is the voltage that is the same for each connection and the current that varies.

The picture becomes a little more blurred when we consider parallel charging several strings of series connected batteries. To fully appreciate how this can be troublesome, it is best to look at both the parallel-connected single batteries and the parallel-connected multi battery strings described earlier.

Case 1: Multi battery series strings connected in parallel

A very common parallel charging construction is the series parallel configuration used in telecoms towers and UPS applications. The configuration consists of a

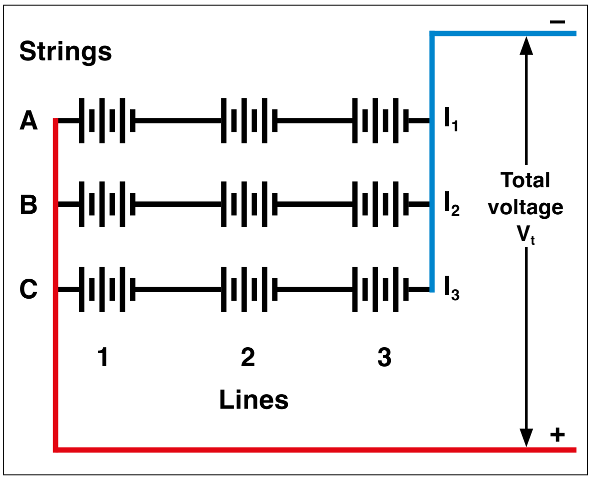


Fig 2: Multiple battery series strings connected in parallel

number of series strings attached in parallel for both charging and discharging. ***Fig 2*** shows the arrangement; in this example it is three series strings attached to a common load and charger. The batteries are divided into groups. There are three lines (1-3) that show a cross section of three parallel-connected batteries. Then there are three strings (A, B, C) in which three batteries are connected in series.

There are advantages to this arrangement:

- Open circuit battery failure in a single line does not stop the operation due to maintaining the line voltage
- The larger the number of strings the less effect it has on the other batteries in the parallel strings
- The lower voltage operation makes it safer than an equivalent power series connected application
- It also saves on capital cost as the inverter and charger are also lower voltage and more efficient at these voltages
- Total resistance is reduced when using parallel connections

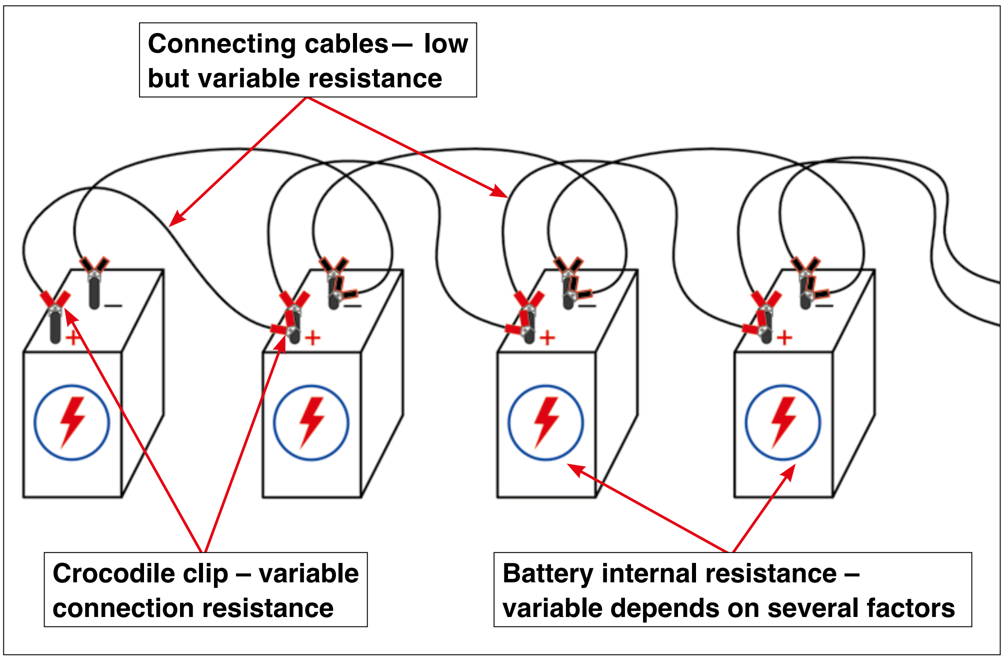
There are operational disadvantages however, and in the case of open circuit failure in a series string, the other two circuits would have to increase their output under a constant load. This would result in the two working strings being discharged with an increased discharge current. This will result in the battery bank being unable to complete its cycle duty and may damage the remaining batteries.

In addition, the voltage across each battery string A, B and C is the same, but within each series string the batteries may be at different voltages, depending on their individual impedances. This can lead to under and overcharging of batteries in a series string; this would lead to batteries going out of balance with the possibility of permanent damage.

