Chapter

A Review on Superconducting Magnetic Energy Storage System Applications

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Abstract

Superconducting Magnetic Energy Storage is one of the most substantial storage devices. Due to its technological advancements in recent years, it has been considered reliable energy storage in many applications. This storage device has been separated into two organizations, toroid and solenoid, selected for the intended application constraints. It has also been used in many industries, such as transportation, renewable energy utilization, power system stabilization, and quality improvement. This chapter discusses various SMES structures and their applications in electric and power systems. Here, the authors try to deliver a comprehensive view for scholars whose research is related to the SMES by examination of the published articles while providing a brief guideline of this modern technology and its applications.

Keywords: energy storage, SMES, electrical power systems, energy systems

1. Introduction

Today, many Energy Storage Systems (ESS) are being used. Users have various options according to the application and parameters such as cost, available room, accuracy, lifetime, and efficiency. Among numerous ESS technologies, Battery Energy Storage Systems (BESS), Super Capacitor Energy Storage Systems (SCES), Flywheel Energy Storage Systems (FESS), Compressed Air Energy Storage Systems (CAES), and Superconducting Magnetic Energy Storage Systems (SMES) are the leading viable technologies. Each of these technologies has strengths and weaknesses. The negative attributes of BESS are limited lifecycle, failure of deep discharge, and processing of lead afterward. Using toxic heavy metals is another issue with some types of BESS [1]. The drawbacks of SCES are a limited range of operating voltage, limited energy output in fast cyclic operation [2], and toxic and corrosive materials [3]. As the limitations of FESS, the possibility of mechanical failure and dissociation [3], considerable standby losses [4, 5], the dependence of stored energy on magnetic sources (usually permanent magnet), and the deterioration of magnetic sources and consequently in energy storage capacity [6] can be mentioned. Furthermore, in some specific applications, such as vehicular applications, increasing the center of gravity height of the vehicle followed by unbalancing issues on the vehicle is problematic [7]. Slow response [8], low round-trip efficiency [1, 9, 10], limitations imposed by topographical conditions, and negative environmental impact [9–11] are the main disadvantages of the CAES system. Quick positioning time (reaction time plus rising to peak discharge power), rapid charging time, considerable capacity, high cycle efficiency, instantaneous power output, reliability, no self-discharge, and low maintenance are some listed benefits of SMES [11–14]. Two major concerns raised to SMES technologies are high cost and strong magnetic force due to the high magnetic field [15]. As mentioned in [16], by improvement in the superconductor manufacturing industry and the downward trend of high-temperature conductors' cost, SMES technology will become an economical and available storage device [17–20]. Besides, there are many ongoing types of research to lessen cooling system costs. Moreover, in some cases, using SMES helps decrease long-term costs. To answer the environmental impact of the magnetic field, the authors propose a Force-Balanced Coil (FBC) in [21, 22].

In this chapter, while briefly reviewing the technologies of control systems and system types in Section 2, Section 3 examines the superconducting magnetic energy storage system applications in the articles related to this technology. Also, the conclusion section is advanced in the fourth section.

2. System type

The SMES system is a DC device that keeps the energy in a magnetic field. The current flows through an inductor kept in specific conditions providing superconductivity; thus, a strong magnetic field is created. The superconducting coil unit, power conditioning, and cryogenic subsystem are the three main parts of a typical SMES. The Power Conditioning System (PCS) plays a crucial role in power exchange between the superconducting coil and the AC system. According to the configuration of this subsystem, there are three types of SMES: thyristor-based SMES, Voltage Source Inverter-based SMES (VSI-SMES), and Current Source Inverter-based SMES (CSI-SMES). Regardless of the kind of SMES control system, its applications are mentioned in the following section.

From the structural viewpoint, there are two types of SMES: Toroidal and Solenoidal. Considering the application, investment, available room, production availability, etc., the structure of the SMES system in the designing step should be selected. The solenoid type is more convenient to build and can also manage mechanical stresses due to less wire consumption. Compared to the toroidal type, it is more cost-effective. Despite the solenoidal geometry, the toroidal SMES has less stray field and decreases the vertical component of the magnetic field on the conductor; therefore, it can be expected that the necessities of the materials and AC losses are overshadowed [17, 23, 24]. **Figure 1** shows both solenoidal and toroidal structures of the SMES.

3. SMES application

The specific characteristics of a superconducting magnetic energy storage system provide outstanding capabilities making it a fitting choice for many applications. Applications of SMES are defined in the following subsections by mentioning many cases in which its effectiveness in power systems has been proven. This section has made an effort to provide a directory of SMES technology.

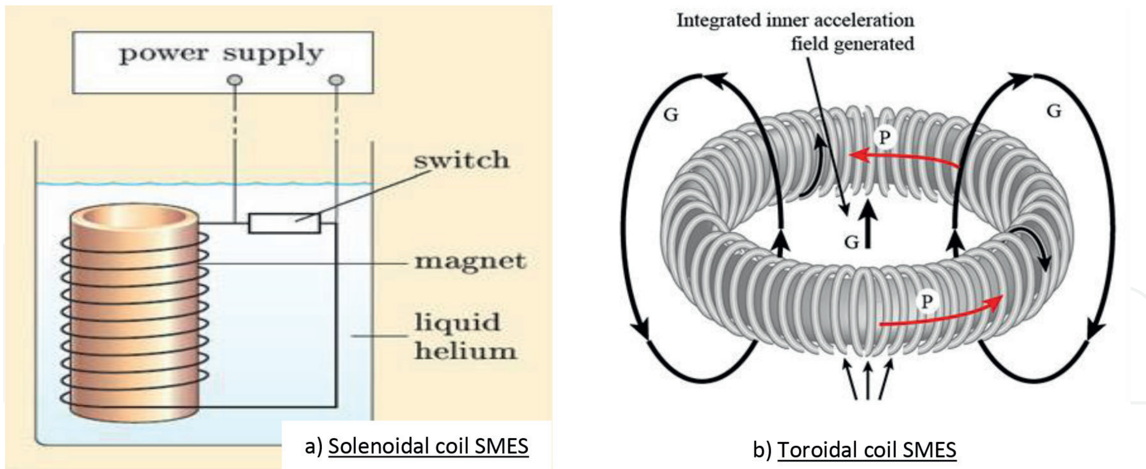

Figure 1.
Different types of SMES structure: (a) solenoidal geography, (b) toroidal geography.

3.1 Power quality improvement

The end-user sensitive loads require undistorted power. Supplying the users at an acceptable voltage range and mitigating disturbances are critical tasks. SMES features such as fast response, large capacity, and ability to control active and reactive power simultaneously make it a suitable option for a power quality boost [8–10]. Mitigating the voltage sag using the stored energy in SMES helps recover the standard voltage range in less than a second, leading to power quality improvement, which is essential for sensitive loads [25–36].

3.2 Power fluctuations compensation

Besides all their benefits, renewable resources may cause unstable power due to the uncertainty of renewable resources. Wind speed variations in a wind farm and sun radiation variations in the case of using PV cells as the power generating system result in problems such as lump flicker, timing device imprecision, and shortened hardware life cycle. Considering its fast response, the SMES unit can compensate for the differences between demand and generation by absorbing or releasing power, minimizing the adverse effects on the demand side. The fast response characteristic of SMES has been proven effective in reacting to the power difference between both sides, smoothing the power fluctuations [37–39]. In Ref. [40–44], different controlling methods are employed due to various resources and load sensitivity.

3.3 Power oscillation compensation

Load changes and system faults cause low-frequency power oscillation between 0.5 and 1 Hz. Considering the probability of such disturbances, it seems the system's oscillation damping is essential that should be applied rapidly. As a storage device capable of exchanging a large amount of active and reactive power simultaneously with the system in the minimum time, SMES is introduced as an efficient power compensator [32]. With the proper controller design, SMES could compensate for system's oscillation under light and heavy load flow and renewable resources uncertainties [45–49].

3.4 Stability

Power system's stability includes voltage, power angle, and frequency stability. To provide these parameters stability, generator excitation control is established to be an effective solution. Still, more is needed due to power networks' rapidly increasing size and complexity. SMES is one of the most encouraging members of the FACTS collection, which can supply/receive active and reactive power immediately and has been highly projected as one of the most effective controllers of power system stabilization. The concept of its operation is simple: a superconducting coil that stores or releases energy by charging or discharging a thyristor-controlled power converter connected to an AC power system. The firing angles of thyristor variation in an appropriate mode determine the course of energy transmission. This process helps to mitigate the released energy during a disturbance and brings back stability to the system [50–71].

3.4.1 Dynamic stability

One of the problems of the isolated power system is the fluctuation and instability caused by abrupt alterations in load or generation unit followed by the grid's deviation of frequency and power. Power system oscillations happen when conflicts such as sudden burden changes occur. The system's suppressing must be so that the synchronous generators can return to steady-state conditions. Particularly when the end of the transmission line is experiencing sudden load distress, the generators must have incessant control to suppress oscillations in the system. Many proceedings have been proposed to fortify the damping process, including power system stabilizers, optimal control of the turbine-governor system, and static phase shifter. Successful tests of the BPA 30 MJ unit and superconductive magnetic energy storage (SMES) systems have gained scholars' attention in power applications. Although the device's original resolution in that experiment was load leveling, another function of the SMES unit was to enhance the system performance by providing precise power modulation in a dynamic period [72–77].

3.5 Shaft oscillation minimization

Despite all assumptions analyzing the power system dynamic performance based on the system integrity, the turbine-generator rotor has built-in a complicated mechanical structure and consists of several predominant masses. The generator under tension leads to twisting stress among the shaft components in a sub-synchronous range which may cause electrical system damage. On the other hand, some disturbances in the electrical system might have the same effect on shafts, so the life expectancy of the generator would decrease. Given the mentioned complications, a proper damper should be applied. Using SMES associated with a controlling system will be helpful as a compensating system as the SMES can compensate for the system fault leading to less electrical tension and, therefore, less mechanical stress on the generators [78, 79].

3.6 Voltage stability

Wind generators, especially squirrel cage induction generators, consume a noticeable amount of reactive power. Moreover, voltage sag induced by a sudden increase in loads is a severe problem in the electrical network. As a result, reactive power control is consequential in maintaining the standard voltage level in the system. A power compensation device should be employed to compensate for the voltage sag. SMES is a capable source due to the rapid charge and discharge periods. Connected to a power system with a power electronic converter, SMES can convey energy into the power system in milliseconds, resulting in maintaining load voltage in a normal range, improving the network stability, and compensating voltage sag properly [80–92]. It should be noted that locating SMES units in the system should be carried out based on the quantitative voltage stability index [93].

3.7 Sub-synchronous resonance compensation

Sub-synchronous resonance usually occurs in power systems containing steam generators and compensated lines by parallel capacitors, which cause shaft resonances and consequential damages. When a disturbance happens in these systems, in the case of the sub-synchronous resonance effect, the shaft rotates at sub-synchronous frequencies along with the base synchronous speed, which, if not confined, results in a shaft break. The sub-synchronous resonances are the effects of improper energy exchanges between turbo-generator and power systems, and they could originate anywhere on the system. The capability of rapidly absorbing and delivering energy has made SMES an appropriate choice for compensating for these disturbances to prevent sub-synchronous resonances [74, 94–98].

3.8 Renewable energy resources

Renewable energy generation is widely used to address energy shortages and environmental problems. Since the output power of the solar cells and the wind turbines changes with the variation of sunlight irradiation and the wind speed and high level of the renewable resources penetration into the power systems can trigger instability, unreliability, and power quality issues, the system must be able to withstand current and reactive power fluctuations, otherwise, the distortion causes harms to the system and critical loads. To cope with these problems, using ESS in renewable power combinations has been greatly noticed. In this case, the performance criteria are energy storage capacity, power output, and life cycle. To alleviate the mentioned issues, SMES can be applied, which can charge and discharge immediately. In other words, it can absorb high quantities of power in the time of lack of demand and deliver high quantities of power in the time of lack of production of electric power. Therefore, the utilization of renewable energy resources, despite their intermittent nature, is associated with more accessibility, and the compensation is applied in less than a minute or some cases, a few minutes [82–85, 99–152].

3.9 Frequency control

The system frequency is a dependent factor on the active power balance of that system. Since frequency is a common parameter in the system, the alternation of the active power in one point reflects on the whole system. Governor is not capable of absorbing the frequency fluctuation in a short time. Because of that, using SMES as storage with quick response time while supplying high power density has been a practical solution in many systems to compensate for the sudden load change and, consequently, frequency control [111, 153–166].

3.10 Automatic generation control (AGC)

Failure to adapt demand and generation in the power system causes unsteady operation and disrupts the system's dynamic performance. Adding a storage device to the system will cause the AGC to achieve its goal of eliminating this disorder faster, improving the transient state operation. Due to features such as a high-density discharge rate, the minimum time required for power flow reversal, and low maintenance requirements, many systems switch to SMES, which is developed to control active and reactive power simultaneously. When an increase step change in power demand occurs, the energy stored in the SMES is injected through the PCS as an alternative to the power system. When the governor and controllers start and retrieve the position, SMES returns to the initial value of the current. When an unexpected drop in power demand occurs, the SMES intervenes and absorbs part of the excess energy. After recovering the position, this absorbed energy is released, and the SMES returns to its standard value [167–170].

3.11 Low voltage ride-through (LVRT)

A neighboring grid fault causes a drop in the grid voltage at the junction point of the generator and network; low voltage ride-through happens. This situation limits the power flow. If there is a considerable input power, the power inequity leads to a surge in the back-to-back converter's turbine speed or DC bus voltage. An ESS could avoid over-speeding of the turbine and even out the DC bus voltage level. High power ability and instant response are essential for this application; thus, SMES is a great storage device to fit [171, 172]. The SMES can restrict the fault current while compensating for voltage drop and eliminate the residual power fluctuation caused by the disturbance [173, 174].

3.12 Protection

Installation of SMES alongside power end-users as a SMES-based UPS can protect critical loads during faults. SMES alone does not affect fault current limitation at ground fault location but, combined with SFCL, plays an influential role in an error. This ESS can retain the network voltage at or near its nominal value in case of a fault. Generator tripping is one of the most critical emergency controls to prevent damage to the power system. Considering the availability of SMES to provide long-time energy or high-density power for a load, it could protect a specific load alongside a proper controller. Therefore, in a system with prioritized loads, the ESS could protect the sensitive loads at any given time. The current flowing through the coil is defined based on the operating point of the given load and the time of protection [175–178].

3.13 Black start

A power loss over a large geographical area for a noticeable period, called a blackout, is a severe threat to the network. Besides all the effects on the residential consumers, the industries face irrecoverable losses at this time. Therefore, power system restoration or black start is vital for a SMES unit to cope. Unlike traditional methods, utilizing SMES has advantages such as faster start speed than other generation methods, multipath black start, and more environmentally friendly than other black start units. