Advel Application Note – AAN2012.1

Industrial DC-UPS systems with battery

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1. Introduction

In the design of any industrial plant/project, it's important to identify the critical loads for which the power failure has a significant impact on the production (and therefore of course on production costs) and especially for the safety of personnel. Infact always some power lines are defined as "privileged" because used for critical loads of the system: for these critical loads is created an uninterruptible power supply system (called **UPS**, Uninterruptible Power Supply) which ensures an uninterrupted, and high quality, AC line. There are various types of UPS (...)

The AC line (network or UPS) is followed by the AC/DC power supplies that directly supply the various loads; these power supplies can be combined to obtain a redundant system, which takes the loads powered even in the event of failure of one of the power supplies (see **AAN2009.1** and **AAN2009.2**).

The use of UPS lines followed by AC/DC redundand power supplies, ensures continuity of DC supply for the loads/users.

However in an industrial plant it may happen that:

- a certain load is not powered by UPS line but you want to protect against casual voltage drops,
- there is UPS but it's necessary periodically to turn off the UPS, even for just few minutes in complete safety (eg. for manteinance),
- certain loads require very high power (>10 times the rated power) for a short time (eg. turn on engines)
- …

In these cases listed above it's necessary an AC/DC system with battery backup, said **DC-UPS**. In this article we will focus on the characteristics of a DC-UPS system, also analyzing practical examples of calculation and sizing.
Before you continue reading, it is suggested to read carefully the **AAN2011.3**, in which were described the characteristics of the battery chargers for industrial use.

2. DC-UPS system

A DC-UPS system consists of:

- a power supply for the load
- a battery charger
- a battery pack

There are several ways to realize a DC-UPS system, which will be briefly illustrated.

Stand-by DC-UPS

Figure 1 schematically shows a typical **Stand-by DC-UPS** system; the operation is as follows:
the battery charger powers the battery, keeping it charged, while the power supply powers the load.
Note: the **INT** switch is normally open and the voltages of the two power supplies are different.
If the V_{in} is missing, the system shuts down but **INT** closes and then the battery powers the load for a period of time T_{aut}.
Battery capacity has been chosen on the basis of the autonomy T_{aut} you want.
The battery charger can be either C-C or C-V and may or may not have certain characteristics (voltage/current charging as a function of the temperature of the battery, system with INHIBIT or reading of R_i, ...) already shown in **AAN2011.3**.

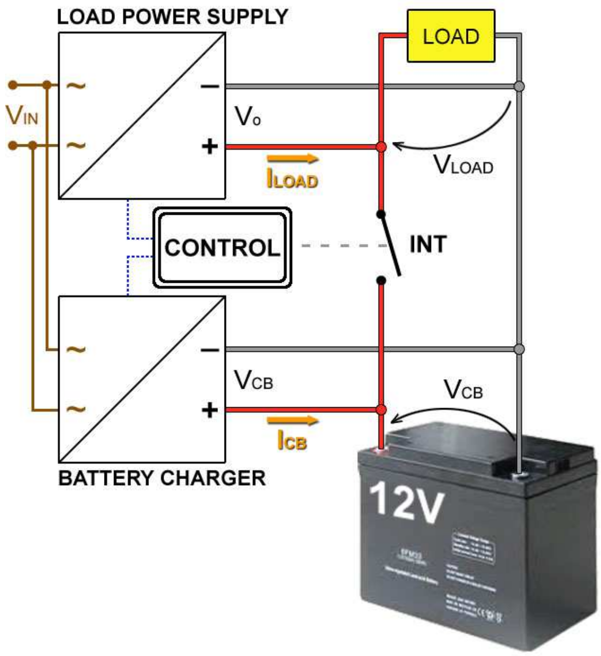


Figure1 *–Stand-by DC-UPS system composed of: a power supply for the load and one for the battery.*

Looking at Figure 1, consider for example the following parameters:

- battery charger C-V type, with V_{cb} = 13,8V
- load = 20A, $V_{load-rated}$ = 12V
- battery pack capacity C = 40Ah

Using the formulas already explained in **AAN2011.3**, we calculate that:

T_{aut} = 1 hour (infact: 40Ah battery → 40A for 1h and then 20A for 2h, however by dividing by safety factor 2, we obtain that the autonomy time is equal to 1 hour).

