Proc. XI National Conference with International Participation "Electronica 2020", July 23 - 24, 2020, Sofia, Bulgaria

# An Overview of Supercapacitors as New Power Sources in Hybrid Energy Storage Systems for Electric Vehicles

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*Abstract* – **Supercapacitors are widely used nowadays. They are known as ultracapacitors or electrochemical double layer capacitors (EDLC), which are energy storage devices providing high energy and efficiency. The supercapacitor pack can be successfully used in HESS (battery-supercapacitor system) combining different energy storage technologies with special control strategy using all the advantages of each energy source for improving and reaching overall performance. This paper summarizes the performance of supercapacitors in terms of energy density, equivalent series resistance and their optimal usage in the automotive sector. The paper also presents a brief review of benefits, features, advantages and disadvantages of hybrid energy systems based on batteries and supercapacitors.**

*Keywords* - **EDLC capacitor, electric vehicle, supercapacitor, hybrid energy storage system, energy storage devices**

## I. Introduction

It is very important to implement high performing electrical energy storage components with regard to their lifetime, energy density, power density, cycle efficiency, cost, size and to obtain higher storage performance. Combining both components - battery and supercapacitor – to form a hybrid energy storage system (HESS) could increase the overall performance efficiency of the electric vehicles by storing the energy from acceleration capabilities to the deceleration of the vehicle. It is known that in the conventional HESSs the battery is directly connected to the DC link while in a half bridge DC/DC converter the battery is placed between the supercapacitor and the DC link. The main advantage of the supercapacitors is the ability to charge and discharge continuously without degrading and capability for operating high power rating compared to batteries. In this approach in order to provide energy storage for electric vehicles both charge sustaining and plug-in designs have to utilize supercapacitors in combination with batteries [1]-[3]. In a battery-capacitor energy system the galvanic battery serves as an energy source for long distance travelling while the supercapacitor pack is used as a peak power source providing battery lifetime improvements, power for acceleration and the possibility for complete regeneration of energy during braking which improves energy efficiency and utilization of electric energy. The overall performance of supercapacitors relies on the chosen materials for the electrode, electrolyte, separator and current collector. Supercapacitors electrolytes have to be carefully selected in order to reduce their internal resistance [2]-[4]. Some of the main characteristics of different supercapacitors are presented and described in this paper.



### *A. A review of the main types and characteristics of supercapacitors and comparison between them and batteries*

The main components in the construction of supercapacitors are two charged electrodes, a current collector and a separator that allows for transfer of ions and prevents direct electrical contact. When an amount of electric charges is accumulated between the first electrode and electrolyte the same amount of charges with opposite polarity will be induced on the second electrode forming two charged layers with very small separated distance. [5], [6]. Fig.1 below depicts a structure of the supercapacitor acting as an electrostatic device which stores its electrical energy as an electric field.

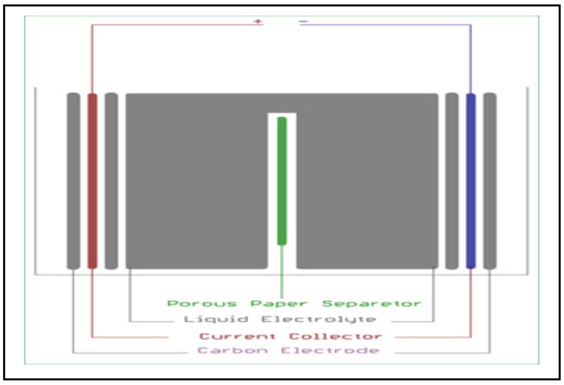


Fig. 1. Structure of a supercapacitor

Supercapacitors are the ideal solution when a quick charge is needed to provide short-term energy while batteries are frequently chosen to provide long-term energy as they can be recharged very quickly. Also they are suitable and more effective to bridge power gaps continuing from a few seconds to a few minutes [5]-[12]. They can be classified and distinguished mainly in three types depending on the cell configuration or energy storage system, electric double layer capacitors, hybrid asymmetric capacitors and pseudo capacitors.

