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Development of supercapacitor based uninterruptible power supply

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Abstract

The given paper deals with uninterruptible power supplies utilizing supercapacitors (ultracapacitors). Different types of supercapacitor are described. Various opportunities of supercapacitor implementation are discussed, pros and cons are compared. Experimental comparison of lead-acid battery with supercapacitor is done.

Keywords

Lead-acid battery, supercapacitors, uninterruptible power supply

Introduction

Nowadays we cannot imagine out life without electricity, but energy faults in the electrical grid are still quite possible. That is why medicine, military, banking objects are connected to the grid from two independent supply transformers and often have also an emergency diesel-generator. Such configuration ensures energy supply, but does not protect against voltage drops during the switching. Besides that other energy problems, like harmonics and disturbances, are not solved by just double feeding.

The solution of these problems – is in feeding the critical equipment through a unit called uninterruptible power supply (UPS). The quality of conversion of UPS depends on its type: off-line, line-interactive and on-line UPS.

"Off-line" or "standby" UPS are the simplest UPS. They consist of a battery, battery charger, voltage inverter and a switch. If input voltage is good enough, the switch connects it to the load. At the same time the battery is being charged. As soon as the input voltage disappears or becomes faulty the switch disconnects it from the load and commutates the load to the inverter that is fed by the battery. Thus the input voltage can either be disconnected or connected directly to the load. The battery feeds the load at all voltage disturbances and deviations from the rated value. That is why battery utilization is high but its life-time is short. Besides that the input and the inverter cannot be connected to the output immediately. Some delay always takes place.

"Line-interactive" UPS include an autotransformer as well. A switch connects the input to the load through the transformer. That is why it is possible to adjust level of the output voltage to the desired level. This feature reduces utilization of the battery and improves quality of the output voltage. Like "off-line" this type of UPS has reconnection delay.

"On-line" UPS perform continuous conversion of the input AC voltage into DC voltage, and then, into the output AC voltage. Such UPS include a rectifier, an inverter and DC-link (with capacitors, batteries and (dis-)chargers). "On-line" UPS are capable to convert almost any kind of the input voltage into the desired level of the output voltage. The battery supplies energy only if the input voltage completely disappears. UPS of this type ensure the best quality of the output voltage, but their efficiency is lower, due to bigger number of parts in such UPS [1].

Autonomous operation time of UPS depends on the capacity of its energy storage, but its power depends on capability of energy storage to give high current. That is why the choice of the storage is an important part of design procedure of UPS. This is the main topic of this paper.

1 Batteries

UPS for independent power supply are usually based on lead-acid batteries (LAB). Amount of returned energy of LAB depends on its discharge current (Fig. 1). If this current is 0,05C the battery discharge time is 20 hours and battery capacity utilization is 100%. If the current is 2C - then the discharge time is 15 minutes, but the capacity utilization – is 50%. With the biggest discharge currents this value is even less. Very often discharge current of the UPS battery is about 4-6 C, discharge time is 3-5, but its capacity efficiency is only about 30%.

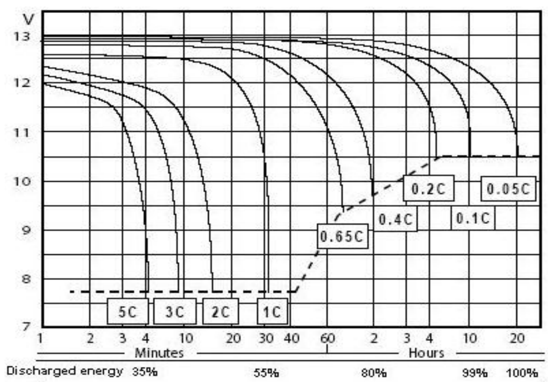

Fig.1.Discharge characteristics of a LAB

Lifetime of the batteries depends also on the discharge depth. The deeper discharge, the fewer charge-discharge cycles they can do (Fig.2).

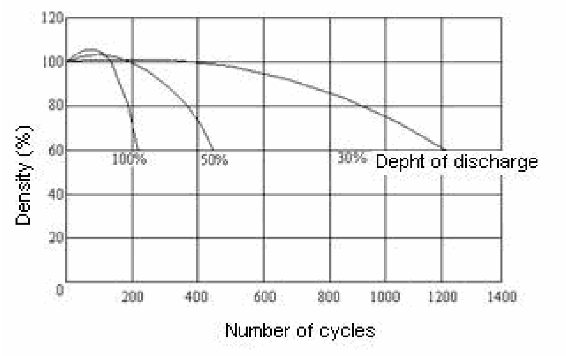

Fig.2. LAB Lifetime versus depth of discharge

One more important factor is charging current. In order to achieve maximum capacity of the battery, it is necessary to charge it correctly (Fig. 3).