The system has this output power:
P = 12V x 20A (for the load)
+ 10%C x 13.8V (for recharging the battery)
= 300W about.

The voltage for the load is:
V_{load} = 12V if V_{in} is present,
V_{load} = 12V ÷ 9.6V is V_{in} missing (infact the voltage of the battery, when the battery powers the load, will drop to a minimum value $V_{batt-rated}$ –20%, typical voltage at which the battery is considered empty and then **INT** opens).

In a stand-by DC-UPS system the CONTROL device performs many activities: it must keep open **INT** in normal situations and close **INT** if there is a V_{in} lack and then re-open **INT** in case V_{in} comes back or in case V_{batt} falls below the typical minimum value $V_{batt-rated}$ –20%.
In case of lack of V_{in}, **INT** must be closed before the V_o goes to zero, to avoid voltage drops for the load: this has to be assured by the Hold-Up time of the Load Power Supply, which must be at least 40msec, namely: 20msec (typical time a circuit breaker to close) + 20msec (time for the system to "realize" that V_{in} is missing).
Finally, the CONTROL device must be able to deal with the failure conditions: what happens if one of the power supplies fails, even if V_{in} is present?
As you can well understand, the CONTROL device must be very sophisticated and reliable.

Simplified Stand-by DC-UPS
Figure 2 shows a simplified stand-by DC-UPS system: this system is identical to the classic stand-by DC-UPS, except for the fact that the **INT** switch is replaced by a diode **D**.
This greatly simplifies the system, but requires that: $V_{BATT} \leq V_{LOAD}$.
In fact, if $V_{BATT} \leq V_{LOAD}$ the diode **D** is not directly polarized and therefore does not conduct (behaves like an open switch); if the primary power supply V_{in} fails, the diode **D** is polarized directly and the load is powered by the V_{BATT} - V_D voltage battery (with a typical value V_D = 0.5V diode bias voltage).

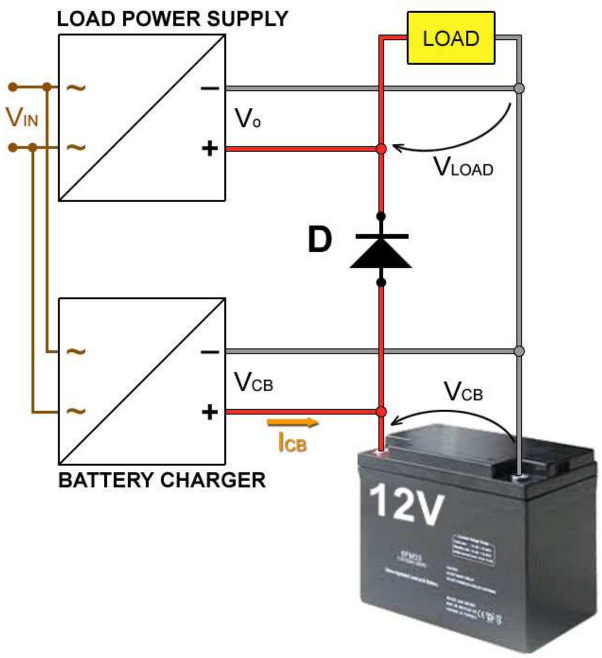


Figure2 *– Simplified Stand-by DC-UPS system: the power supply for the load and the charger are decoupled by a diode instead of a switch.*

The operation of the simplified Stand-by DC-UPS system is very similar to the classic one, with the following considerations:

- the load voltage (V_{LOAD}) and the battery recharge voltage (V_{BATT}) are independent, but we must be sure that $V_{BATT} \leq V_{LOAD}$. So for example considering the system seen above ($V_{load-nom}$ = 12V) should be set:
  V_{BATT} = 13.8V (typical charging voltage)
  V_{LOAD} = 13.8V (it is assumed that the load can be supplied at this voltage level without problems).
- The charging current of the battery can no longer be controlled at will, as it was in the classic case: in fact it is no longer possible to use a constant-current battery charger (type CC), since that it typically raises a lot the charging voltage of the battery. It is therefore necessary to use a constant voltage battery charger (type C-V).
- The load, when powered by the battery, is at V_{BATT} – V_D voltage, and therefore at lower voltage compared to the classic case.

