A SURVEY ON SUPERCAPACITORS APPLICATIONS IN POWER ELECTRONICS

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***Abstract* –The main objective of this paper is to present a survey on supercapacitor, also called ultracapacitor, and its applications related to power electronics. An extensive bibliographic research has allowed identifying the main applications. After a brief presentation of fundamental aspects, the applications are discussed.**

***Keywords* – electrochemical double layer capacitor, supercapacitor, ultracapacitor.**

I. INTRODUCTION

Supercapacitor (SC) is the usual term that describes the Electrochemical Double Layer Capacitors. Commercially, it is known as ultracapacitor. This energy storage device has high capacitance value, low series equivalent resistance, fast and very high current capability.

The supercapacitors are specified to supply high peak-power and medium energy applications. Generally, they are employed in hybrid systems with batteries or fuel cells. In this way, the SCs have a very important role, as a supplementary power source, for improving stability, maintaining system reliability and power quality. Due to recent technological improvements and cost decrease, SCs are becoming viable for power electronics applications [1]-[4].

II. FUNDAMENTALS

Basically, a supercapacitor consists of two metal foil coated by highly porous carbon, called electrodes, isolated by separator material (paper, polymer membranes or glass fiber), as shown in Fig.1. They are immersed into a highly conductive electrolyte to allow freely ion movement during charge and discharge cycles.

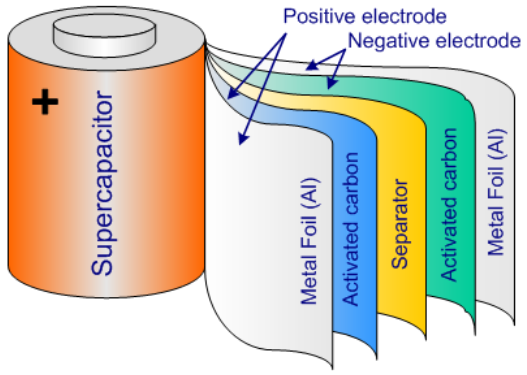

Fig. 1: Schematic of supercapacitor's layer.

The Fig. 2 illustrates the distribution of charges in a supercapacitor cell. In the charging process, the electrons are accumulated on the carbon activated connected to the negative terminal of the device. In the other electrode, positive charges are accumulated. The electric field orients the movement of the ions present in the electrolyte through separator paper towards the electrodes of opposite polarity (into pores of the carbon), compensating electronic charge at the electrode surface. Charge and discharge occur due to ions movement inside the electrolyte, without any chemical reaction. Thus, the supercapacitor posses a very low internal resistance and charging or discharging current limit is quite high [1] [4] [5].

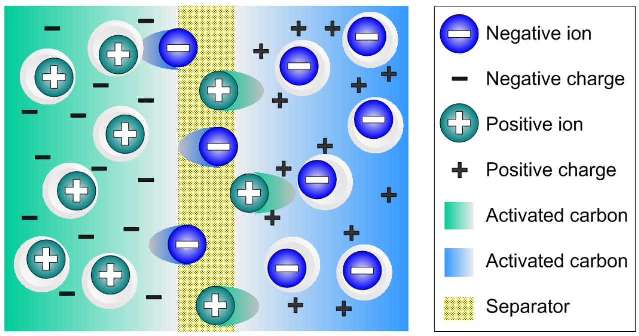

Fig. 2: Distribution of charges in a supercapacitor cell.

SC has high-energy storage capability (high capacitance) because the porous electrodes provide extremely large internal effective surface (about 2000 m^2/g) and a minimal distance between opposite charges (2-5 nm).

The electrolyte of SC may be aqueous, which limits nominal cell voltage to about 1 V and its specific energy to about 3.5 Wh/kg of active mass. Electrolytes made of organic solvents allow the voltage cell increase up to 2.5 V and the specific energy to 18 Wh/kg, although the internal resistance is higher [1]-[6]. The Fig. 3 shows a commercially available supercapacitor cell from EPCOS, with 10F and 2.3V. This device has 1.9 kW/kg and 1.2 Wh/kg. In the top, there is a typical 9V alkaline battery for size comparison.

Fig. 3: Typical available supercapacitor cell of 10F/2.3V.

