A REVIEW OF BATTERY-SUPERCAPACITOR HYBRID ENERGY STORAGE SYSTEM SCHEMES FOR POWER SYSTEMS APPLICATIONS

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ABSTRACT

The paper discusses typical hybrid energy storage applications in power systems, such as frequency and voltage regulation, demand management, load shaving and energy arbitrage. The review has provided the state of the art in the field of battery-supercapacitor hybrid energy storage topologies for power systems application. A comparison of advantages and disadvantages of the passive, the semi-active and the active dc and ac schemes has been made. The parallel active hybridization scheme has been chosen as the most appropriate solution for power system application. The review has proven relevancy of the research in the field. The steps for the future research have been identified.

Keywords: battery, super capacitor, hybrid energy storage system


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1. INTRODUCTION

Power systems around the world are changing. Simultaneously with the increase in power consumption, it is necessary to find a way to solve the problem of global warming due to the greenhouse effect and high $\text{CO}_2$ concentration in the atmosphere. A need for a greener energy drives the employment of the renewable energy resources and electric transport. The drawback of wind and solar energy utilization is the volatility and intermittence of the power supply. The electric vehicles integration into power systems results in stochastic behaviour and frequent changes of the load. In the new conditions, the operation of the power grids becomes more complicated than it used to be. In order to overcome these technical problems, new technologies concepts are being developed such as demand side management, smart
A Review of Battery-Supercapacitor Hybrid Energy Storage System Schemes for Power Systems Applications

grids[1], microgrids and energy storage systems [2]. Development of the new types of electrical energy storage and their massive production is making their cost competitive and the technology becomes applicable in power systems.

Table 1 shows the range of available electrical energy storage technologies and their averaged characteristics [3].

<table>
<thead>
<tr>
<th>Characteristics of different electrical energy storage technologies</th>
<th>Supercapacitors</th>
<th>Lead-acid</th>
<th>Li-Ion</th>
<th>NaS</th>
<th>Redox-flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy density, Wh/l</td>
<td>2-10</td>
<td>50-100</td>
<td>200-350</td>
<td>150-250</td>
<td>20-70</td>
</tr>
<tr>
<td>Installation costs, €/kW</td>
<td>150-200</td>
<td>150-200</td>
<td>150-200</td>
<td>150-200</td>
<td>1000-1500</td>
</tr>
<tr>
<td>Installation costs, €/kWh</td>
<td>10000-20000</td>
<td>1000-250</td>
<td>300-800</td>
<td>500-700</td>
<td>300-500</td>
</tr>
<tr>
<td>Reaction time, ms</td>
<td>&lt;10</td>
<td>3-5</td>
<td>3-5</td>
<td>3-5</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Self-discharge rate</td>
<td>≤25% / 24hrs</td>
<td>0.1-0.4%/day</td>
<td>5%/month</td>
<td>10%/day</td>
<td>0.1-0.4%/day</td>
</tr>
<tr>
<td>Cycle lifetime</td>
<td>&gt;1mln</td>
<td>500-2000</td>
<td>2000-7000</td>
<td>5000-10000</td>
<td>&gt;10000</td>
</tr>
<tr>
<td>Lifetime, years</td>
<td>15</td>
<td>5-15</td>
<td>5-20</td>
<td>15-20</td>
<td>10-15</td>
</tr>
<tr>
<td>Transformation efficiency</td>
<td>0,75-0,83</td>
<td>0,70-0,75</td>
<td>0,80-0,85</td>
<td>0,68-0,75</td>
<td>0,7-0,8</td>
</tr>
</tbody>
</table>

Despite a large selection of technologies, none of them alone can provide a fast response and a long cycle-lifetime at the same time. The hybrid energy storage system (HESS) approach is aimed to effectively combine storage technologies with supplementary operating characteristics.

The concept of hybrid energy storage system was first introduced in [4]. HESS technology has been applied in many applications, such as electric vehicles (EVs) [5],[6],[7],[8], microgrids [9],[10],[11], and renewable energy systems [12],[13],[14],[15],[16]. HESS for residential use has been proposed [17]. HESS technology for EVs integration in microgrids and large power systems is being studied [18],[19].

This paper is aimed to discuss the ESS-applications in power systems and provide an overview of the energy storage coupling topologies.