The advantage of the simplified DC-UPS stand-by system, compared to the classical one, is basically the lack of the circuit-breaker (replaced by a simple diode) and the related control card: this leads to greater reliability and above all lower system costs .

Online DC-UPS
Figure 3 schematically shows an Online DC-UPS system; the operation is as follows:
the battery charger powers both the battery and the DC/DC converter, which in turn powers the load.

In case of a V_{in} lack, the battery charger shuts off but the battery powers the DC/DC converter for a certain time, T_{aut}.
The battery charger can be either C-C or C-V and may or may not have certain characteristics (voltage/current charging as function of the temperature of the battery, system with INHIBIT or reading of R_i, ...) already shown in **AAN2011.3**.

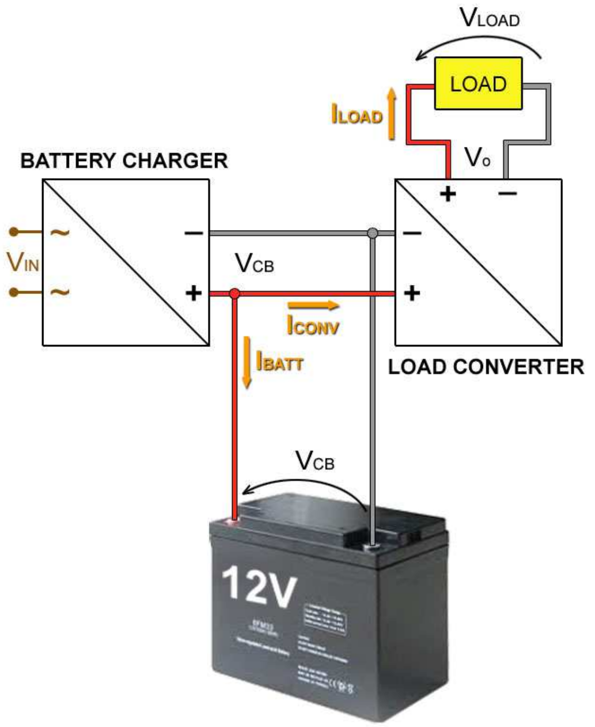


Figure3 *– Online DC-UPS system composed of a cattery charger and a DC/DC converter.*

Consider the same parameters used for the previous example:

- battery charger C-V type, with V_{cb} = 13,8V
- load = 20A, $V_{load\text{-}rated}$ = 12V
- battery pack capacity C = 40Ah

Using the calculations already used in the previous paragraph, we have:

T_{aut} = 1 hour.

The system has this output power:
P = 12V x 20A (for the load)
+ 12V x 20A / η_{conv} (for the DC/DC converter)
+ 10%C x 13.8V (to recharging the battery)
= 600W about.

in which we have considered an efficiency of the DC/DC converter η_{conv} = 80%.

The voltage for the load is:
V_{load} = 12V fixed and stabilized by the DC/DC converter.

In a Online DC-UPS system the CONTROL device is much less sophisticated than that of a Stand-By DC-UPS system, infact it simply have to open **INT** when V_{batt} falls below the typical value $V_{batt\text{-}rated}$ –20%.

<u>*Stand-by DC-UPS vs online DC-UPS*</u>
The online DC-UPS, compared to the Stand-by system seen above, does not present any voltage hole when V_{in} is no longer present, furthermore it allows to always maintain a stabilized voltage to the load.

In case the load requires a higher voltage, for example $V_{load\text{-}nom}$ = 48V:
with the DC-UPS Stand-by you must use a 48V battery pack (can be installed with 4 x 12V batteries in series), while with the DC-UPS online the battery pack remains at 12V (which is a stantard).

However, the Online DC-UPS system is very bulky, as the charger must provide power both for charging the battery and for powering the DC/DC converter, in cascade. Furthermore, it should be considered that in the Online DC-UPS in the event of a DC/DC converter failure, the load would remain de-energized and therefore it would be advisable to redundate the DC/DC converter, for example by putting two in parallel.

<u>*Single power supply DC-UPS*</u>
There is another DC-UPS system easier than those described above.

This comes from a very pratical consideration:
<u>typically an electronic device which requires to be supplied at a certain rated voltage $V_{load\text{-}rated}$, accepts indeed a voltage between $V_{load\text{-}rated}$ – 20% and $V_{load\text{-}rated}$ + 20%</u>.

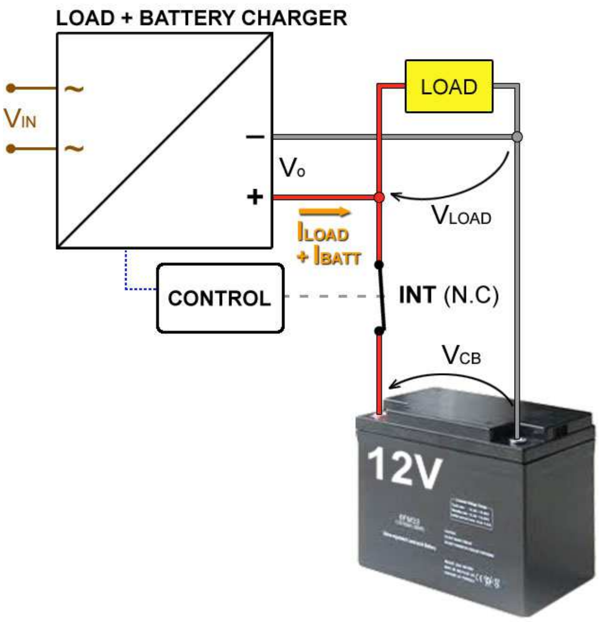


Figure4 *– DC-UPS system composed of a single power supply for the load and the battery recharging.*

After this consideration, returning to the previous example:
if the LOAD, which requires to be powered at 12V, agrees a voltage range 12V±20% or 9.6V÷14.4V (see the datasheet of your LOAD), then you can use a single power supply that serves both to power the load and to charge the battery, as shown in Figure4.

In the end you get a total power equal to that of a Stand-By DC-UPS.

The voltage for the load is:
V_{load} = 13.8V if V_{in} is present,
V_{load} = 13.8V ÷ 9.6V if V_{in} is missing.

As for the Online DC-UPS, with this system the switch **INT** remains normally closed both in presence and absence of V_{in}, and must be opened only if V_{batt} falls below $V_{batt\text{-}rated}$–20%, simplifying the CONTROL device, and particularly eliminating the voltage drop.
Of course this type of system costs much less than the two preceding, and presumably has a higher reliability, because of the greater simplicity.

Note that a 'single power supply' DC-UPS system imposes the choice of a C-V type power supply, in fact it would be risky (for the load) using a C-C power supply, which during charging of the battery may bring the voltage at extremely high levels.

Sizing the single power supply DC-UPS
Using a single C-V power supply DC-UPS for load and battery charging (Figure 3) requires an appropriate sizing of the power supply.
The classic question is: "*if you use a single power supply for load and battery, how can I prevent the battery to absorb all the available current, leaving the load with zero current?*"
The question is wrong: the battery CAN NOT absorb the current, removing it to load!
We need to clarify in this regard, because this wrong question is very recurrent.

Figure 5 shows the typical I / V characteristic of a 12V-40Ah battery @25°C depending on the state of charge.

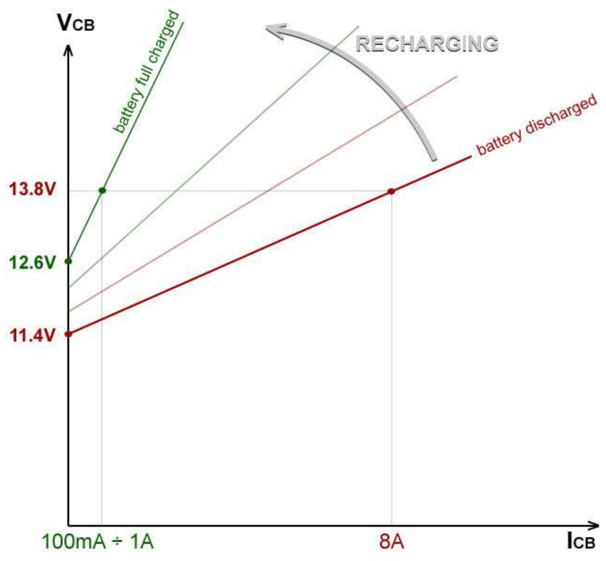


Figure5 *– Qualitative characteristic I / V of a 12V-40Ah battery depending on the state of charge, @25°C.*

The battery during recharging, as explained in **AAN2011.3**, can be modeled as a variable resistor, whose value depends on the state of charge of the battery, in fact, the I/V characteristic is a straight line, which varies the inclination as function of the state of charge of the battery (Figure5).

Let's take a practical example, suppose you have:

- a single power supply DC-UPS, C-V type, output voltage = 13.8V, maximum output current = 8A,
- a 4A load (@$V_{load\text{-}rated}$ = 12V),
- 40Ah battery (I-V characteristic in Figure4)

We consider the worst case: the battery is initially empty. Looking at the characteristic of the battery seems clear that if the battery is empty and put in charge at 13.8V, it tends to absorb 8A (see Figure4, brown line).

The battery and load current demand is respectively 4A and 8A, but the DC-UPS can give up to 8A, then: what happens? How the current will be divided between battery and load?

The LOAD absorbs 4A@12V, a total of 48W. In this qualitative speech, <u>we can model LOAD as a variable resistance at constant power</u>:
LOAD absorbs 48W or 4A@12V, or 13.8V@3.5A or 5A@9.6 V.
In Figure 6 is represented the characteristic of our LOAD.

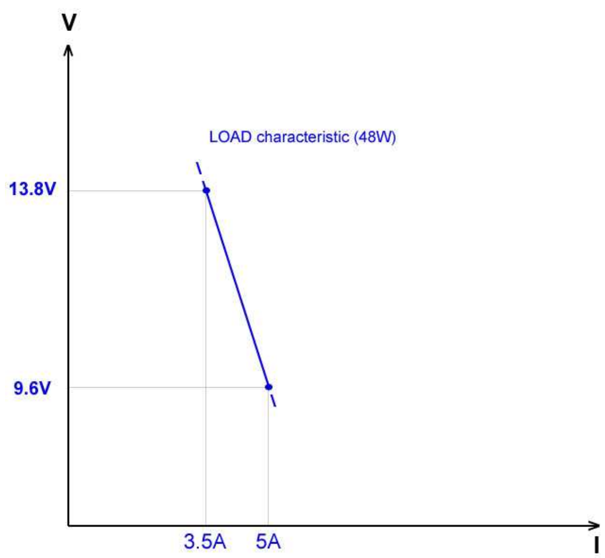


Figure6 *– I/V characteristic of a "constant power" load, powered between 9.6V and 13.8V.*

Now attention please:
<u>if the power supply is asked to provide more current than it can give, as in this case, its voltage will drop</u>. It is a normal behavior of any C-V power supply, which in 'overcurrent' (or 'overload') condition tends precisely to reduce its output voltage (and hence its output power) to protect itself.

Go back to our example: the power supply can give an output current I_{max} = 8A, and therefore can't provide the "required" 12A current for load and battery, then the nominal voltage of the power supply starts to drop.
Note that the LOAD, which behaves as a constant power load, tends to absorb more current as the voltage drops, while the battery tends to absorb less current as the voltage drops (see characteristics of battery and LOAD, Figure 5 and Figure 6 respectively) .
It's easy to see that the output voltage of the power supply will drop to the point where the sum of currents of LOAD and the battery will be equal to 8A.
You can solve the problem graphically, as LOAD and batteries (which are effectively in parallel) are subjected to the same voltage.
From Figure 7 is estimated that: for V_o = 12.6V the battery and the load absorb in total 8A (respectively 3.88A and 4.12A).