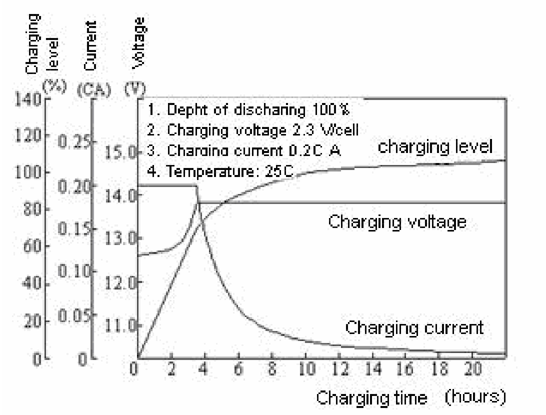

Fig.3. Charging current of a LAB

There are many other methods how to charge battery, but all these methods have one the same aim. In the beginning they prevent battery overheating, but at the end – its overcharging. The fast charging (4-6 hours) is often used in UPS, but this method is not good – lifetime of LAB is short.

2 Supercapacitors

As soon as supercapacitors (SC) appeared it became possible to use capacitors not only as reformative element, but also as a current source. First electrical double layer capacitor (EDLC) was developed in 1957 by General Electric. In this capacitor was using a porous carbon electrode. Company NEC in 1971 was produce first commercial capacitor with electrical double layer and name it "supercapacitor". It was low voltage capacitor with high ESR and basically it was used for memory module supply. But now are investigated many other types of supercapacitors such pseudocapacitor and hybrid capacitor (table 1). Pseudocapacitors store charge Faradaically through the transfer of charge between electrode and electrolyte. Three types of electrochemical processes may be utilized: surface adsorbtion of ions from electrolyte, reduction-oxidation reactions, and doping and undoping of active polymer material in the electrode. These Faradaic processes may allow pseudocapacitors to achieve greater capacitances and energy densities than EDLCs. There are two possible electrode materials that are used in pseudocapacitors, conducting polymers and metal oxides [14,15]. However pseudocapacitors energy densities is higher than EDLCs, especially hydrous ruthenium oxide which can achieve extraordinary capacitances, but it is not prevailing in market.

Table 1. Type of supercapacitors

Supercapacitor							
Non-Faradaic mechanism, does not use a chemical mechanism				Faradaic processes, use a chemical mechanism			
Electrochemical double layer capacitor (EDLC)			Hybrid capacitors (use faradaic and non-faradaic processes)			Pseudocapacitors	
Electrodes from activated carbons	Electrodes from carbon aerogels	Electrodes from carbon nanotubes	Composite - integrate carbon-based materials with either conducting polymer or metal oxide materials	Asymmetric - combine Faradaic and non-Faradaic processes by coupling an EDLC electrode with a pseudocapacitor electrode	Battery-Type - coupling a supercapacitor electrode with a battery electrode	Conducting Polymers	Metal Oxides
Aqueous electrolyte or organic electrolyte	Aqueous electrolyte or organic electrolyte	Aqueous electrolyte or organic electrolyte					

Ddisadvantages of pseudocapacitors are:

- Generally, lower power densities than EDLCs
- Cycle life can be limited by mechanical stress caused during reduction-oxidation reactions
- Negatively charged conducting polymer electrodes are not very efficient
- The best metal-oxide electrodes are very expensive and require aqueous electrolytes, which means lower voltage.

Better characteristics may be achieved by hybrid devices – combination of Faradaic and non-Faradaic SC. Hybrid SC combine advantages and mitigate the disadvantages of EDLCs and pseudocapacitors. Hybrid capacitor can achieve very high energy density and without the losses in cycling, but disadvantages that it is relatively new and unproven technology and research is needed to better potential of hybrid capacitors. The company that produces hybrid SC is russian company “ESMA”.

