ENERGY STORAGE SYSTEMS

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Contents

Summary

A brief description and performance analysis of four different energy storage technologies is presented and general observations are made. Energy storage systems can provide valuable added benefits to improve stability, power quality and reliability of power systems. Among them are battery, flywheels, advanced capacitors, and superconducting technologies, which have significantly improved in the last decade. However, a significant component of these technologies is the power electronic interface. It plays a major role in enabling and defining the performance of the energy storage application. This chapter concentrates on the power electronics requirements, characteristics, alternatives and performance benefits of adding energy storage to power utility applications. Energy storage technologies interfaced via advanced, efficient and intelligent power electronics can play a major role in increasing the performance and security of power systems and its fundamental life support function.

1. Introduction

Energy storage systems are necessary in a number of levels:

A. Device level: where devices, such as motors, are equipped with energy storage systems that maintain constant torque or speed. A typical example is the use of governors in the generators.
B. Medium level: where storage systems are used in industrial applications to provide ride-through during voltage sags.
C. System level: where the entire power system is equipped with storage systems for applications such as load leveling or stability enhancement.

This chapter provides a summary of viable storage technologies including batteries, flywheels, ultracapacitors, and superconducting energy storage systems. These summaries followed by a detailed characterization of the power electronic interface design options, since power converters are an enabling technology for many of the storage technologies described here. This chapter shows that energy storage devices can be integrated to power electronic converters to provide power system stability, enhanced transmission capability and improved power quality. Adding energy storage to static compensators not only enhances the performance of the device but can also provide the possibility of reducing the MVA ratings requirements of the front-end power electronic conversion system. Finally, this paper provides several computer simulations demonstrating enhanced power system performance with energy storage systems present.

Continuing electric load growth and higher regional power transfers in a largely interconnected network lead to complex and less secure power system operation. Power generation and transmission facilities have not been able to grow to meet these new demands due to economic, environmental, technical and governmental regulation constraints. When power system disturbances occur, synchronous generators aren't always able to respond rapidly enough to keep the system stable. If high-speed real or reactive power control is available, load shedding or generator dropping may be avoided during a disturbance. High-speed reactive power control is possible through the use of flexible AC transmission systems (FACTS) devices. In a few cases, these devices are also able to provide some measure of high-speed real power control through power circulation within the converter, with the real power coming from the same line or in some cases from adjacent lines leaving the same substation. However, a better solution would be to have the ability to rapidly vary real power without impacting the system through power circulation. This is where energy storage technology plays a very important role in maintaining system reliability and power quality. The ideal solution is to have means to rapidly damp dynamic system oscillations, respond to sudden changes in load, supply critical loads during transmission or distribution interruptions, correct load voltage profiles with rapid reactive power control, and still allow the generators to maintain steady-state balance with the system load. Recent developments and advances in energy storage and power electronic technologies are making the application of energy storage technologies a viable solution for modern power applications.

2. Energy Storage Systems

Electrical energy in an alternating current (AC) system cannot be stored electrically, and must typically be generated at the time of demand. However, energy can be stored by converting the electrical energy and storing it electromagnetically, electrochemically, kinetically or as potential energy. Each energy storage technology usually requires an energy conversion unit to convert the energy from one form into another and back again (charging and discharging the storage system).

The possible applications of energy storage in utility systems include: transmission enhancement, power oscillation damping, dynamic voltage stability, tie-line control, short-term spinning reserve, load leveling, reducing the need for under-frequency load shedding, allowing less stringent time limits for circuit break reclosing, sub-synchronous resonance damping, and power quality improvement.

Descriptions of four leading storage technologies for transmission and distribution applications are presented in the following.