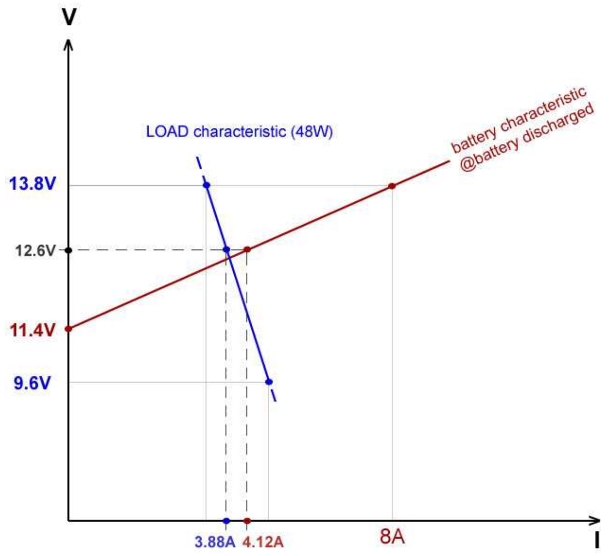


***Figure 7** – Graphical calculation to find the voltage such that $I_{batt} + I_{load}$ = 8A.*

As the battery charges, its characteristic varies (Figure5), the current demanded by the battery I_{BATT} falls, and consequently the output voltage of the power supply V_o slowly returns to the rated value 13.8V.
This example makes it clear that putting directly in parallel load and battery, the load will surely be well powered, if the power supply of the DC-UPS is good sized.

Advel, after years of experience in this applications, suggests sizing the power supply to at least be able to support the load current plus 10% of the battery capacity, as done for the example just seen.
In this case the charging time of the battery is equal to 10 theoretical hours (let's say 12 hours in the reality, because of the dissipative phenomena of the battery, the voltage drop across the cables, etc. ... see **AAN2011.3**).

3. DC-UPS design
It may be useful now to analyze a real example. Consider that our customer need a DC-UPS system.

Customer specifications:
power required by the load = 500W
input voltage of the load = 24V ±20%
autonomy given by the batteries: 5 hours
recharging time required: < 24 hours

Considerations for the design of a DC-UPS system proposed by Advel:

- the load can be supplied in the range 24V±20%, then it's better using a single-power supply DC-UPS system;
- load current I_{LOAD} = 500W / 24V = 20.8A about;
- the theoretical battery pack has a capacity 20.8A x 5h = 104Ah → in reality it's suggested to use a battery pack with a capacity 208Ah about (safety factor 2); commercially are available 100Ah batteries, then putting two 24V 100Ah batteries in parallel we will obtain a 200Ah battery pack, that is perfect;
- the 200Ah battery pack chosen must be able to absorb at least 20A (10% of its capacity) to recharge in 10÷12 hours about.

Ultimately, the power supply must be able to supply a current of at least:
20.8A (load) + 20A (battery pack) = 40.8A
Advel suggests to use a 1200W power supply, with V_{out} = 27.6V ($I_{out\text{-}max}$ = 43A), for example the rack 19" SPS-R series containing two 600W modules in parallel (Figure 8), with the following characteristics:

- output for load and battery on a back side terminal block;
- internal control device **BCD** (that gives the command for disconnecting the battery if its voltage is outside the range $V_{batt.\ rated}$ ± 20%);
- **RMCB** alarm, that indicates if the battery is disconnected or faulty (optional);
- manual **Inhibit**, to test the battery health;
- temperature compensation (option not necessary because the recharging current is very low, but it's recommended if the batteries are in a non air-conditioned environment);
- possibility of hot swapping of the modules;
- forced ventilation inside the rack, with control of the healty of the fans (**FCD**);
- external protective fuse in series with the battery pack (recommended but not necessary);
- …

If the battery is full charged, the output current of the power supply is:
20.8A (load) + 100mA÷1A (holding current of the battery) and the output voltage of the power supply is 27,6V.

If the battery is empty, the output current of the power supply would be:
20.8A (load) + 40A (or 20% of the rated capacity of the battery) = 60.8A!
But... the power supply CAN NOT give the requested 60.8A (because it has a maximum output current $I_{out-max}$ = 43A) and as a result the output voltage of the power supply V_{out} starts to go down, as explained in the previous paragraph:
presumably V_{out} will fall to about 25 ÷ 26V, at this voltage in fact the battery absorbs about 10% of its capacity, or about 20A, and then the power supply is capable to support the load current + recharging current of the battery. As the battery recharges, the charging current decreases and consequently the V_{out} goes up to return back to the rated value 27.6V (after some time).
In a time equal to about 12 hours, the battery will be fully charged.

NOTE - charging time: if the customer had demanded a lower charging time (eg. 5 hours), we might have had to choose a larger power supply (about 2000W). However, please note that C-V charging type at fixed voltage V_{batt} +15% does not allow a good control of charging time. In fact, to reduce the charging time it should be necessary to increase the recharging voltage V_{batt} more than 15%, as well explained in **AAN2011.3**, which should be avoided in order not to leave the power specifications of the load.
So the DC-UPS with single power supply does not allow to speed up the charging time below 5 or 6 hours.