In spite of some advantages of hybrid SC, EDLCs have wider representation: Maxwell, Panasonic, Cap xx, NEC, EPCOS, Nesscap, ELNA produce them. Most of them utilize electrodes from activated carbon, but electrolyte is organic. Activated carbon common used because it is one of the cheapest material for electrode, but organic electrolyte allow produce supercapacitor cells with nominal voltage 2.3-3V. Supercapacitor with aqueous electrolyte nominal voltage is 0.8-1.2V to the cell, but it has lower ESR and lower leakage current. It use to supply microchips, memory modules and other low power devices. In high power applications common utilize supercapacitor with organic electrolyte. But in such application usually operate with voltage than is higher than 12V. Technological process of supercapacitor production not allow to produce capacitor cells with equal capacity and leakage current, because that series connection of supercapacitor cause problem and it is different voltage drop on it. Because that, when they are charged, some cells may be charged not fully and other may be overcharged. To prevent this problem it is necessary to use voltage balancing. Passive method of voltage balancing is the simplest. There is shunting resistor connected parallel to each supercapacitor cell, but it work as voltage divider that equalizes voltage on cells (fig. 4). The major disadvantage of such a solution is the power lost on the resistors.

The most efficient way of supercapacitor voltage balancing is to use active method (fig. 5). The central element of circuit is high-precision comparator. Reference voltage (V_{ref}) are compared through voltage divider with supercapacitor voltage and if cell voltage is higher than allowable comparator close S and connect shunting resistor to the cell. After voltage is decreased to the nominal voltage comparator open S and the power lost on the resistors stop.

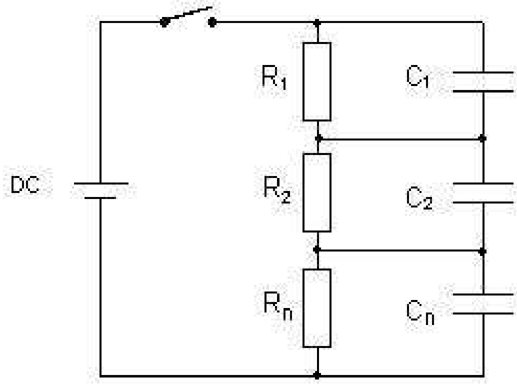

Fig. 4. Topology for passive voltage balancing

Table 2. Supercapacitors and lead-acid battery comparison

Supercapacitor		Lead-acid battery	
High power density 1-14 kW/kg	++	Low power density 200-400 W/kg	-
Low energy density 2-10 W*h/kg (*)	-	High energy density 40-60 W*h/kg	+
High price	-	Low price	++
Long cycle life 10k – 1000k cycles	++	Short cycle life 300-1200 cycles	-
Long shelf life more then 10 years	+	Shelf life 3-7 years	-
High efficiency of cycles	+	Low efficiency of cycles	-
Low internal resistance	+		
Environment safety	+	Environment dangerous	-
Fast self-discharge	-	Low self-discharge	+
No maintenance	+	No maintenance if SLA(sealed lead-acid battery)	
Easy to control stored energy (depends on voltage $E=0.5U^2C$)	+		
Easy to charge	+		
Voltage depends on a degree of charge (is necessary dc converter)	-		

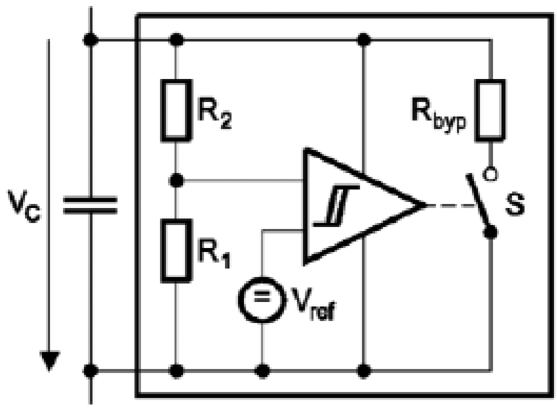

Fig. 5. Topology for active voltage balancing

Similar circuits are usable in applications where supercapacitor utilized as energy storage. For example: uninterruptible power supply, hybrid electrical vehicles, wind and solar systems, fuel cell. As energy storage supercapacitor has some advantages over lead-acid batteries (table 2).

3 Implementation of SC in UPS

There are few different topologies of UPS. These topologies differ in prices and in quality of the output voltage, as well as affect utilization of SC.

High price of the supercapacitors defines high total price of the UPS. That's why the cost of the UPS topology itself is less important. Thus, it is reasonable, to choose better on-line topology for supercapacitor based UPS. It validates advantages of the ultracapacitors.

On-line UPS topology is shown in Figure 6. It helps us to understand that a supercapacitor can be built-in in two places. Directly to the DC bus (position A in Fig. 6) and through the DC/DC converter (position C in Fig. 6). Combining these methods it is possible to get UPS with various properties. We will consider some of them.

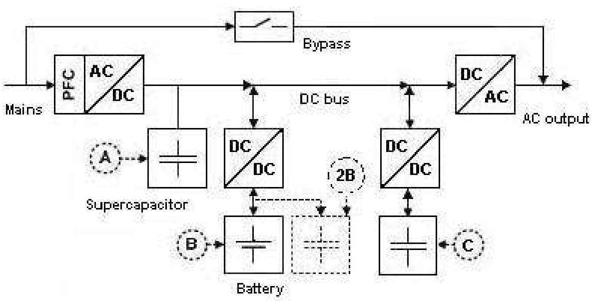

Fig. 6. Topology of on-line UPS

1) Only supercapacitor is directly connected to DC bus (position A in Fig. 6). Such UPS can be very powerful. But DC bus has high voltage. As the voltage of the supercapacitor is above 1.5-3 volt, it is necessary to connect about 200-300 supercapacitors in series. But serial connection of many capacitors causes some problems. The voltage distribution of supercapacitors will not be equal, and that's why their energy densities cannot be used at full. Secondly, voltage on the supercapacitor depends on a degree of its charge. So it allows to operate with a small part of stored energy, because the voltage drop of a supercapacitor cannot be smaller than the output peak voltage. Thirdly, if UPS with discharged supercapacitor is turned on in mains, there will be a huge starting current.

2) Supercapacitor is directly connected to DC bus and battery connected through the DC/DC converter (position A and B in Fig. 6). Characteristics of such connection method are similar to the connection in the first case. Advantages of battery usage are in its larger energy density. Using batteries, UPS weight with same energy, will be smaller but also power will be smaller

3) Replace battery with supercapacitor (position C in Fig. 6). Advantages of this method are that UPS becomes more powerful, needs less maintenance and has faster charge. Comparing to the first case there is a possibility to limit a charging current and accordingly to limit a starting current. The supercapacitor battery of high voltage is not required and this method enables to use almost all stored energy of supercapacitor. Power of UPS can be above ten times larger when using supercapacitor which has the same weight as battery, that is due to the fact that power density of batteries is 200-400 W/kg, whereas power density of supercapacitor may amount 10 kW/kg.

Lifetime of supercapacitor can be more then 10 years and supercapacitor can perform for over one million discharge-recharge cycles, whereas batteries only 1000 cycles.

As a result of the fact that supercapacitor charging time is very short, UPS preparation for repeated mains disconnection can be made within about 10 minutes. In UPS with batteries, charging time is above 4-6 hours

4) Connect supercapacitor parallel to battery (position B and 2B in Fig. 6). This is not good connection, because it is not possible to use all stored energy, since voltage of battery cannot fall lower of the fixed one in order not to damage battery. Advantage of this method is that supercapacitor can supply large power but in short-term and battery can supply small power but a longer period of time.

5) Connect supercapacitor and battery through different DC/DC converters (position B and C in Fig. 6). This type of connection is similar to the fourth case, due to the, that the supercapacitor is connected through the second DC/DC converter UPS disappears disadvantages that have fourth connection method. There is a possibility to charge and discharge the battery and supercapacitor independently and accordingly to use supercapacitor more efficiently.

4 Numerical comparison

For example, supercapacitor may be used instead of battery if in emergency power system there is a diesel-generator. In that case UPS must operate on reserve power supply only that time what is needed to diesel-generator to begin operating in nominal mode. In modern diesel-generator with engine heating this time is 5-15 seconds.

In such a system, as reserve power supply there is no need to use a heavy lead-acid battery, but it can be used smaller and more effective supercapacitor. For example, if you need in 100kW UPS you must use 250-500 kg of lead-acid battery or 20-100 kg supercapacitor. 500 kg of battery is about 33 pieces of lead-acid battery with capacity 55 A*h and nominal voltage 12 volts. If it is connected in series we get 396 V battery. It means that battery discharge current may be:

$$I = \frac{P}{U} = \frac{100000}{396} = 252.52A \quad (1)$$

For 55A*h battery it is 4,5 C and hence discharge time is about 4 -5 minutes (fig. 1.). But if we use 50 kg of supercapacitor we get 2 MJ [6]. But because of that fact that boost converter has limits we can't discharge reserve power supply to very low voltage. If boost converter discharges supercapacitor to 30 percent of nominal voltage then discharged energy from it:

$$\frac{E_0 - E_f}{E_0} \cdot 100\% = \frac{0.5CV_0^2 - 0.5CV_f^2}{0.5CV_0^2} = 91\% \quad (2)$$

Where Eo – stored energy, E_o-E_f – delivered energy, V_o – initial voltage, V_f – final voltage, C – capacity.