2.1 Superconducting Magnetic Energy Storage (SMES)

The core element of an SMES unit is a superconducting coil of high inductance (L_{Coil} in Henrys). It stores energy in the magnetic field generated by a DC current (I_{Coil} in Amperes) flowing through the coil. The inductively stored energy (E in Joules) and the rated power (P in Watts) are commonly given specifications for SMES devices, and they are expressed in Eqs. (1) and (2).

$$E = \frac{1}{2} L I_{\mathrm{Coil}}{}^2 \tag{1}$$

$$P = \frac{dE}{dt} = L I_{\mathrm{Coil}} \frac{dI_{\mathrm{Coil}}}{dt} = V_{\mathrm{Coil}} I_{\mathrm{Coil}} \tag{2}$$

Since energy is stored as circulating current, energy can be discharged from, or stored in, a SMES unit with almost instantaneous response over periods ranging from a fraction of a second to several hours.

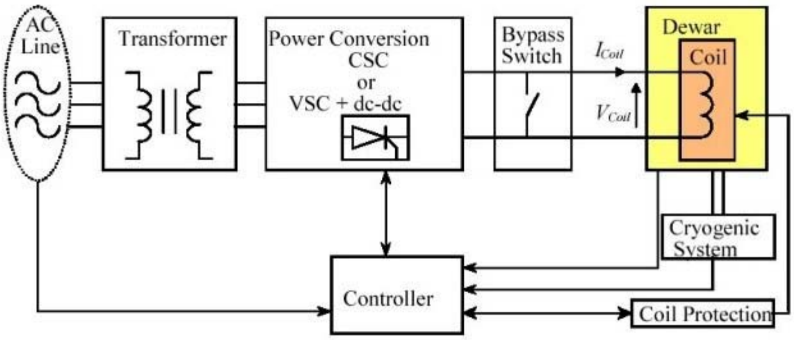

Figure 1: Components of a Typical SMES System

The entire SMES unit consists of a large superconducting coil at the cryogenic temperature and controlled by a power electronic conversion system. Power conversion may be achieved through two main power electronic converter topologies. One approach is to use current source converter (CSC) to interface to the AC system and charge/discharge the coil. The second approach uses a voltage source converter (VSC) to interface to the AC system and a DC-DC chopper to charge/discharge the coil. In this approach, the VSC and DC-DC chopper share a common DC bus. The components of a typical SMES system are shown in Figure 1. The modes of charge/discharge/standby are obtained by controlling the voltage across the SMES coil (V_{coil}).

Several factors must be considered in the design of the coil to achieve the best performance of a SMES system at least cost. These factors include coil configuration, energy capacity, structure, and operating temperature. The coil can be configured as a solenoid that producers fairly large fringe fields (external magnetic field) or a toroid that features a very low fringe field. The fringe field level is the only environmental concern associated with a SMES, since no toxic materials are used within the SMES, nor does it contain the inherent potential of catastrophic physical failure. The solenoid configuration has been used widely due to its simplicity and cost effectiveness, though toroid-coil designs have also been incorporated into a number of small-scale SMES projects. Coil inductance (L) or PCS maximum voltage (V_{max}) and current (I_{max}) ratings determine the maximum energy/power that can be drawn or injected by a SMES coil.

SMES was originally proposed as a bulk energy storage technology for electric power systems. SMES systems have attracted the attention of both electric utilities and the military due to their fast response and high efficiency (charge-discharge efficiency over 95%). SMES systems are still costly when compared with other currently available energy storage technologies, but the on-going development of high temperature superconductors should make SMES increasingly cost effective due to reductions in refrigeration needs. SMES' efficiency and fast response capability (MW/millisecond) have been exploited in electric power system applications at all levels. Since the 1970's, numerous potential utility applications have been proposed. SMES development continues in power conversion systems and control schemes, evaluation of design and cost factors, and analyses for various power system applications. Currently, there are a number of utility application SMES projects installed or in development throughout the world.