Case 2: Single batteries per string

It may appear on the surface that if we have just a single battery per string, rather than several, then the voltage across the battery will be the same in lines 1-3. Any differences in voltage will be compensated on connection by the higher voltage batteries discharging into the lower voltage ones, until there is a negligible EMF difference. This is partially true, and, providing the batteries are left long enough, there will be a levelling up of the battery voltages giving a theoretical equal starting point for the charging process. However, we do not operate in an ideal world and there are always differences in battery internal resistance. Generally chargers are turned on immediately the batteries are

Fig 3: Single battery string connected in parallel



connected, which limits the time available for any self-levelling mechanism.

To minimise these problems, it is difficult to overestimate the importance of having batteries of the same internal resistance when charging in parallel. We also have to add in the circuit resistance of each string. Despite there only being one battery per string, there are cables and connectors attached to each battery ***(Fig 3)***. Each of these strings will have a total resistance made up of those components, i.e. the battery internal resistance $R_{1,2,3}$, the connecting cables $r_{1,3,5}$ and the connections themselves $r_{2,4,6}$.

Taking parallel string A from ***Fig 4***, we can add up the resistance contributions from each terminal connector and cable, see ***Fig 5***. Applying this nomenclature to all the strings we can derive the following relationships for the whole circuit:

$$R_{L1} = r_1 + R_1 + r_2$$

$$R_{L2} = r_3 + R_2 + r_4$$

$$R_{L3} = r_5 + R_3 + r_6$$

The total current output from the charger, I_t, will be shared between the lines according to their respective resistances:

$$I_t = V/R_{L1} + V/R_{L2} + V/R_{L3}$$

The voltage is the same across every line so the current through each line can be defined as:

$$I_1 = V/(r_1 + R_1 + r_2)$$

$$I_2 = V/(r_3 + R_2 + r_4)$$

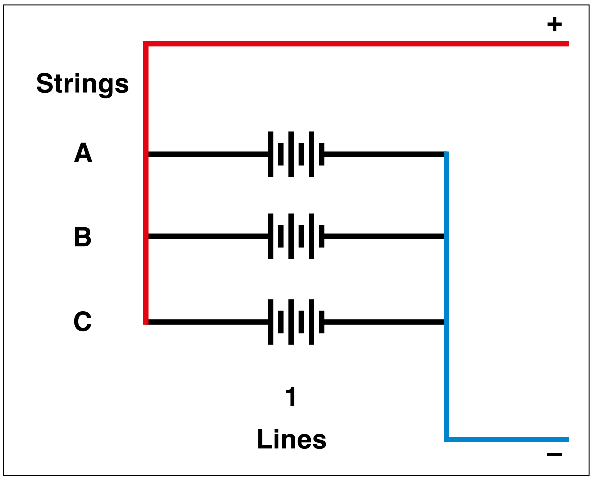


Fig 4: representative schematic of single batteries connected in parallel

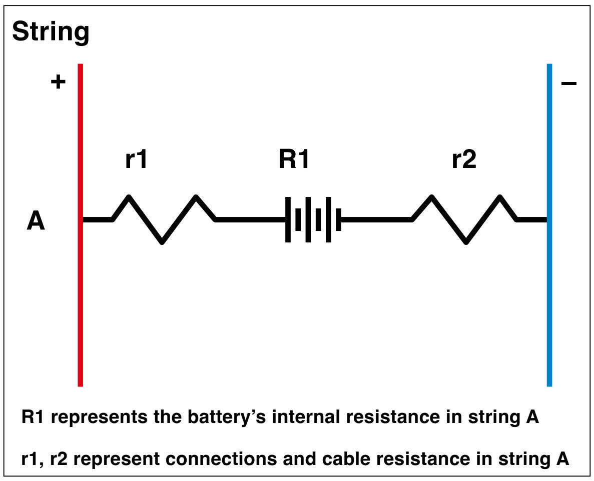
$$I3 = V/(r_5 + R_3 + r_6)$$

The implications for the charging voltage for each battery in each line can be summarised as:

Line 1: $V = v_1 + V_1 + v_2$ Where V = total voltage, v_1 = left connection and cable V_1 = battery one and v_2 = right battery connection and cable.

Line 2: $V = v_3 + V_2 + v_4$ Where V = total voltage, v_3 = left connection and cable V_2 = battery two and v_4 = right battery connection and cable.

Fig 5: Schematic of series connected resistance components in first single battery string



Line 3: $V = v_5 + V_3 + v_6$ Where V = total voltage, v_5 = left connection and cable V_3 = battery three and v_6 = right battery connection and cable.

The voltage across the battery will depend not only on the two obvious parameters of current and internal resistance but also on the limiting value of total voltage of the parallel line. When there is voltage limited charging, the voltage of the battery will be limited to the total available voltage, minus the sum of the voltages created by the other resistive parts of the circuit.

Taking line one in ***Fig 2*** as an example, the voltage across the battery can be calculated as:

$V = I_1 \times (r_1 + R_1 + r_2)$ where the voltage across the battery is:

$$V_1 = V - I_1 \times (r_1 + r_2)$$

There is an available voltage for the battery, dependent on the accumulated resistance of the connections and wires as well as the line current and internal battery resistance. The higher the line resistance the lower the current and the lower the battery voltage in that line.

The line current is affected by the total line resistance, including that of the battery. Because of this, many companies have recommended criteria for batteries chosen to be connected in series parallel circuits. The battery parameters that can have an impact on its internal resistance or impedance (R_{1-3} in our equations) can be listed as:

- State of charge ***(Fig 6)***
- Battery age
- Battery cycle duty
- Production batch
- Previous use history
- Electrolyte SG
- Measured impedance of a new battery at 100% SoC.

Many manufacturers and battery suppliers, if they are aware of their products being used in a parallel or parallel series configuration, will rank batteries according to the above criteria. They will supply groups of batteries that have similar backgrounds, to ensure minimum voltage and current variation across the batteries' terminals, when connected in a series parallel configuration. If, for example, a VRLA battery with a fully charged IR of 6m-ohms was paired with a similar battery at 20% SoC with an IR of 16m-ohms, there would be a voltage difference according to the applied current. If that were 20A in a parallel arrangement, then the on-charge voltage difference would be **dV** where **dV = 0.01 x 20 = 0.2 mv**. Which is a significant difference when considering a voltage dependant step, such as a gassing phase in the charging profile. Of course, the other consideration is the current difference that would occur in each parallel line due to the individual batteries' IR. The lower the battery IR the higher the current, the more Ah that would be put into that battery, assuming all other components were of equal resistance.

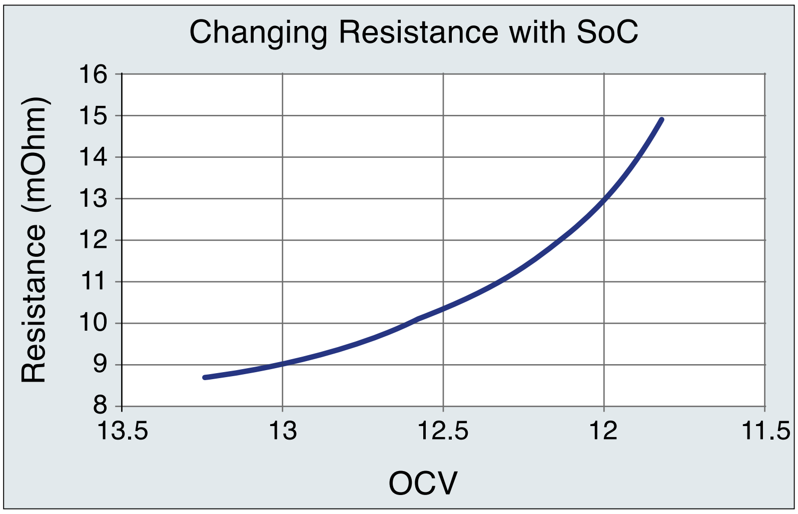


Fig 6: Internal battery resistance vs. state of charge (OCV represents SoC)

The other consequence of parallel charging is the lower current available to charge each battery. Unless the charger used is specifically designed for multiple batteries in parallel, the output current will be far lower than that designed to recharge a battery in a reasonable time. For example, if a designated charger for a single battery is designed to provide a full recharge in 10 hours then it will need approximately 10% more Ah than the capacity of the battery. In the case of a 200Ah battery that would be a total of 220Ah in 10 hours. The average current then would be around 22A, with big variations between bulk phase and gassing phase charging. For two identical batteries being charged in parallel on the same charger, that would mean doubling the time to 20 hours, or 40 hours for four batteries and so on for multiple parallel connections.

> **"Parallel-connected battery charging may often be convenient, but if not done correctly could be disastrous"**

In summary, despite the perceived advantage of getting extra 'free' space in a charging circuit, there are real dangers in adopting this measure as a routine practice. The fact that has to be appreciated is that it is not only long, multi-battery strings connected in parallel that present a danger; it is also parallel strings of single batteries if the batteries and the connected wiring are not virtually identical. Apart from the inconvenience of longer charging times, there is also the distinct danger of over and under charging batteries due to differences in SoC, battery internal resistance and the resistance of the connections and wiring in the circuits. Taking all factors into account, parallel-connected battery charging may often be convenient, but if not done correctly could be disastrous.