It mean that discharge time will be:

$$t = \frac{k \cdot E}{P} = \frac{0.91 \cdot 2000000}{100000} = 18.2s \quad (3)$$

Where E – stored energy, P – power of UPS, k – coefficient of used energy.

For diesel-generator it is enough to begin operating at nominal power.

5 Experiments

In order to experimentally test theoretical comparison (fourth part) in RTU was projected and realized laboratory prototype of UPS. UPS topology was realized by fifth method. Supercapacitor was used with capacity 169 F and nominal voltage 12.5V. Stored energy in supercapacitor is:

$$E = \frac{V^2 \cdot C}{2} = \frac{12.5^2 \cdot 169}{2} = 13203\ J = 3.67\ W \cdot h \quad (4)$$

where: E - value of energy, C - capacity of supercapacitor, V - rated voltage of the supercapacitor.

Almost the same energy store battery with capacity 1.2 A*h and nominal voltage 12 volts. Stored energy in battery is:

$$E = V \cdot C = 12 \cdot 1.2 = 51840\ J = 14.4\ W \cdot h \quad (5)$$

During the experimenting a resistive load was used (power of load is 48W). The boost converter of UPS discharged the battery or supercapacitor and supply DC-bus. DC converter also compensated voltage drift over the discharging supercapacitor. As it shown in Figure 7 supercapacitor discharge time is about 200 seconds and battery discharge time is about 330 s.

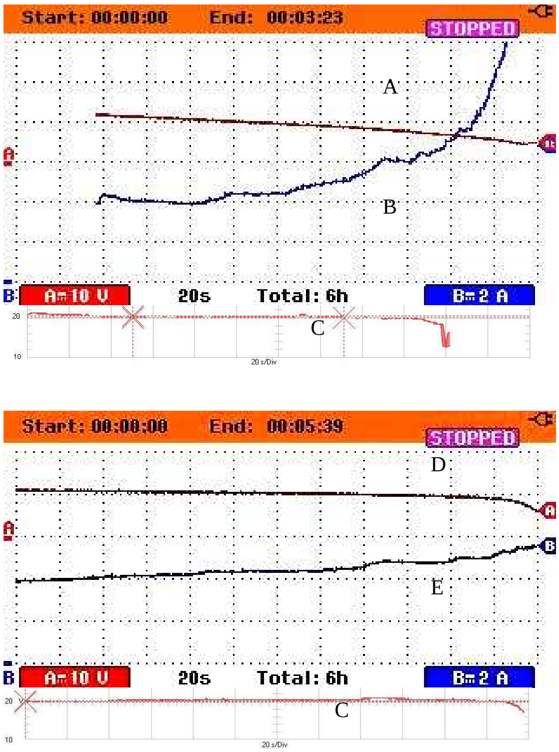

Fig. 7. Discharging characteristic of battery and supercapacitor (A – supercapacitor voltage, B- supercapacitor current, C- DC-bus voltage, D – battery voltage, F – battery current).

Although battery capacity is 3.9 times higher then supercapacitors, but battery discharge time only 1.65 times longer. It happens because battery discharge current, as we see from figure 7, is about 4-5A (3-4 C). It is relatively high for this battery. Because of that fact battery return only a part of the stored energy and it is:

$$E = P \cdot t = 48 \cdot 330 = 15840\ J \quad (6)$$

It is only 30% of stored energy. Supercapacitor given energy is:

$$E = P \cdot t = 48 \cdot 200 = 9600\ J \quad (7)$$

And it is 72% of stored energy. It can be concluded from this experiment, that supercapacitor are useful instead battery when discharge current is high and UPS must work short time.

6 Conclusions

In the given synopsis possibilities of utilization of supercapacitors in uninterruptible power supply were discussed. Possible topologies were analysed and it was found that the "On-line" type with separate converter for each storage is preferable. It was calculated that high power ratings are more easy achievable with supercapacitors rather than with batteries. It was experimentally found that at higher currents supercapacitors are comparable with batteries and getting better from the point of view of energy utilization. However, from the economical point of view, at the present time, direct substitution of batteries with supercapacitors is not effective, nowadays it is better to combine traditional battery for high capacity and supercapacitirs - for higher power, but shorter operation time. It must also be noted, that ultracapacitors undergo intensive development and become more and more available in size and price. That is why utilization of them in UPS is perspective.

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