2.2 Battery Energy Storage (BESS)

Batteries store energy electrochemically and are one of the most cost-effective energy storage technologies available. A battery system is made up of a set of low-voltage/low-power battery modules connected in parallel or series to achieve the desired electrical characteristic. Batteries are "charged" when they undergo an internal chemical reaction resulting from a voltage potential applied to the terminals. They deliver the absorbed energy, or "discharge," when the chemical reaction is reversed. The primary advantages of battery energy storage are high energy density, high energy capability, round trip efficiency, cycling capability, life span, and initial cost. However, due to the chemical kinetics involved, batteries cannot operate at high power levels for long periods of time. In addition, rapid, deep discharges may lead to the need for early replacement of the battery, since resultant heating reduces battery lifetime. There may also be environmental concerns related to battery storage as a result of gas generation during battery charge/discharge. The disposal of hazardous materials also presents battery disposal problems.

Lead-acid batteries represent an established, mature technology. Lead-acid batteries can be designed for bulk energy storage or for rapid charge/discharge. On-going research with different chemical additives has let to improvements in energy density and charging characteristics. Lead-acid batteries still represent one of the best low cost options for most applications requiring large storage capabilities, if repeated deep discharges are not required. Mobile applications favor sealed lead-acid battery technologies for safety and ease of maintenance. Valve regulated lead-acid (VRLA) batteries exhibit better cost and performance characteristics for stationary applications.

Batteries charge and discharge via a DC current, thus a power conversion is required to interface a battery with an AC system. This conversion system is very similar to power conversion system of a SMES. Battery systems with appropriate power electronic converters can provide four-quadrant operation (bi-directional current flow and bi-directional voltage polarity) with rapid response. Recent advances in battery technologies also offer increased energy storage densities, greater cycling capabilities, higher reliability, and lower cost.

Battery energy storage systems have recently emerged as one of the more promising near-term storage technologies for power applications, offering a wide range of power system applications such as area regulation, area protection, spinning reserve and power factor correction. Several BESS units have been designed and installed in existing systems for the purposes of load leveling, stabilizing, and load frequency control. The optimal placement and capacity of BESS is dependent upon its application. Also, the integration of battery energy storage with a FACTS power flow controller can improve the power system operation and control.

2.3 Advanced Capacitors

Capacitors store electric energy by accumulating positive and negative charges on metallic electrodes (often on parallel plates) that are separated by an insulating dielectric. The capacitance, C, represents the relationship between the stored charge (q) and the voltage between the plates (V) as shown in Eq. (3). The capacitance depends on the permittivity of the dielectric, ε, the surface area of the electrodes, A, and the distance between them d as shown in Eq. (4). Equation (5) indicates that the energy stored on the capacitor depends on the capacitance and on the square of the voltage.

$$q = CV \tag{3}$$

$$C = \frac{\varepsilon A}{d} \tag{4}$$

$$E = \frac{1}{2} C V^2 \tag{5}$$

$$V = I \cdot \frac{t}{C_{\text{tot}}} + I \cdot R_{\text{tot}} \tag{6}$$

The amount of energy a capacitor is capable of storing can be increased by either increasing the capacitance or the voltage. The voltage is limited by the voltage withstand strength of the dielectric (which basically decreases with the distance between the electrodes for a given dielectric material). Capacitance can be increased by increasing the area of the electrodes, increasing the permittivity, or by decreasing the distance between the electrodes. The effective series resistance (ESR) of the capacitor has a significant impact on both the turn around efficiency and the system response time. The total voltage required to charge a capacitor from zero voltage with a DC current over time t is given in Eq. (6).

Note that C_{tot} and R_{tot} result from a combined series/parallel configuration of capacitor cells to increase the total capacitance and the voltage level. The product $R_{\text{tot}}C_{\text{tot}}$ determines the response time of the capacitor for charging or discharging.

DC storage capacitors can be used for energy storage for power applications. They have been used extensively in pulsed power applications for high-energy physics and weapons applications. However, the present generation of DC storage capacitors has only been used for very specific short-term storage applications in bulk power systems. For example, capacitors can be added to the DC bus of motor drives and consumer electronics to provide the ability to ride through voltage sags and momentary interruptions, thus providing energy storage in a very distributed manner within the system.

Ceramic hypercapacitors have both a fairly high voltage withstand capability (about 1 kV) and a high permittivity, making them good candidates for future storage applications. The combination of higher voltage withstand and low effective series resistance will make it easier to use hypercapacitors in high power applications with simpler configurations possible.