Different types of supercapacitors are shown and presented in Fig.2. With regard to EDLC capacitors the storage of electric energy is achieved by charge separation in Helmholtz double layer acting as a boundary between the conductor electrode and electrolyte. Pseudocapacitors have polymer conducting electrodes or metal oxide based on electrodes combining the electrostatic and pseudocapacitance charge storage process. Hybrid capacitors have asymmetric electrodes composed of a double layer capacitor electrode and a pseudocapacitive electrode thus incorporating the best features of both technologies [6], [8]. Li-ion capacitors use one electrostatic electrode and one electrochemical electrode allowing for better energy density and self-discharge characteristic than an EDLC capacitor, more charge-discharge cycles than a Li-ion battery without the potential for risky thermal runaway.

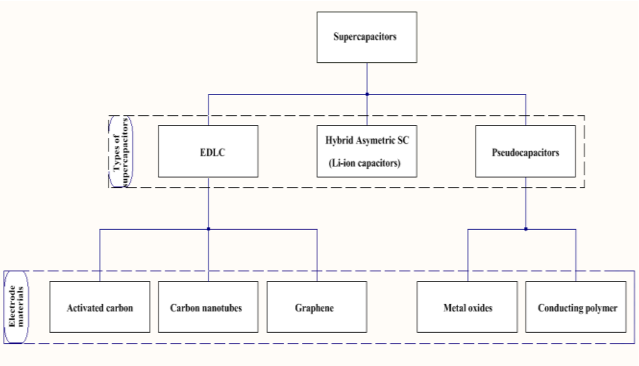


Fig. 2. Classification of different types of supercapacitors

Table 1 presents the parameters of different Li-ion batteries. Table 2 shows the characteristics of supercapacitors. Comparing the tables it can be confirmed that batteries have much higher energy density in the range of 35-260 Wh/kg. On the other hand, supercapacitors have much power density between 3 to 6 times more than that of Li-ion batteries.

TABLE 1. MAIN CHARACTERISTICS OF LI-ION, NICKEL BASED BATTERIES AND LEAD ACID BATTERIES

| Types of Li-Ion batteries | Power Density [Kw/kg] | Energy Density [Wh/kg] | Life Cycle | Operating temp. [°C] | Op. Volt. [V] |
|---|---|---|---|---|---|
| Lead Acid | 0.18 | 35-40 | <350 | -35 to 45°C | 2.1 |
| LTO (Li-Titanate) | 3.0-5.1 | 50-80 | 3000-7000 | 0 to 45 °C/-20 to 60°C | 1.8-2.85 |
| LFP (Li-phosphate | 1.3-3.5 | 90-120 | 2000 | 0 to 45 °C/-20 to 60°C | 2.5-3.65 |
| LMO (Li-manganese | 0.25-0.4 | 100-150 | 300-700 | 0 to 45 °C/-20 to 60°C | 3.0-4.2 |
| NMC (Li-NI-MH) | 0.4-1.2 | 150-220 | 1000-2000 | 0 to 45 °C/-20 to 60°C | 3.0-4.2 |
| LCO (Li-Cobalt) | 0.8-2 | 150-200 | 500-1000 | 0 to 45 °C/-20 to 60°C | 3.0-4.2 |
| NCA (Li-aluminum) | | 200-260 | 500 | 0 to 45 °C/-20 to 60°C | 3.0-4.2 |

TABLE 2. TYPICAL CHARACTERISTICS OF SUPERCAPACITORS AS COMPARED TO LI-ION BATTERIES

| Chemistry | Power Density [Kw/kg | Energy Density [Wh/kg] | Life Cycle | Operating temperature [°C] | Overall Efficiency [%] |
|---|---|---|---|---|---|
| EDLC | 1.5-6.0 | 5-20 | 1 00 0 000 | -40 to 70°C | 82-98 |
| Pseudo | Up to 6.0 | 10-25 | 100 000 | -40 to 65°C | 82-98 |
| Hybrid Asymm. | 0.01-1.0 | 20-30 | 500 000 | -40 to 65°C | <90 |
| Li-Ion SC | 2.0-9.0 | 100-150 | 100 000 | -40 to 85°C | 95-98 |
| Li-Ion batteries | 0.15-2.0 | 120-250 | 500 Up to 2000 | -20 to 60°C | 85-95 |

## *B. Analysis and comparison of Different Topologies of HESS*

Many topologies of HESS are known such as supercapacitor/battery, battery/supercapacitors, half bridge, full bridge and multiple input converter topologies that have been investigated, developed, designed and examined over the last twenty years. As mentioned above the combination of a battery and a supercapacitor forms a HESS. There are several main advantages of using a hybrid energy storage system: 1) extension of battery cycle-life, 2) increase of the overall powertrain efficiency, 3) increase of the power capability of the powertrain. Well-designed HESS and its overall performance depending on the ability to meet the power requirement which is defined by the individual performance parameters of the battery and supercapacitor packs and increased operational flexibility [10]-[15]. The passive HESS topology is shown in Fig.3. As for the limitation of power flow management the bidirectional DC/DC converters need to be utilized in active HESS.

