Advel Application Note – AAN2011.3

Industrial battery chargers

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1. Introduction

The variuos type of batteries, or accumulators of electrical charge, differ not only for the characteristics of voltage (expressed in volts) and capacity (expressed in Ah), but also and especially for the different internal chemical compositions, the shape, the size, the use.
The most common families of batteries are:

- Lead-acid battery (eg. in automobile vehicles, alarm systems), which are inexpensive and have low energy density, but can give high peak current required by some loads (eg. starter motors);
- AGM and GEL batteries, which cost slightly more than the previous ones, but have better features (...) and require less maintenance;
- Lithium-ion battery (eg. in laptops or cell phones) that have a high charge density and have no "memory effect" (...) but they are very expensive;
- Sodium-sulfur batteries,
- Batteries basic nickel (Ni-Fe, Ni-Mh, ...)
- ...

Investigate the characteristics of each family of batteries goes beyond the scope of this article; nowadays for industrial use are preferred GEL or AGM sealed batteries, which compared to Lead-Acid (in use until the year 2000 about) can tolerate higher charging voltages (and therefore higher internal temperatures) without damage, and also being hermetic have no problems of emissions of hazardous gases or acid spills (which makes them suitable for transport by ship or by air) and require almost no maintenance (no need of topping with distilled or demineralized water).
That said, what features should have the battery charger to be used in an industrial system with GEL or AGM batteries? And how do you size the "battery pack"? And what precautions are necessary for the wiring of the batteries?

2. Batteries AGM and GEL

AGM and "GEL" batteries are often considered, identical, but it's not correct. In fact, while both AGM and GEL are sealed type batteries and maintenance-free, technologically are different each other and then for the use in some services may be more suitable one or the other type .
The AGM technology is suitable to support a lot of full discharge cycles. These accumulators are in fact made inside with plates of lead-calcium type in which is wound an absorbent material soaked in acid; such technology allows electrolyte to evaporate during the charge and discharge (when the temperature inside increases), after which the bubbles produced are mixed with the acid bringing the battery to maintain a yield efficient.
The GEL batteries are instead internally composed of gelatinized acid and lead-calcium plates, are more delicate and easily are damaged if often charged and discharged because of the high temperature difference generated internally causing the solidification of the gel. For this reason GEL batteries are considered more suitable for buffer-use (eg. UPS or other uses that rarely require energy).

3. Capacity of a battery

The capacity of the batteries, **C**, defines the amount of electric charge that can be stored and is commonly expressed in Ampere-hour (Ah). To get the energy in Watt-hour is necessary to multiply the capacity (Ah) for the rated voltage (V). It's a good rule to consider the range 10 ÷ 100 hours as reference time and so for example: a 40Ah battery can give 4A for 10 hours... or 0.4A for 100 hours. This time range is to avoid misjudgments like:"*I have a 40 Ah battery so I can absorb 80A for half an hour*" or "*a 40Ah battery can give 10mA for 4000 hours*" that is almost 6 months!!! Infact it's good for a battery, except a very short time (a few seconds) not to give current that exceeds 10 to 20% of its capacity. Also, due to auto-discharge, the supplying of the load must not continue for more than few days (up to one week) since otherwise the self-discharge itself becomes important source of consumption.
In addition, the actual capacity of a battery is very dependent on the rate of discharge, decreasing with increasing current demand; the battery also getting old will worsen its nominal capacity C; moreover it should also be taken into account the working temperature of the battery... For these reasons, a 40Ah battery in reality can't give 4A for 10 hours, so that after the theoretical calculation of the battery required to obtain the requested autonomy of the system, it is good practice to use a safety factor of 2 which takes account all the real effects.

Let's make an example:

our system requires current 4A for 10 hours, then it should be good to have a battery-pack equal to:

2 *(safety factor)* **x 40Ah = 80Ah**

Empty battery

When a battery is defined empty? We defines empty a battery that, put a load, reaches the voltage $V_{nominal}$ – 20% or 9.6V for a 12V battery.
When a battery is giving current its voltage decreases more and more: it is important there is a control system that monitors the voltage across the battery, V_{batt}, and when V_{batt} touches the threshold V_{nom} – 20%, it disconnects the battery (as shown in Figure 1), preventing the "deep discharge" of the battery, that would damage irreparably the battery.