2. METHODS

The review was aimed to provide the state of the art in the field of battery-supercapacitor hybrid energy storage topologies for power systems application and prove relevancy of the research in the field. The review has included 29 literature sources over the past 5 years. The search has been conducted among peer-reviewed academic and industrial journals. Five databases have been included in the search, namely SciVerse ScienceDirect, SciVerse Scopus, Web of Knowledge, IEEE Xplore, Google Scholar.

2.1. HESS in power systems

Application of energy storage technology in power system is still in the development state. The effective ways of energy storage are being actively explored. Electrical energy storage technologies can provide a great benefit to power systems, enable RES integration and help to increase supply security and system stability.

Power transmission from generators to consumers in the electric power system occurs instantaneously and continuously. At the same time, power demand during the day is unequal. For this reason, it is necessary to constantly regulate the supply of electricity to the network, maintaining at any time the balance between the generated and consumed active power. This power balance determines the frequency of the electric current, which is the one of the essential power quality indicators and the most important parameter of the regime of the
power system. According to the state standard of Russian Federation GOST R 54149-2010, the frequency should be within 50 ± 0.2 Hz during not less than 95% of a day, and not exceeding the maximum permissible 50 ± 0.4 Hz.

Usually, the power balance in the network is maintained by changing the output power of generators at power plants. This mode of control significantly increases the wear rate and lower utilization cost of the generating equipment, and as well, results in an additional fuel consumption. The over-consumption of fuel is especially noticeable when large power plant units are involved in the regulation of the variable part of the load schedule. Apart from the regulation costs, there is not always a technological ability to quickly start/stop a generating unit. In addition, in case of emergency situations, when capacity reserves of power plants are not enough, demand management is applied to restore the permissible frequency level. This in its turn can lead to a significant damage cost associated with the interruption of consumers power supply.

The new type of electrical load such as the electrical vehicles (EVs) is penetrating the power system. The nature of this type of load is stochastic and fast changing. The conventional generators will soon face the limit of regulation capability to follow the high-frequency load fluctuations. The promising solution may be the application of the energy storage systems along with the renewable energy sources (RES) and conventional generators.

The key application of the energy storage technology in power systems is the development of RES integration. One of the main problems associated with the use of RES is the volatility and intermittency of the power generation, negatively affecting system stability.

RES are typically distributed energy resources (DER) up to 10 MW. They are normally located close to the load they feed at low-voltage and medium-voltage level. RES integration brings additional issues to the power system, such as power quality, power system stability, protection issues due to reversed power flows, etc. [20]. Apart from a conventional power system, DER systems are decentralized, therefore they require a novel approach to the energy system control. The concept of Smart Grid is dedicated to solving the problem of RES integration to the conventional power system [1]. It relies on communication between different objects of the power system providing a reliable, economical and environmentally friendly power supply system.

In order to overcome the problems of the volatility of RES, they are often used in combination with a diesel, gasoline or gas generator. Electrical energy storage (ESS) can become a potential competitor to gas, which is now commonly used for power balancing during peak electricity demand. Due to the faster response and flexibility of control ESS can participate in primary and secondary frequency regulation [21]. Provided the cost of the ESS technologies will continue to decrease, the large-scale ESS units will be available in the future. So far, ESS has proved to be efficient and effective in ancillary services, such as load shifting and energy arbitrage.

In most regions of the world strong winds are observed at night, thus the wind power generation is the highest. On contrary, the demand is at the minimum at night. ESS can store this energy and give it out when the demand is at maximum, performing the load shifting. This helps to flatten the excess of power demand and increase the workability of RES. Energy storage technologies suitable for this application must be able to operate and react in the range of a few minutes and hours.

At the wholesale power market, the cost of energy is low when the demand is low and vice versa. EES can be used to store energy when it is cheap and be discharged during the periods of high demand and price, i.e. for energy arbitrage, thus making a profit.
Considering the increasing growth of the power demand much of transmission and
distribution systems are now close to their maximum loading capacities. Taking into account
the length of the transmission and distribution lines it is becoming apparent that the capital
investments for the system upgrade are huge. Installation of either a temporary or a permanent
EES in the overloaded node allows delaying or deferring the upgrade of existing
infrastructure. The upgrade deferral can allow avoiding the annual carrying charges for capital
investment and releasing funds for other infrastructure projects.

In case of large blackouts, the system restoration known as the black start is a technically
difficult task. EES can be used to help this procedure as a source of power to start generation
units supplying the auxiliary systems.