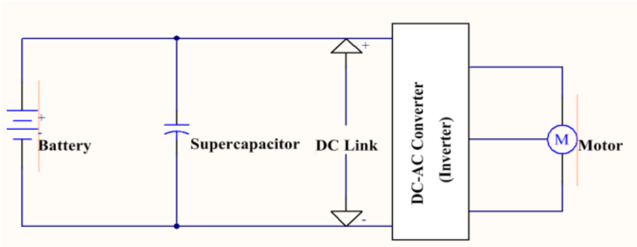


Fig. 3. Passive topology

The next topology in Fig. 4 is a partially–decoupled HESS. In this configuration the supercapacitor is connected directly to a bidirectional DC/DC converter and the battery is connected to the terminal of the inverter (DC/AC converter). The DC link voltage will have small voltage fluctuations as the battery is linked to the DC link. But here the energy density of the supercapacitor can be fully utilized as it can be discharge to zero volts. The disadvantages of this configuration are that the DC/DC converter must regulate the power quickly which increases the implementation complexity.

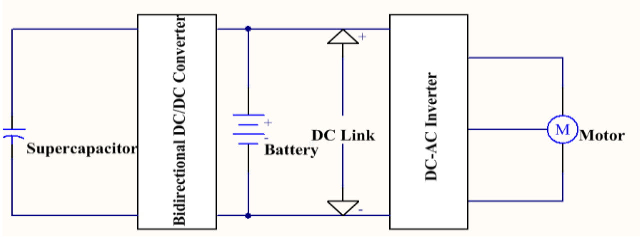


Fig. 4. Supercapacitor/Battery topology

The HESS topology in Fig.5 is another partially-decoupled structure where the battery is connected to a bi-directional DC/DC converter and the supercapacitor is connected to the terminals of the DC link. The power flow can be effectively controlled, the supercapacitor can work in a wider range and the DC link voltage can experience high fluctuations.

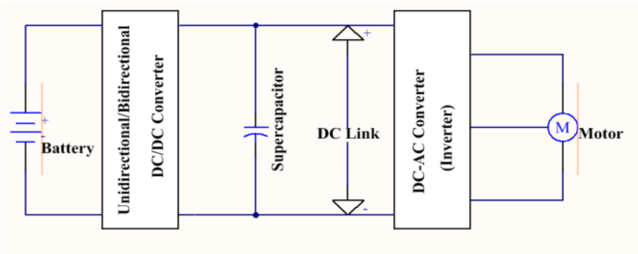


Fig. 5. Battery/Supercapacitor topology

Fig. 6 shows a configuration forming a cascaded fully decoupled system with a cascaded battery connection and a supercapacitor with utilization of the DC/DC converters. For this topology the battery and supercapacitor are connected to the inverter terminal via two separate DC/DC converters in series. The second converter rating matches the full traction demand because the battery needs to supply the load to sustain the DC link voltage.

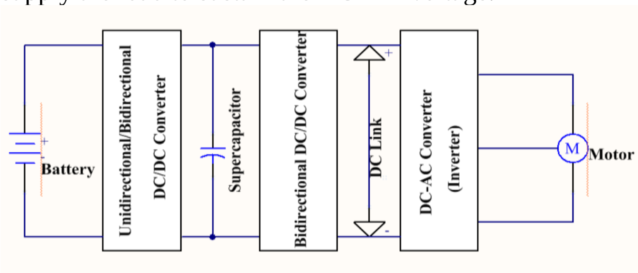


Fig. 6. Cascaded battery/supercapacitor topology

The second variant of a cascaded HESS topology is shown in Fig. 7 where the positions of the battery and the supercapacitor are changed. The DC link voltage in this topology can be controlled via the DC/DC converter.