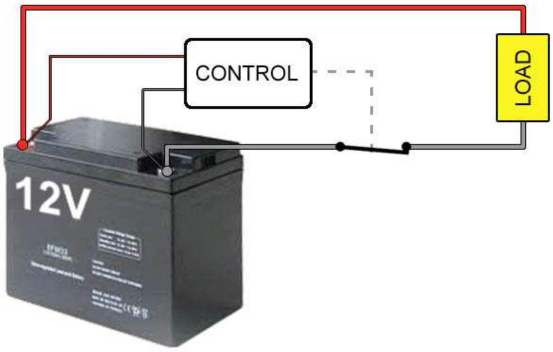

Figure1 *– Control system that monitors the battery voltage: @V_{nom} – 20% the battery is disconnected from the load.*

From now: battery empty, or "low battery" means that it reached the value V_{nom} – 20%.

4. Recharging of battery

A charging battery behaves in this way: it absorbs a current that depends on: the charging voltage, its state of charge, its internal temperature, the type of battery, the wiring, and even the manufacturer of the battery!
As the parameters involved are many, here we prefer to make a qualitative speech, at least initially, and will not be considered the variability dependent on temperature and wiring.

It can be said that a battery during recharge phase behaves as a variable resistance, whose value is inversely proportional to the state of charge:
when the battery is full discharged, it behaves as a very low resistance (→ high current recharging), as the battery charges this behaves like a resistor value gradually higher (→ recharging current gradually lower).
Helped by experience we can say that a 12V battery empty (or "full discharged" or in "low battery" state), subjected to V_{nom} +15% or 13.8V, starts to absorb a current equal to 20% of its capacity (in reality for a lead-acid battery the current would be lower, while for an AGM or GEL one the current would be higher, but here we considered an average value) .
Example: a 12V-40Ah battery <u>empty</u> → subjected to 13.8V will absorb 8A.
Always hepled by the experience we can say that a 12V battery completely discharged, subjected to V_{nom}+5% or 11.4V, absorbs zero current.

Increasing the charge level of the battery, at constant voltage charging, the current absorbed by the battery is lowered.
From experience we know that a 12V battery full charged, subjected to V_{nom}+15%, or 13.8V, absorbs a current of about 100mA÷1A (depending on battery type) called **holding current**, while subjected to V_{nom}+5%, or 12.6V , absorbs zero current.

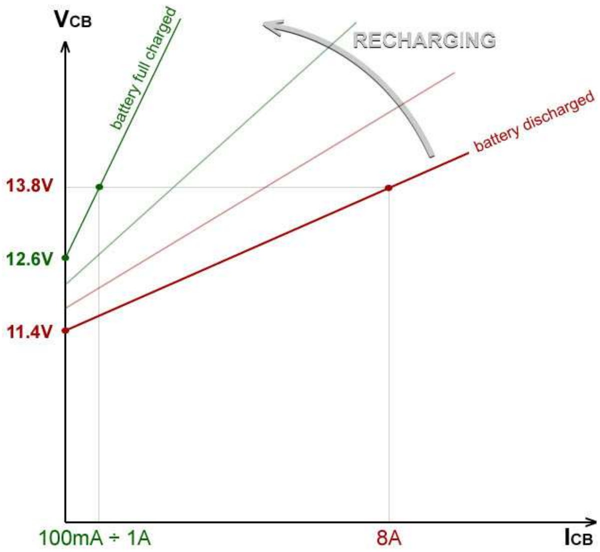

Figure2 *– Qualitative V / I characteristic for a 12V-40Ah battery, in different charge states, @25°C.*

In Figure2 is represented the I/V characteristic of a 12V-40Ah battery in various states of charge. The curves are qualitative, but based on direct detections made on real batteries (lead-acid and AGM, then averaging the values), at temperature 25°C.

The modeling of the battery with a resistor will allow us to make useful considerations later.
That said, how have to be charged a battery? A battery can be recharged in two basic ways: with constant current or at constant voltage.

Constant current recharge

The battery manufacturers recommend to <u>recharge the battery at a constant current equal to 10% of rated capacity</u>, we take the example of the usual 40Ah battery → suggested recharging current is 4A.
In reality this rule was true for lead-acid batteries, but using AGM or GEL batteries this limit could easily be exceeded (think for example that for GEL batteries the maximum recharging current can be equal to 0.5A for Ah and therefore 20A for a 40Ah-battery), however it is common practice to

use the old rule, that ensure a "quiet" recharge, which prevents the battery to get too hot, thereby increasing the longevity of the battery.

Recharging a battery at a current equal to 10% of rated capacity, the time for a complete recharge should be equal to 10 hours, but in reality the recharging time is typically higher as previously said, because the charging process has not 100% efficiency (think that the battery heats up during charging: the waste heat implies that a part of energy is lost as heat). We can assume that the recharging time in this condition is equal to about 12 hours (we have assumed a 20% loss in heat).