A. Energy and Power Densities

SCs fill the gap between conventional electrolytic capacitors and batteries in terms of energy and power density [1] [4]. Energy density represents the relationship between the storage energy and the volume or mass, while power density represents relationship between how fast the energy can be transferred and the volume or mass [7]. These two parameters are showed in the Ragone diagram (Fig. 4) [2] [8].

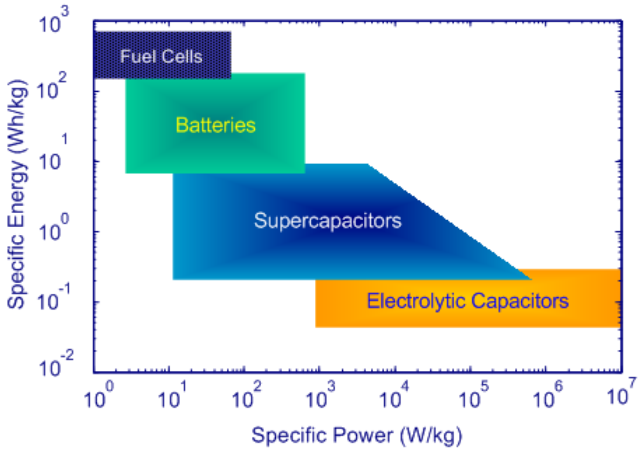

Fig. 4: Ragone Diagram.

Conventional (electrolytic) capacitors have more power density than supercapacitors, but they can supply current peaks only during few milliseconds, due to its low energy density. Batteries are one of most cost-effective energy storage device, but they can't absorb and deliver energy as fast as supercapacitors do, due the chemical reactions on the electrodes [1] [2].

B. SC module: association of cells

The SC power modules have cells connected in series to achieve higher voltages. In order to prevent voltage unbalance and electrolyte decomposition (electrolysis and generation of gas) due to cells over-voltage, passive and/or active voltage cell balancing are recommended [1] [4] [9].

The passive balancing consists in several resistors connected in parallel with the cells terminals (resistive divider). The active balancing can be implemented with electronic circuit connected in parallel with each cell, as shown Fig. 5. When voltage level of a cell is higher than a precise internal voltage reference, the internal transistor of the comparator conducts, bypassing the cell [1] [9] [10].

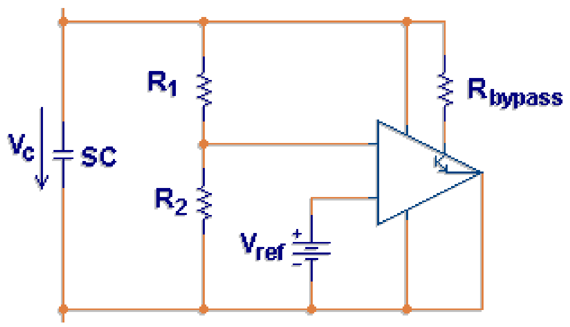

Fig. 5: Voltage cell balancing.

The Fig. 6 illustrates a supercapacitor module from EPCOS, with 42V and 150F. This device has active cell balancing for 18 single cells of 2700F, specific power of 6.9 kW/kg and specific energy of 2.3 Wh/kg. In the same photo, there is an electrolytic capacitor from SIEMENS (bottom right), with 3700μF and 200V. In the bottom of this capacitor there is the supercapacitor shown in Fig. 3.

Fig. 6: Supercapacitor module of 150F/42V.

III. CHARACTERISTICS

The main characteristics of supercapacitors are listed below:

- *High power densities*, 10 times greater than batteries.
- *Poor energy density*, compared to batteries, but about 100 times greater than conventional capacitors. For example, a lead-acid battery of 12V and 44Ah has 40Wh/kg and 300W/kg while supercacitor module of 42V and 150F has 2.3 Wh/kg and 6,900 W/kg;
- *Fast charging and discharging ratio*, because it is based on ions movement. This results in *low series equivalent resistance* (ESR), and *high current capability*;
- Recharging process can be done with random currents, *without memory effects*, due to *absence of chemical reactions*;
- *Wide voltage range*, achievable by modules of cells connected in series/parallel, protected by balancing circuits;
- *Wide temperature range*, *expected long operational lifetime*, *maintenance-free*, because the storage process is completely reversible;
- Since the transient conditions are supplied by supercapacitor, it is also expected enhancement of battery and/or fuel cell, and other associated energy storage devices life-time;
- *Environmental friendly*, due to absence of hazardous and toxic materials. When applied for vehicles with internal combustion engines there is fuel combustion and pollutions emission reduction;
- *High cost per Watt*, but when it is used in combination with batteries or fuel cells, can result in hybrid system solutions more efficient and cost-effective than non-hybrid solutions [11].

IV. APPLICATIONS

A. Consumer Electronic Products

As the need for smaller and more lightweight systems increases, design engineers require innovative design approaches to reduce size and heaviness without sacrificing overall performance and reliability, especially of portable products.

In several devices of information technology, like personal computers, notebooks, PDAs (or handhelds), electronic agendas, calculators, GPS systems, cellular phones, digital video and photo cameras, the SCs are used as temporary backup source to avoid lost of BIOS configuration or missing of data in memory. However, the SCs can be used to delivery a large amount of current over a short period of time, to realize functions like zoom, flash, image capture, wireless communication and initial power-up. The Fig. 7 shows schematic electronic circuits, in which the SC provides power backup or ride-though in the critical load [4] [7] [12].

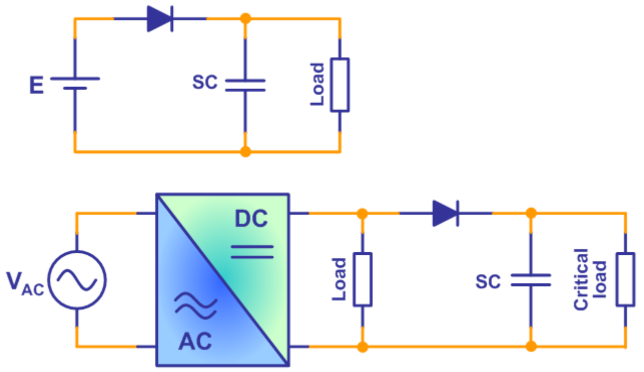

Fig.7: Supercapacitor in electronic circuits.

In other applications, with low energy requirement, the SC is used as the main power source. For example, a variety of toys, such as airplanes and automatic cars, use the SC like main and unique source to operate. These toys are smaller and more cost-effective than toys powered by battery [4].

B. Renewable Energy

Fig. 8 shows the schematic diagram of two renewable energy sources (windmill and photovoltaic).

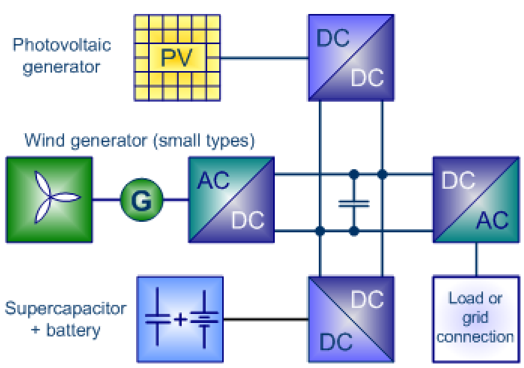

Fig. 8: Schematic diagram of renewable energy sources integration.

In these applications, the SCs are used to compensate and stabilize intermittent energy output of the generators, preventing from power drops. Working together with the battery, the supercapacitor discharges its power during load peaks and recharges between the peaks, extending the life of the batteries [1] [13].

C. UPS systems

An uninterruptible power supply (UPS) system is designed to be able to immediately take over of a load during power outage or out-of-tolerance situation in order to avoid data loss, uncontrolled system shutdown or malfunction device. Some critical loads does not allow some tens of milliseconds power interruption and batteries or fuel cells are not able to react so quickly. For this reason, supercapacitor module is employed, as shown in the Fig. 9, to improve time response, by supplying the required instantaneous energy, which was stored during the normal operation [14].

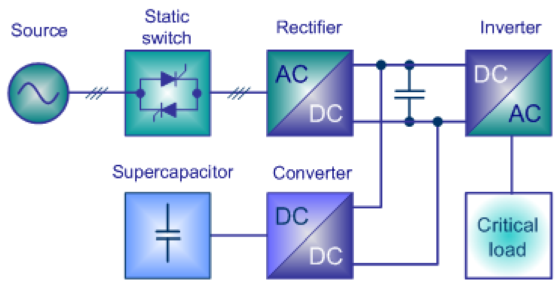

Fig 9: Schematic diagram of an off-line UPS system.