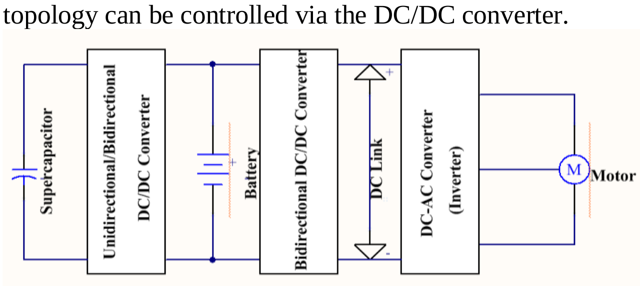


Fig. 7. Cascaded supercapacitor/battery configuration

The fully active decoupled configuration is shown in Fig. 8. This topology needs two unidirectional/bidirectional DC/DC converters. The supercapacitor, inverter, battery are isolated completely and the voltage of the supercapacitor could reach a larger voltage range. The basic disadvantage of this topology is a complicated structure and high cost of two DC/DC converters. This configuration has the same feature as a multi-input converter topology.

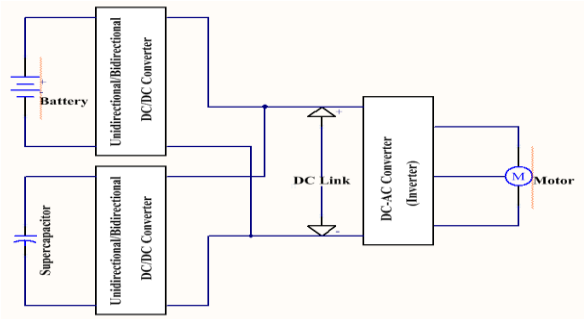


Fig. 8. Fully active topology

All the mentioned HESS topologies comprising DC/DC converters have to be bidirectional in order to allow for provision and absorption of the power from the source. To increase the benefits of HESS it is important to properly operate the energy derived from the system and into the system. The energy management system has important and essential role in minimizing the size and ratings of HESS and in obtaining an optimal operation. Also a proper control strategy is necessary for detection of the mode of operation, amount of power transfer to and from the energy storage unit in order to ensure power quality and stability. In the passive configuration there is no control algorithm and the supercapacitor unit performance cannot be fully used. The configurations with DC-DC converter can provide full regulation of voltage and current in order to achieve greater overall efficiency. Comparing and analyzing the HESS configurations mentioned above it can be said that the battery double DC-DC supercapacitor topology is more feasible and appropriate than the others due to the lower cost, fully controlled battery current, higher efficiency, higher reliability and good utilization of the advantages of supercapacitors. In order to optimize the HESS system it is necessary to take into account some parameters like battery capacity, supercapacitor capacitance and DC-DC converter rated power which have to be properly sized.

### *C. Design consideration of HESS*

The DC/DC converters in the mentioned HESS topologies above have to be bidirectional in order to allow for the delivery and absorption of the power from the source. Before developing a HESS combining a supercapacitor and a battery it is necessary to evaluate both the advantages and the disadvantages of these systems. These considerations are: a) cost and size of power electronics design, b) voltage strategy in terms of the two energy sources, c) current and voltage protection of the battery, d) reliability, stability and power quality of HESS and etc. In the design of a high power converter power is essential but on the other hand it is necessary to consider thermal management (heat dissipation) of the DC converter. Supercapacitors can be used to deliver the power needed by the system and also to absorb the surge current which can decrease battery life. Regarding the reliability of the system when designing the topology it is very important for the system to be able to operate and work in case some problems with power electronic devices or energy storage components occur.

## II. Conclusion

This paper examines and analyzes in detail different types of supercapacitors and batteries and their characteristics. It also makes an overview and explains different HESS topologies, their operating fundamentals and design considerations. . The analysis of current HESS topology configurations, battery technologies and modern innovations in the supercapacitor field reveals the advantages they provide for electric vehicles with respect to size, weight and large increase in speed. In the reviewed HESS topology configurations supercapacitors could smooth the current flows from and to the battery. Considering their charge/discharge cycle capabilities, high power density, ability to operate at high temperatures supercapacitors can increase the system overall performance and extend battery life. Moreover, supercapacitors can offer an alternative approach to meet the increasing demands of electronic devices and hybrid energy storage systems. Minimization of battery current could extend the battery life and the use of battery electric vehicles with supercapacitors could reduce peak battery current.

## Acknowledgment

This work was supported by the European Regional Development Fund within the Operational Programme ”Science and Education for Smart Growth 2014-2020 under the Project CoE “National Center of Mechatronics and Clean Technology”, Contract No. BG05M2OP001-1.001-0008, L10S7 SynChaLab.

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