Consider a 12V battery: when recharging at constant current, the battery voltage is variable, ranging from about 12.5 ÷ 12.6V (moment when the battery is empty) to more than 14V (charged battery). It's very important that the battery charger may monitor the battery's voltage to determine when it's fully charged (or upon reaching a certain voltage) and consequently limits the charging current to the value of maintenance (100mA ÷ 1A depending on battery capacity), or typically set the voltage 13.8V.

Consider for example a 12V-40Ah battery, empty and put in recharging at constant current I_{CB}.
In Figure 3 are shown the qualitative trends in the two conditions of constant current recharging: of course if you charge the battery at 6A the charging time is less than recharging at 4A. The voltage at the beginning of recharging (battery empty) are extrapolated from the characteristic of the battery of Figure 2.

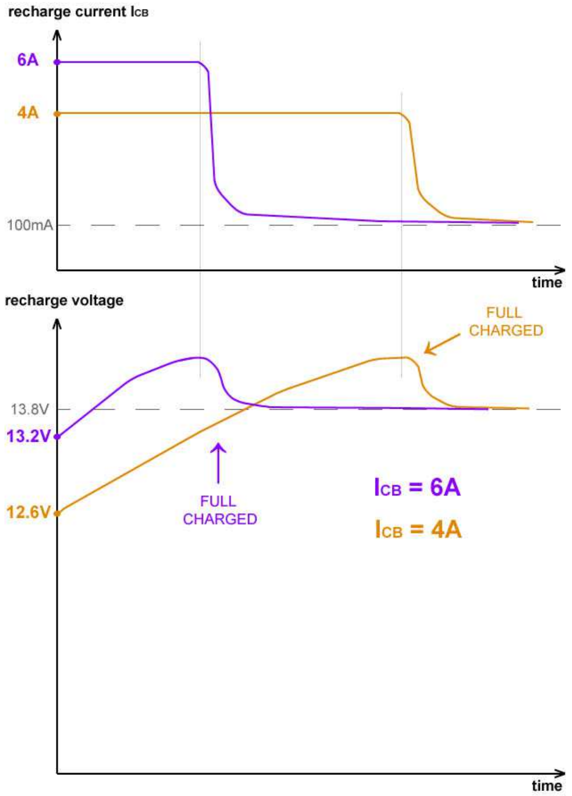

Figure3 *– Qualitative I / T and V / T characteristic of a 12V-40Ah battery recharged at constant current, for different values of recharging current* I_{CB}.

This type of battery recharging is very reliable and safe, and is recommended if you have a "small" system, with a single battery charger; but if the system is composed by more battery chargers in parallel (for example, to achieve redundancy, or because the system is very large) it should be implemented a system that allows the power supplies to equally divide the charging current, to increase the reliability of the system (see **AAN 2009.1**), which could complicate the system.

Constant voltage recharge

The battery can also be recharged at constant voltage. In this case the manufacturers recommend recharging at rated V_{nom} + 15%.
When a 12V battery is connected to a battery charger with a constant voltage V_{CB}, this absorbs a variable current:
the maximum peak charging current is when the battery is low (empty), as the battery recharges the current absorbed by the battery drops. When the battery is full charged the current absorbed by the battery is very low and tends to typically 100mA ÷ 1A depending on the battery capacity and $V_{CB} = V_{nom} + 15\%$.

Consider for example the 12V-40Ah battery empty and put in recharging at constant voltage V_{CB}. In Figure 4 some recharging curves.

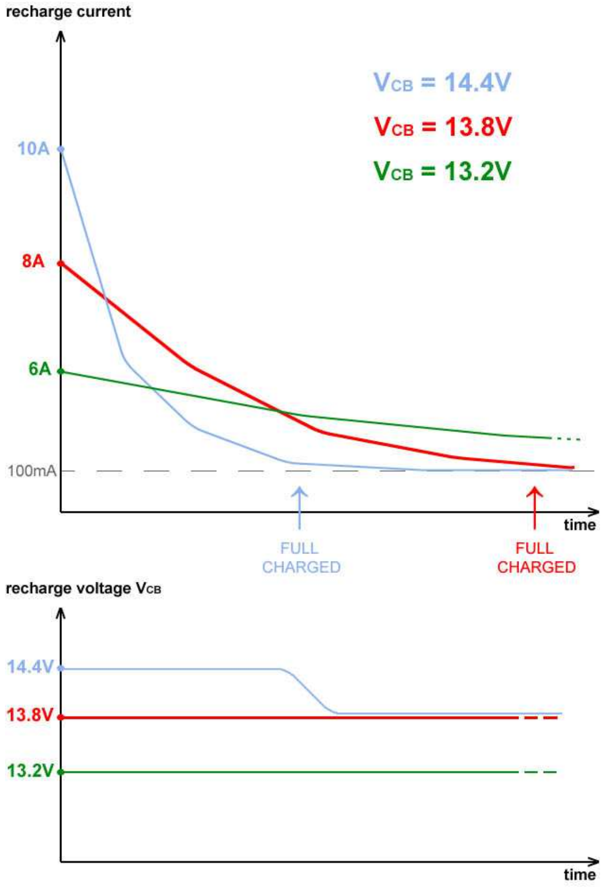

Figura4 *– Qualitative I / T and V / T characteristic of a 12V-40Ah battery recharged at constant voltage, for different values of recharging voltage* V_{CB}.