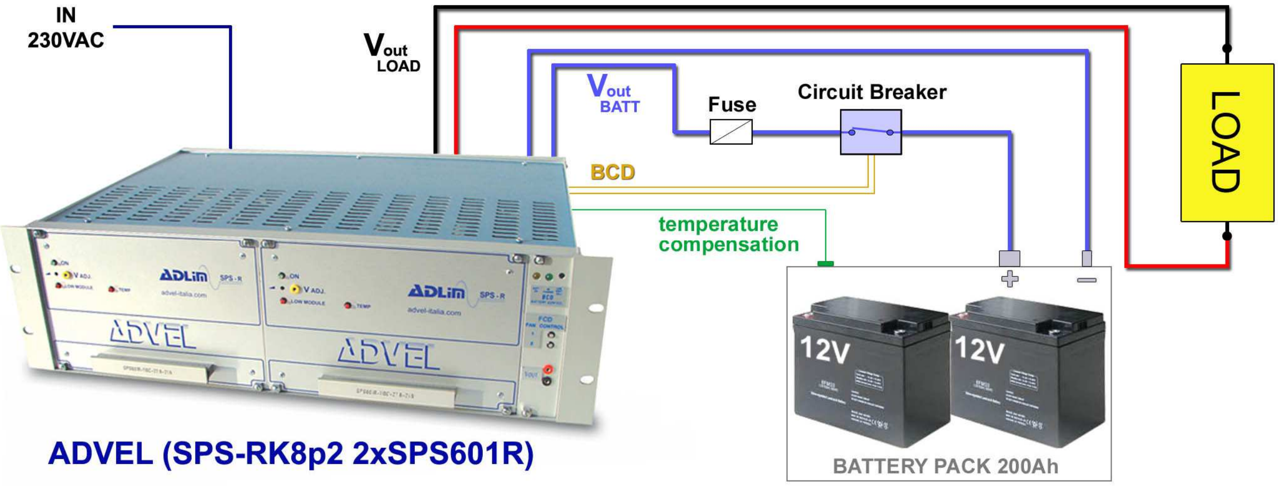


Figure8 *– DC-UPS system, realized with an Advel power supply (rack 19" SPS-R series, containing two hot-plug 600W modules, the SPS601R) with battery control and temperature compensation.*

4. Conclusions
We analyzed the characteristics of the DC-UPS systems: Stand-By, Online, and single power supply types.
With Advel power supplies you can make all 3 types of DC-UPS, the customer has to choose the one he prefers, on the basis of his technical needs.
Table 1 summarizes the main characteristics of the three types of DC-UPS.

The example analyzed in paragraph 3, completely realistic, suggests that the 'single power supply' DC-UPS, constant voltage (C-V), if properly sized, allows a full recharge of the battery pack without "steal" current to the load.
Furthermore, if the system is sized so as to allow a maximum charging current not exceeding 10% of its capacity (as suggested by Advel) is not strictly necessary any expedient to monitor the temperature of the battery.

The negative aspects of a 'single power supply' DC-UPS are basically two:
1) it's not possible to reduce the battery recharging time below 5-6hours,
2) there is a wide voltage range for the load.
The positive aspects instead are numerous: low price, high reliability, relatively low size, …

If is required a recharging time for the batteries very low, it's necessary to use a DC-UPS with a dedicated power supply for the battery, like a Stand-By or Online type. However, in case of very low recharging time, the recharging current for the battery will certainly be high and therefore will be required to take appropriate measures to control the temperature of the batteries and appropriate sizing of cables.

If, and only if, the load requires a fixed voltage and well stabilized in every situation (eg. V_{nom} ± 5%) will be necessary the use of Online DC-UPS system, which however has a high size and cost.

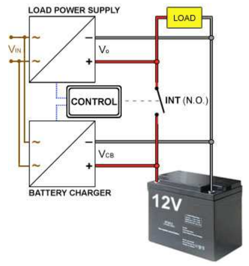
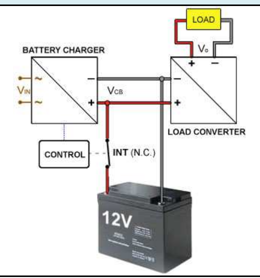
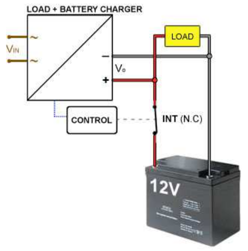
	Stand-by DC-UPS	Online DC-UPS	Single power supply DC-UPS
principle scheme			
cost	high	very high	medium
voltage for the load	V_{rated} –20% ÷ V_{rated} (ie. 19.2V ÷ 24V)	V_{rated} (ie 24V)	V_{nom}–20% ÷ V_{nom}+15% (es. 19.2V ÷ 27.6V)
type of battery charger	C-C or C-V	C-C or C-V	C-V
typical voltage drop for V_{in} lack	~20÷40msec	0 sec	0 sec
size	normal	high	low
typical power	< 500W	500 ÷ 1000W	> 500W
rechargint tipe for the battery	1h ÷ 12h	1h ÷ 12h	5h ÷ 12h

Table1 *– Main characteristics of the three DC-UPS types: Stand-by, Online, and single power supply.*

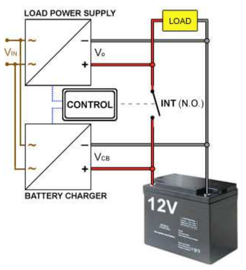
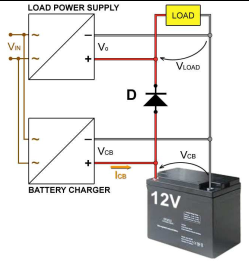
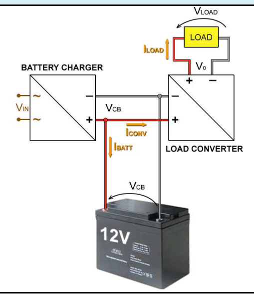
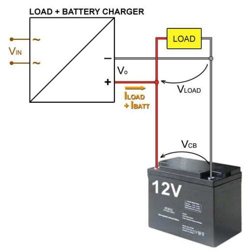
	Stand-by DC-UPS	Silmplified Stand-by DC-UPS	Online DC-UPS	Single power supply DC-UPS
Scheme				
Cost	high	medium	very high	medium
LOAD_12V voltage for the load V_{LOAD}	Battery pack 12V → V_{LOAD} = 9.6V ÷ 12V	Battery pack 12V → V_{LOAD} = 9.1V ÷ 13.3V (typ. V_D = 0,5V)	Battery pack 12V → V_{LOAD} = 12V fisso	Battery pack 12V → V_{LOAD} = 9.6V ÷ 13.8V
LOAD_24V voltage for the load V_{LOAD}	Battery pack 24V → V_{LOAD} = 19.2V ÷ 24V	Battery pack 24V → V_{LOAD} = 18.7V ÷ 23.5V (typ. V_D = 0,5V)	Battery pack 12V → V_{LOAD} = 24V steady	Battery pack 24V → V_{LOAD} = 19.2V ÷ 27,6V
LOAD_48V voltage for the load V_{LOAD}	Battery pack 48V (4x12V in series) → V_{LOAD} = 38.4V ÷ 48V	Battery pack 48V (4x12V in series) → V_{LOAD} = 38.9V ÷ 47.5V (typ. V_D = 0,5V)	Battery pack 12V → V_{LOAD} = 48V steady	Battery pack 48V (4x12V in series) → V_{LOAD} = 38.9V ÷ 55V
LOAD_110V voltage for the load V_{LOAD}	Battery pack 108V (9x12V in series) → V_{LOAD} = 86.4V ÷ 108V	Battery pack 108V (9x12V in series) → V_{LOAD}= 85.9V ÷ 107.5V (typ. V_D = 0,5V)	Battery pack 12V → V_{LOAD} = 48V steady	Battery pack 108V (9x12V in series) → V_{LOAD} = 86.4V ÷ 124V
Type of battery charger	C-C or C-V	C-V	C-C or C-V	C-V
Voltage hole for V_{in} lack	~20÷40msec	0 sec	0 sec	0 sec
System encumbrance	normal	Medium-low	high	low
Typical load power	< 500W	> 500W	< 1000W	> 500W
Battery charging time	1h ÷ 12h	5h ÷ 12h	1h ÷ 12h	5h ÷ 12h

Table1 *– Main characteristics of the three DC-UPS types: Stand-by, Online, and single power supply.*

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