D. Adjustable Speed Driver

Modern sensitive machinery is mainly affected by voltage sags and interruptions, which cause significant economic losses due to unexpected interruptions of an industrial process [3] [15]. In adjustable speed drive (ASD), voltage sag may potentially cause speed fluctuations that can damage the final product. The compensator, powered by SC, is employed to provide ride-through for voltage sags and short-term interruptions, because the DC link voltage is maintained stabilized. Fig. 10 illustrates the use of supercapacitor in an ASD system. Batteries could be combined with SC to achieve large energy capability [16] [17].

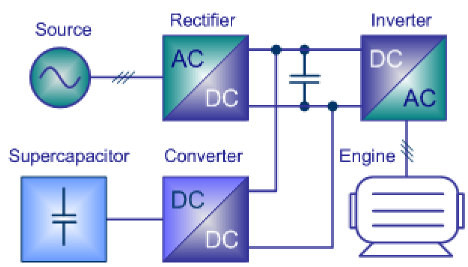

Fig. 10: Schematic diagram of ASD system.

In this application, the capacitance value (C) is given by the equation (1).

$$C = \frac{2.t.P}{V_0^2 - V_f^2} \qquad (1)$$

Where t is the total elapsed time in which the SC must provide compensation, P is the power required by load, V_0 and V_f are the initial and final terminal voltage of the capacitor.

E. Power Conditioning

A Power Conditioning System (PCS) that uses a supercapacitor module as energy storage is proposed in [18] as a viable solution for quality and reliability improvements of the power supply. The PCS system behaves like a dynamic voltage restorer (DVR) when voltage sag or short-time interruption occurs in electrical network. In this case, the device injects the required active power during short-time perturbation. In normal operation, the PCS can operate like an active power filter and it can be able to compensate reactive power, current harmonic reduction, load unbalance and flicker. The Fig. 11 shows the schematic topology of PCS.

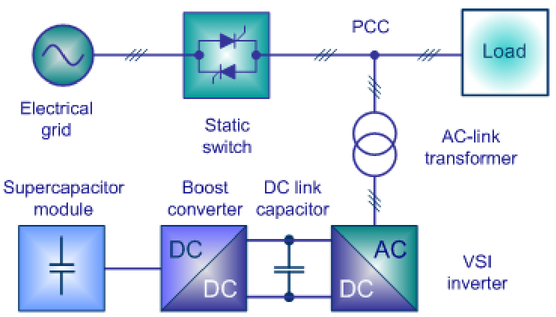

Fig. 11: Schematic drawing of the PCS structure.

F. Transportation

Trolleybus and tramways urban transportation systems use DC low-voltage (500-700V) feeders, based on rectifier substations. Nowadays, these vehicles have powerful drive systems, with variable-frequency AC drivers. During acceleration and breaking the voltage along the feeder presents substantial voltage fluctuations, affecting other vehicles in the same feeder. Instead of installing additional and expensive rectifier substations, it is possible to use a SC based energy storage substation for voltage fluctuations compensation, as shown in Fig. 12. These supercapacitor substations would allow voltage stabilization at critical points of transportation networks like non-supplied end-of-lines[19].

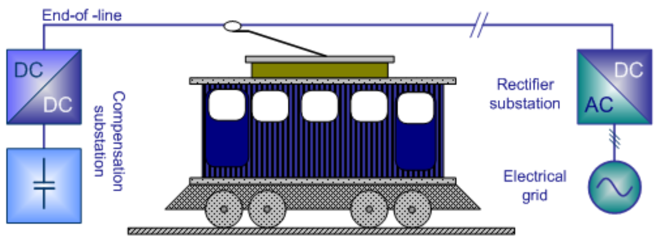

Fig. 12: Network transportation with compensation substation.

G. Automotive Vehicles

The use of SC in electric traction systems have lead to significant performance improvements of Electric Vehicles (EV) and Hybrid Electric Vehicle (HEV); such as the increase of batteries life time, lower sizing of energy devices, regenerative braking, higher efficiency, energy saving and lower emission.

For these systems, an efficient solution is to use a primary source, such as fuel cell, to provide constant power; common batteries, to increase the vehicle performance in urban applications, in which the instantaneous power consumption varies a lot due to traffic jam; and, finally, SCs sized to supply power peaks to accelerate and to absorb kinetic energy from braking of vehicle (regenerative braking), as shown in Fig. 13. This topology allows energy savings of up to 25% [8] [20] – [24].