This recharging system is absolutely recommended, because of its simplicity, if the battery is used in buffer and not subjected to frequent discharge-recharge cycles.
However, it can also be used for systems with frequent deep discharge of the batteries, but in this case it must be keep under control the recharging current, especially at the beginning of charging, infact in this period the absorbed current is very high and therefore the batteries tend to heat very much.

Recharging at constant voltage is also suitable for very large systems, since working at constant voltage is very easy to build systems composed of multiple battery chargers in parallel with active current sharing (for the equitable sharing of the load current between the battery chargers).

Another big advantage of this type of recharging is the fact that it's possible to use the (constant) voltage of the battery charger also to directly supply the load, with obvious economic savings of the system. We will see later an example.

In Figure 4 are showed the qualitative trends I / T and V / T in three conditions at a constant voltage charging: of course the charging time is lower if the charging voltage V_{CB} is higher.
Note that the battery manufacturers don't recommend to use a charging voltage exceeding V_{nom} + 20% (or 14.4V in our example) for an indefinite time. For this reason some battery chargers provide a voltage $V_{CB} = V_{nom}$ + 20% just to speed up the charging time and once the battery is fully charged, the charging voltage drops to $V_{CB} = V_{nom}$ +15%, see blue curve in Figure4.
If there aren't special requests from the user on recharging times, it's suggested to use indefinitely a fixed voltage $V_{CB} = V_{nom}$ +15%, so as to simplify the battery charger.
Also note that using an indefinitely fixed recharging voltage lower than V_{nom} +15% (green curve in Figure 3), in addition to very slow down the charging process, it doesn't allow to charge the battery at 100% of its capacity.

Comparison of the two charging systems
It is appropriate now to make a distinction between: small power system, if formed by a single battery charger, and big power system, if consists of more battery chargers in parallel, necessary to achieve the required power or to achieve redundancy (typical industrial systems).
For these two macro-systems, depending on the use of the batteries (in buffer and / or with frequent deep discharges) in the following tables are summarized the pros and cons of the two charging systems: **C-C** (constant-current) or **C-V** (constant voltage).

SMALL POWER SYSTEM	
Battery used in buffer	Battery subjected to frequent full discharges
Equally good both the recharging systems: ***C-C** or **C-V** (NOTE: **C-V** is cheaper).*	*It's recommended a **C-C** system, which ensure a longer life of the battery.*

BIG POWER SYSTEM	
Battery used in buffer.	Battery subjected to frequent full discharges
*The **C-V** system is perfect, for the easiness to put in parallel more battery chargers (for redundancy or obtain more power).*	*The **C-C** system is fine to ensure greater longevity of the batteries but it's complicated to put in parallel more battery chargers.* *The **C-V** system is good because it's easy to put in parallel more battery chargers (with active current sharing) but it's important to find solutions to put a limit to the maximum current absorbed by the batteries.*

Recharging with temperature compensation
In both cases, **C-C** or **C-V** battery chargers, the battery manufacturers, for an optimal recharging aimed to increasing the average life of the batteries, recommend that the charging voltage V_{CB} is function of the battery temperature T_{batt}, typically -18mV/°C for a 12V battery.
Consider for example a 12V battery recharged at constant voltage and temperature compensation, as in Figure 5.

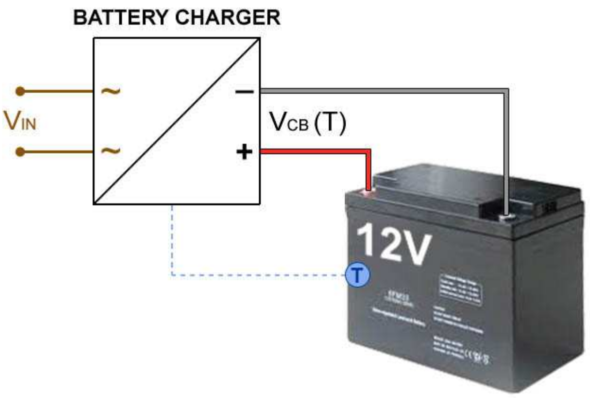

***Figure5** – Battery charger with voltage $V_{CB}(T)$ function of the temperature of the battery.*

The suggested voltage at temperature 25°C is:
V_{CB} @25°C = $(12V + 15\%) = 13.8V$

while at different temperature applies the formula:

V_{CB} @T°C = $(12V + 15\%) - 18\frac{mV}{°C} \cdot \Delta T$

eg. if T_{batt}=38°C it's obtained: V_{CB}@38°C =

$$(12V + 15\%) - 18\frac{mV}{°C} \cdot (38 - 25)\ °C = 13.56V$$

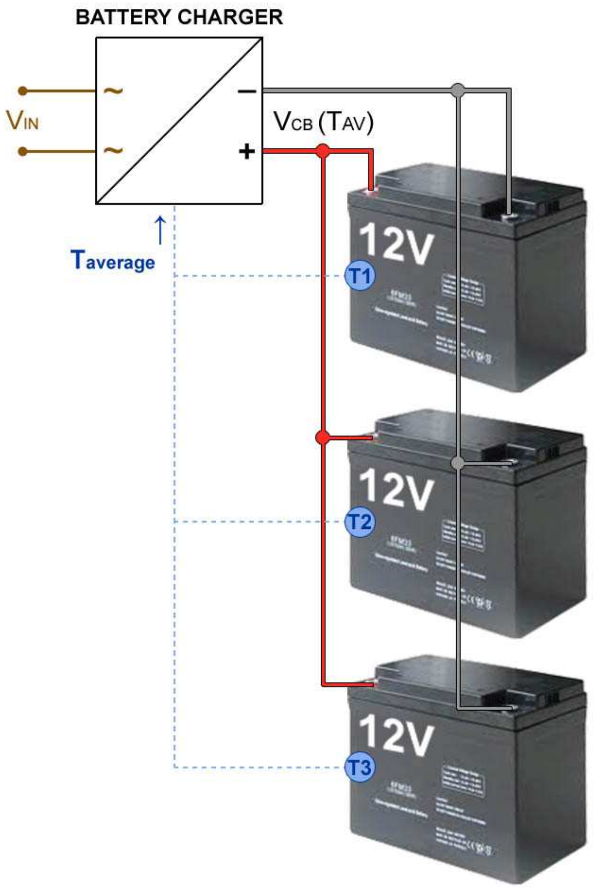

***Figure6** – Single battery charger with voltage $V_{CB}(T_{AV})$ function of the <u>average</u> temperature of the 3 batteries.*

The problem of reading the temperature of the battery is complicated with a system containing more batteries in series/parallel and powered by the same battery charger, as in Figure 6: in this case should be detected the temperature of the individual batteries, with obvious complications both in the wiring phase and in the management of the signals.

In fact, it is obvious that the batteries are not all the same temperature, and the most obvious solution is to vary the V_{CB} as a function of the <u>average</u> temperature T_{AV} of the 3 recorded temperatures.

But at this point a question arises: if one of the 3 batteries fails, and becomes very hot, this leads to a T_{AV} that is not optimal for the remaining batteries. This example shows that such a system (single charger with multiple batteries in parallel and <u>average</u> battery temperature compensation) should not be used.

An ideal system should have a single battery charger for each battery and relative temperature compensation. But of course this would mean a significant increase in costs and as often happens, we have to make compromises.

It can be said that a battery charger with temperature compensation is only recommended if the battery is single and it's in thermal conditions not predictable or very far from 25°C.

Instead, for a typical industrial system (often composed of more batteries) is a good idea to place the battery pack in a room with controlled temperature (20 to 30°C) and not provide any battery temperature compensation.

Sometimes is detected a single average temperature of the battery pack that is only used to stop recharging when exceeding a certain maximum temperature $T_{max\text{-}batt}$, typically 45 to 50°C (although the AGM or GEL could also work at higher temperatures, as previously said); in this case the recharging resumes later when the temperature of the battery pack returns back to lower values.

6. Wiring of the batteries

The battery wiring is often wrongly overlooked, however is crucial to make a good wiring especially if you need to put more batteries in parallel.

<u>Ideal and real wires</u>

The "real" wiring cables have a certain ohmic resistance: the non-ideality of the cables causes all the problems related to the battery wiring.

The cable resistance is calculated using the formula

$$R_{cable} = \frac{\sigma \cdot L}{S}$$

with:

σ_{copper} = 0.017Ω mm^2/m

L = cable lenght [m]

S = cable section [mm^2]

An example will clarify definitely the problem introduced by the cables:

consider a **C-V** battery charger (constant voltage) with output voltage 13.8V, 12V-40Ah battery, distance from the battery charger L=1m, wiring cable with section S=2.5mm^2, as in Figure7.

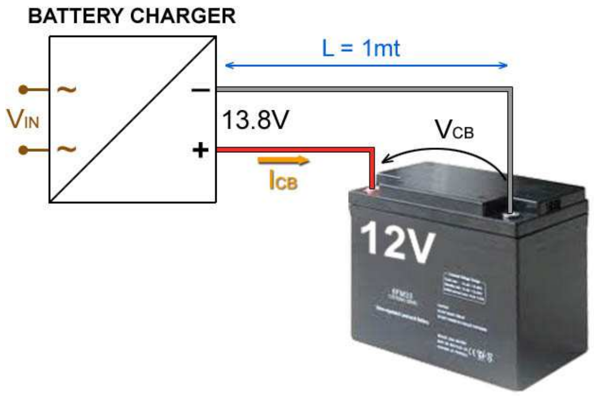

***Figure7** – C-V battery charger 1mt far from the battery.*

If the cable is ideal, the R_{cable} = 0Ω, the recharging current would be as the red curve of Figure 4.

Instead the cable has a resistance R_{cable} > 0Ω:

$$R_{cable} = \frac{0.017 \cdot (2mt)}{2.5mm^2} = 13.6m\Omega$$

NOTE: the cable lenght is twice the distance, because there is the positive and the negative wire.

Considering the resistance of the contacts, approximately $5m\Omega$ for contact (typical value), we have:

$$R_{cable+contacts} = 13.6m\Omega + 2\times 5m\Omega \approx 25m\Omega$$

$$V_{CB} = 13.8V - I_{CB}\cdot 25m\Omega$$

Solving the system graphically, with the characteristic I/V of Figure 2, we find that the battery, empty and put at a constant voltage 13.8V, wired with a 2.5mm^2 cable, is initially subjected to 13.6V (not 13.8V) because of the voltage drop (0.2V) on the cable.
As a result of lower charging voltage of the battery, the charging current is even lower: it's no longer 8A as ideally assumed, but 7.4A, as shown in Figure8.
This results is a slight increase in charging time.

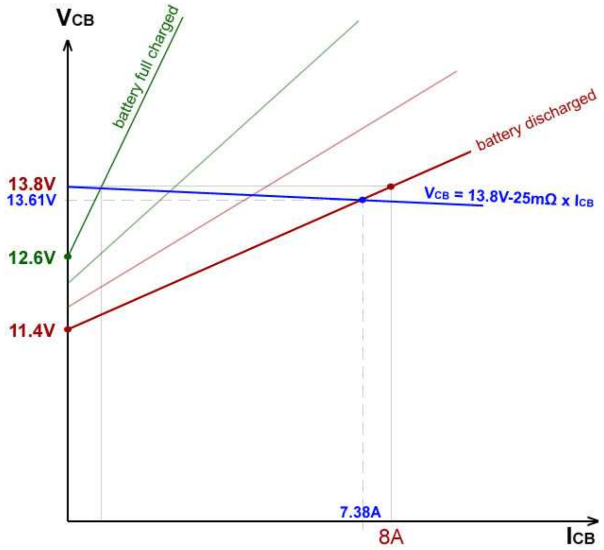

Figure8 *– Battery charger 1mt far from the battery, considering a real wiring cable (with a non null ohmic resistance).*

This simple example can be extended to case of more batteries in parallel, as in Figure 9.
Looking at the example in Figura9, making a purely qualitative speech, we can realize perfectly well that, even if the battery charger is setted at 13.8V:

- the first battery is subjected to a voltage V_{CB1} that is $V_{CB1} < 13.8V$
- the second battery is subjected to a voltage V_{CB2} that is $V_{CB2} < V_{CB1} < 13.8V$

this is due to the voltage drop on the connecting cables, that are not negligible in reality.

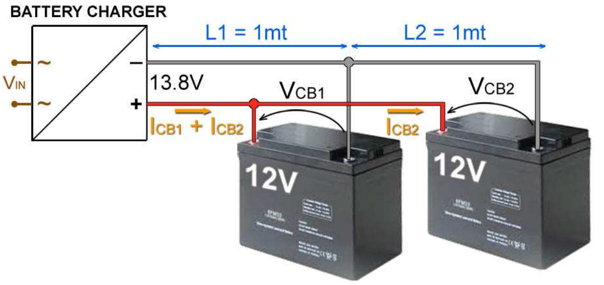

Figure9 *– Added a battery in parallel to the system of Figure 7 (C-V): the new battery is subjected to a lower voltage.*

The problem gets worse the more batteries are put in parallel: the farest batteries from the battery charger will have recharging times gradually higher, and the differences are also during the discharging.
This is a problem because the batteries are not used in the same way and they will age differently.