Ultracapacitors (also known as supercapacitors) are double layer capacitors that increase energy storage capability due to a large increase in surface area through use of a porous electrolyte (they still have relatively low permittivity and voltage withstand capabilities). Several different combinations of electrode and electrolyte materials have been used in ultracapacitors, with different combinations resulting in varying capacitance, energy density, cycle-life and cost characteristics. Near term applications will most likely use these capacitors in power quality applications. For example, ultracapacitors can be added to the DC bus of motor drives to improve ride through during voltage sags.

2.4 Flywheel Energy Storage (FES)

Flywheels store energy in kinetic form in the rotating mass of the wheel. They can be used for power system applications when the flywheel is coupled to a rotating electric machine such as a generator. The amount of stored energy depends on the moment of inertia (J) of the rotor and the square of the angular (or rotational) velocity (ω) of the flywheel as shown in Eq. (7). The moment of inertia is depends on the radius (r), mass (m), and axial height (h) of the wheel as given in Eq. (8). Energy is transferred into the flywheel and stored as kinetic energy when the electric machine operates as a motor causing the flywheel to accelerate. The flywheel is discharged when the electric machine regenerates through the drive thus decelerating the flywheel.

$$E = \frac{1}{2} J\omega^2 \tag{7}$$

$$J = \frac{r^2 mh}{2} \tag{8}$$

Increasing the moment of inertia and rotating at higher velocities can increase the energy storage capability of flywheels. Some designs utilize hollow cylinders for the rotor allowing the mass to be concentrated at the outer radius of the flywheel, thus improving storage capability without a large increase in weight.

Although a FES utilizes an AC generator/motor to convert from kinetic energy to electric power, in most cases an additional power electronic interface is used to gain more flexibility in power flow control. When a FES system is incorporated into a FACTS or custom power device with a DC bus, an inverter is added to couple the flywheel motor/generator to this DC bus. For example, a flywheel based on an AC machine could have an inverter interface to the DC bus of the dynamic voltage restorer custom power device shown in Figure 2.

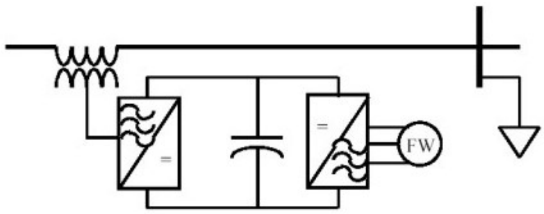

Figure 2: Flywheel Energy Storage Coupled to a Dynamic Voltage Restorer

Two strategies have been utilized in the development of flywheels for power system applications. One option is to increase the inertia by using a steel mass with a large radius with rotational velocities up to approximately 10,000 RPM. Several flywheels utilizing this type of design are available commercially as uninterruptible power supplies (UPS). These systems utilize a fairly standard motor and power electronic drive as the power conversion interface. This design results in relatively large, heavy flywheel system. Rotational energy losses also limit the long-term storage ability of this type of flywheel.

The second design strategy is to produce flywheels with a lightweight rotor turning at very high rotational velocities (up to 100,000 RPM). This approach results in compact and lightweight energy storage devices. This approach also allows modular designs, where a large number of small flywheels are used as an alternative to a small number of large flywheels. Rotational losses due to drag from air and bearing losses result in significant self-discharge. Therefore, high-velocity flywheels are usually operated in vacuum vessels to eliminate air resistance. The use of magnetic bearings further reduces friction losses, thus recent research has focused on developing superconducting magnetic bearings for high-velocity flywheels,. The high rotational velocity also results in the need for a containment vessel around the flywheel to prevent dangerous disruptive failure in case the rotor fails mechanically where rotational forces tear the rotor apart at high speeds. Flywheel applications under consideration include automobiles, buses, high-speed rail locomotives, and energy storage for electromagnetic catapults on next generation aircraft carriers.

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