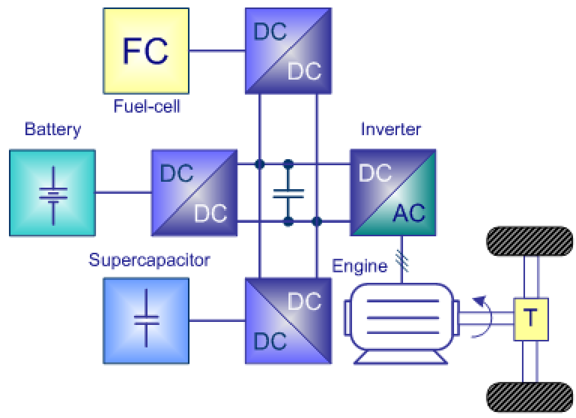

Fig. 13: Multiple-input power converter for hybrid vehicle.

The SC can be sized according to the worst-case transient condition and the time constant of the fuel cell or battery. This avoids that the batteries and/or fuel cell be sized to supply high current levels, allows that DC link voltage to be more stable and increases starter torque [8] [25] [26].

The regenerative braking can also be applied for vehicles with internal combustion engines. Typically, it is possible to combine a diesel engine with an electrical power train. This topology allows reduction of fuel consumption and emission, due to efficiency increase [7] [27].

Fig. 14 illustrates electrical vehicle developed at Hydrogen Laboratory (LH2) of the Institute of Physics “Gleb Wataghin” at UNICAMP. This vehicle is powered by an electric motor. Currently the main power supply is hydrogen fuel cell, combined with batteries.

Fig 14: VEGA project – electrical car. Coutesy LH2.

The idea is to use ultracapacitor, as supplementary power source, in next version of this car. Nowadays, the car has weight of 2000kg and maximum speed of 40km/h. The objective is to increase the maximum speed and to decrease the weight.

The energy (E) of the electrical vehicle is given by:

$$E = \frac{m_{EV} . v_{EV}^2}{2} \qquad (2)$$

Where m_{EV} is the mass and v_{EV} is the speed of electrical vehicle.

Rewriting the equation 1, the capacitance necessary to provide the variation energy request is given by equation (3).

$$C = \frac{2.\Delta E}{V_0^2 - V_f^2} \qquad (3)$$

For example, for the VEGA car to arrive 80 km/h, with $V_0 = 210V$ and $V_f = 100V$, it is necessary a SC of 29 F.

H. Internal combustion engine

The same solution of electrical car can be adopted for induction generators driven by internal combustion engines (ICE), connected or not to the utility, as shown in Fig. 15. A SC bank allows AC voltage stabilization even for heavy load variations, while the slow ICE regulators find the new operation point [28].

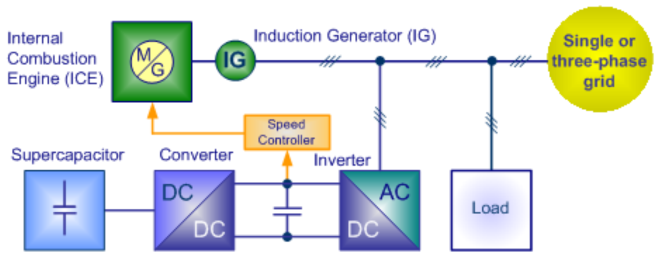

Fig. 15: Schematic drawing of an ICE-driven induction generator.

V. CONCLUSION

Basically, a supercapacitor is used to supply fast and high currents requirements. The association of supercapacitor with other energy sources allows the optimization of integrated power sources design with substantial benefits in terms performance and efficiency.

In spite of the very high initial costs of supercapacitors modules, the maintenance costs are reduced and adverse environmental effects are minimized. As far as lifecycle costs is concerned, the benefits of SC modules inclusion in electrical vehicles still are unclear. However, it is expected that the costs of supercapacitor will decrease significantly, due to production quantities increase, automation of the whole production process and reduction of building modules due increase of nominal cell voltage to 3V within next five years. In power quality applications the economical benefits is higher, if the costs of loss production in industries with critical loads is taken into account.

For all identified power electronics applications of SCs, the most important issue is to keep DC link voltage stable. Multiples power sources and the coordination of power electronics converters control are crucial to reach this goal and, additionally, optimize power management, improve stability, power quality and reliability of supply.

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