The consequences of a wiring such as Figure9 would be even worse with **C-C** battery charger (constant-current), since there would certainly be a big difference of the recharging current between the batteries, and thus the first battery (nearest to the battery charger) absorbs certainly more current than the second. As the number of batteries increases, the problem gets worse and in a relatively short time the first battery would tend to "bloat" due to excessive recharging current, and would be irreparably damaged.

Suitable types of wiring

The problems arising from the non-ideality of the cables can be solved using appropriate wiring techniques.
The "star" wiring put cables of equal length between each battery and the battery charger, as in Figure 10. The consequence of this wiring is that $V_{CB1} = V_{CB2} = V_{CB3}$: the batteries are charged in the same way, for both C-V or C-C type battery charger.

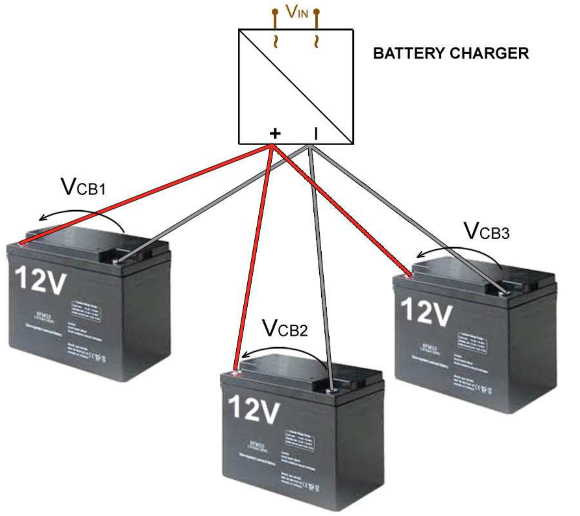

Figure10 *– N.3 batteries in parallel, in "star" wiring: the cables between each battery and the battery charger are identical in lenght, then $V_{CB1} = V_{CB2} = V_{CB3}$.*

The star wiring, however, is not easy to achieve with more than 2 batteries. In the industrial systems, in which often are used battery packs composed of many batteries, the star wiring is almost never used.

On the contrary the wiring shown in Figure 11 is very interesting.

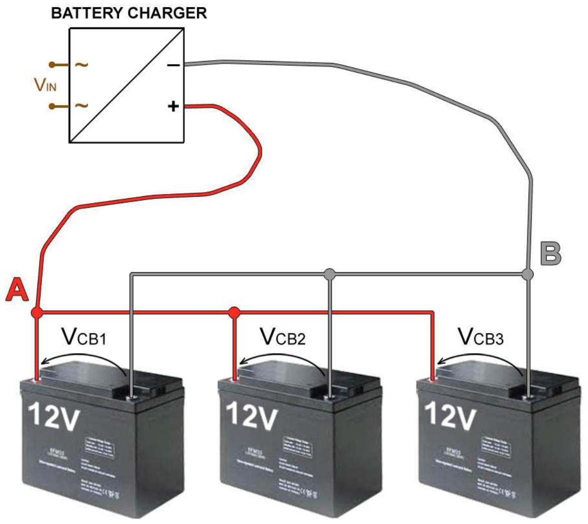

Figure11 *–N.3 batteries in parallel, wired so as to eliminate the asymmetries in voltage due to wiring.*

The batteries in Figure 11 have charging voltages $V_{CB1} = V_{CB2} = V_{CB3}$ thanks to the fact that the positive of the battery pack is taken on the positive of the first battery, and the negative of the battery pack is taken on the negative of the last battery. In addition, this type of wiring is quite simple and easy to accomplish even with battery packs consisting of a lot of batteries.

7. Health of a battery

Of course the battery over time tends to lose its nominal capacity: an old battery does not ensure the originally planned autonomy. But it is not easy to realize if a battery is health or not; for example, often happens that a faulty battery with no load presents yet the nominal voltage, but if put under load (even using a small load) the battery voltage drops instantaneously.

Internal resistor R_i

A real battery in the discharging phase can be modeled as an ideal battery with a resistor in series, said Internal Resistor or R_i, as shown in Figure12.

The nominal Internal Resistaor of a full-charged and healthy battery is indicated on the datasheet. Typically it depends on the type of battery, the size and temperature. In any case, the internal resistor increases as the battery discharges and especially with increasing the age of the battery, and therefore it can be used to establish the degree of health of the battery.