Voltage/VAR support is an ancillary service provided by system operators in order to
achieve system stability. Voltage support provides the supply or absorption of reactive power
in order to control voltage within allowable limits. Distributed energy storage system can
provide an alternative to power generators and rotating compensators because of the fact that
reactive power cannot be effectively transmitted over long distances.

The application of the energy storage technology can make the energy system more
secure, stable and economical, improve RES consumption capacity and promote utilization
and development of renewables.

The abovementioned factors form the requirements for energy storage technologies.

As the voltage and frequency fluctuations caused by the intermittent nature of RES can
occur quickly and often, it is important to use energy storage technologies with high cycling
lifetime and short response times. At the same time, the load shifting and energy arbitrage
require the energy storage to absorb or give out the energy for hours.

Lithium-Ion batteries are a promising technology that has already found use in many
applications, such as hybrid and fuel-cell powered electric vehicles [22], renewable
autonomous energy supply systems [23], large-scale wind- and PV-park power management
[24], and other applications. Lithium-Ion technology can be as the “high energy” storage with
a low self-discharge rate and lower energy specific installation costs. The drawback of this
technology is the low cycle lifetime. In order to increase the total system efficiency and
storage lifetime and reduce the total investment cost compared to a battery-only energy
storage, the supercapacitor technology is applied. Supercapacitors are dedicated to cover
“high power” demand, transients and fast load fluctuations and they are characterized by a
fast response time, high efficiency and high cycle lifetime.

Hybridization of batteries and supercapacitors allows decoupling energy and power (the
batteries only have to cover average power demand, whereas the SC undertakes fast
fluctuations), optimizing the operation of the batteries at high efficiency operating points and
reducing dynamic losses and stress of the batteries. In order to achieve the abovementioned
characteristics an effective HESS energy management system has to be applied. A number of
research papers are devoted to the problem of development of effective real-time management
strategies [25],[26],[27].

The next chapter represents the review of the battery-supercapacitor HESS hybridization
schemes.

3. REVIEW ON BATTERY-SUPERCAPACITOR HESS
HYBRIDIZATION SCHEMES

As it was mentioned, in the battery-alone system suffers from the natural limitations of the
batteries technology, i.e. short cycle life and low cycle efficiency due to fast charge and
discharge cycles for regulation services. A solution helping to overcome these problems is the
hybridization of batteries and supercapacitors. The supercapacitors can effectively absorb and
give out the fluctuating power requests and reduce the stress of the batteries. The different
ways of connecting the energy storages into a HESS are known.

The simplest HESS scheme is the passive parallel configuration. Fig. 1 shows a passive
HESS scheme. In this scheme, the battery and the supercapacitor are connected in parallel
without any power electronic converters. The power drawn from each element will be shared
in the proportion of their internal impedances. As the internal impedance of the
supercapacitors is much lower than that of the battery, it acts as a low-pass filter and handles
the most of the dynamic power fluctuations. Compared to the battery-alone system, the
passive HESS shows an obvious improvement on peak power capability under a pulsed load
profile. This scheme is easy for implementation and does not require any power distribution
control. However, since the supercapacitors impedance is finite they cannot fully shield the
batteries from frequent charge and discharge operations. The disadvantage of this scheme is
that it does not allow efficiently utilizing the energy stored in the supercapacitors. Since the
supercapacitors are connected parallel to the batteries, they cannot operate beyond the voltage
range allowed for the batteries resulting in the limitation of the effective supercapacitors
capacity.

**Figure 1** Passive HESS scheme

Figure 2 shows the supercapacitor semi-active scheme. In this scheme, the battery is
connected directly to dc link and the supercapacitor bank is connected to a converter. This
scheme uses a bidirectional dc/dc converter in order to handle the power of the supercapacitor
in a wide range of voltages. The nominal voltage of the supercapacitor bank can be lower than
that of the battery bank. Since the battery is connected directly to the dc link, the dc-link
voltage cannot be varied. The disadvantages of this scheme are the high rating of the dc/dc
converter and the fact that the battery may still sometimes partly supply the dynamic currents.

**Figure 2** Supercapacitor semi-active HESS scheme

Battery semi-active scheme is represented in Fig. 3. The battery is connected to a
converter and the supercapacitor bank is connected directly to the dc link. The battery current
can be independently limited to a safe near constant value. This scheme allows the voltage of
the battery to be lower or higher than the supercapacitor voltage, which extends the design
freedom of the battery and supercapacitor banks. The supercapacitor bank performs as a low-
pass filter. The dc/dc converter rating can be chosen according to the average load power (a
few times lower than the peak power). The dc/dc converter operates in current-controlled
mode. The drawback of this solution is that the dc-link voltage variation is allowed during the
supercapacitor charging and discharging. However, thus the supercapacitor energy can be
more effectively used. In order to adjust the voltage variations to the permissible range for the load, the capacitance may be increased to a very large value.

**Figure 3** Battery semi-active HESS scheme

Active cascade or series active hybrid scheme (Figure 4) allows extending the working range of the supercapacitor of the previous scheme. The second dc/dc converter is added between the supercapacitor bank and the dc link. It solves the problems of supercapacitor voltage variation and adjustment. The main disadvantages of this scheme are the requirement for a full-scaled dc/dc converter and reduced efficiency because of the two conversion stages between the battery and the dc link. Series cascade scheme is generally more expensive and more difficult to be controlled that the parallel one.

**Figure 4** Series active HESS scheme (cascade)

The parallel active hybrid scheme (Figure 5) combines the output of the two converters. This scheme is the most flexible and optimal solution. It allows maintaining the voltages of both the UC and the battery lower than dc-link voltage. It helps to ensure less balancing problems of the cells and maximum utilization of the supercapacitor energy. Besides, it allows keeping the current flow from the battery at nearly constant value. The main disadvantage of the scheme is that it needs two dc/dc converters. One converter (battery-connected) should be rated at the load average power. Another one (supercapacitor-connected) should be rated in accordance with the dynamic peak power. The trade-off of the flexibility of control is the complexity and additional losses in the system.

**Figure 5** Parallel active HESS scheme

There are different dc/dc converter topologies, isolated and non-isolated, can be applied in HESS, such as buck/boost, half-bridge, full-bridge. A special trend to highly efficient and cost-effective multi-port converters. Due to a reduced number of conversion stages a multiple input converter configuration allows reducing the cost of the overall system [28].
There is also a HESS topology that does not use common dc link (Fig. 6). Instead of it, two parallel bi-directional dc/ac power converters are used. This scheme has been implemented in 200kW peak-power prototype and tested in nearly-real conditions [29].

4. RESULTS AND DISCUSSIONS

In order to summarize the review of the battery-supercapacitor, HESS hybridization schemes let us consider the advantages and disadvantages of the schemes.

The main advantages of passive topology are the simplicity and the lack of power electronics and control, and high overall energy, and power density. The main disadvantage is the uncontrollable current flows, determined only by the elements impedances and low utilization of the supercapacitor. The utilized energy of the supercapacitor is limited in the passive scheme by the battery terminal voltage, which has to be increased by connecting a number of capacitors in parallel. Compared with the fully active HESS, the semi-active HESS is considered a practical solution in terms of reduced complexity and losses because only a single dc/dc converter is required. The active scheme provides full regulation of power distribution control between the batteries and the supercapacitors and seems the most promising solution for the power systems application. The parallel AC coupling scheme can also be considered, provided the proper control algorithm is applied.

5. CONCLUSION

Hybrid energy storage systems showed good efficiency in many areas, such as electric vehicles, renewable energy systems and microgrids. Electrical energy storage is the enabling technology for wide application of renewable energy resources. In power systems, HESS can be successfully applied for frequency and voltage regulation, demand management, load shaving and energy arbitrage, as well as to help upgrade deferral of the existing infrastructure.

Lithium-Ion technology has obtained highly promising characteristics, such as high power density, high power transformation efficiency and low self-discharge current. However, they rapidly deteriorate if applied for rapidly fluctuating power regulation in power systems. Supercapacitors effectively supplement the characteristics of the batteries and allow the system lifetime extension, thus reducing the operational costs.

A review of hybridization schemes has been represented. Advantages of each scheme and the drawbacks were discussed. Despite the increased cost of the required power converters, the parallel active hybrid scheme is the most appropriate scheme for power system application due to control flexibility.

Determination of batteries and supercapacitors capacities is not a straightforward task taking into account a tradeoff between revenue and costs. Considering HESS application for power systems, a further research in HESS sizing and optimal power management strategies has to be continued.
A Review of Battery-Supercapacitor Hybrid Energy Storage System Schemes for Power Systems Applications

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REFERENCES