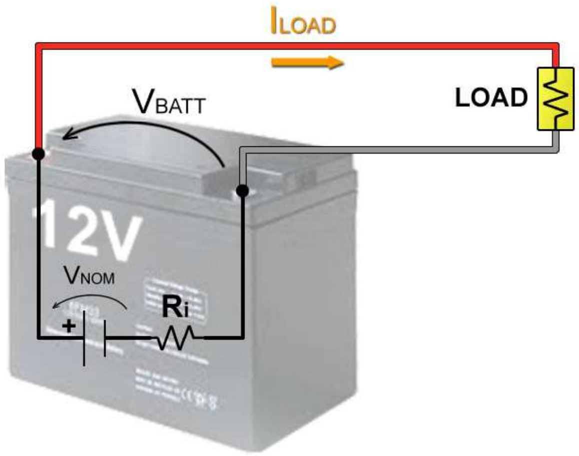

Figura12 *– Real battery, modeled as an ideal V_{nom} battery with a series resistor R_i.*

Looking at the modeling of the battery of Figure 12 is now clear that if the internal resistor R_i is high (because the battery is empty or faulty) a load ask current from the battery, the V_{batt} decreases because of internal voltage drop of V_{Ri}.

R_i calculation

A system for R_i calculation of a battery should be as follow:

- the battery charger disconnects the battery, which remains with no load,
- the battery voltage of the battery with no load is recorded, $V_{batt.\ no\ load}$
- a known load R' is put on the battery, and the new battery voltage is recorded, $V_{batt.\ @R'}$
- the battery is connected back to the battery charger.

To determine the R_i symply use the Ohm Law, whick drive us to the following equation:

$$R_i = R' \times \left(\frac{V_{batt.no\ load}}{V_{batt.@R'}} - 1 \right)$$

If the calculated R_i exceeds a certain value (that is predefined and temperature dependent), the battery is defined faulty.

Some battery chargers perform this test automatically once every period of time T (for eg. 4 hours as required by legislation **EN54.4 2011**).

The system just described is very accurate, but it's not always required such precision.

There are in fact other ways to get the health of the battery, much more practical than the previous. Some battery charging systems for example have the ability to perform an **INHIBIT** of the battery charger that lower the voltage of the battery charger at a known value $V_{inhibit}$, so as the load is totally left on the battery; the battery is considered good if it's able to power the load for a certain time. On the contrary, if the battery voltage drops to $V_{inhibit}$, it means the battery if faulty.

This test can be performed manually or automated: it doesn't provide a true measure of

the state of the battery, but it gives an indication that the battery does or does not perform its function in our system.
The "inhibit method" is certainly much cheaper than the method which calculates R_i precisely.

8. Examples of battery chargers from Advel

Advel manufactures power chargers in two series: for DIN rail mounting (SPS-CBD) and in rack format (SPS-R).

DIN rail mounting series

The single power supplies for DIN rail mounting are available in different power sizes, between 100W and 600W (however parallelable to get more power) and contain onboard a battery control device.
Take as an example the **SPS251CBDZ** (Figure 13), which has the following characteristics:

- output for load and battery (max 100Ah);
- battery fuse onboard;
- battery empty alarm (*);
- V_{in} lack alarm (*);
- manual inhibit;
- internal relay for battery disconnection.

(*) Features required by **EN54-4**.

Figure13 *– Battery charger manufactured by Advel, series SPS251CBDZ.*

For higher power the SPS251CBDZ can be connected in parallel to another one or use a greater size power supply (up to 600W).
This power supply, C-V type, allows you to get a complete DC-UPS system (see **AAN2012.1**).

Rack series

The power supplies in the standard rack 19" rack, **SPS-R**, have their strenght in reliability and easy of manteinance.
The main features are:

- output for load and battery (> 500Ah);
- hot plug-in/out internal modules;
- internal battery fuse (optional);
- battery empty alarm (*);
- V_{in} lack alarm (*);
- manual inhibit;
- relay for battery disconnection is: external (as default) to be sized according to the capacity of the battery, or internal (on request) realized with a solid state relay.

You can choose the size of the rack (wall mount or back panel), the position of the terminals (front, rear), the position of the fans (top or rear), the internal wiring (2 inputs or one input, outputs in parallel or output for each power supply module, ...). In Figure 14 an example of a rack of SPS-R

Figure14 *– Rack SPS-R, format RK8p2 (wall mounting) with n.2 600W modules, rear terminal block, battery control devices (BCD, RMCB).*

Inside the SPS-R rack the customer can decide to include a multitude of options:

- voltmeter and / or ammeter;
- temperature compensation;
- circuit breakers for input and / or output;
- isolation controllers;
- ...

9. Conclusions

After this qualitative, but dense, introduction to the world of batteries, it can be concluded that the battery charger perfect for every situation does not exist, but it must be chosen according to the specific need.
Also, once defined the characteristics that must have the power charger, it is very important not to overlook the wiring, and pay attention to the temperature of the batteries, which for safety reasons should never exceed certain limits (typically 45 to 50°C).

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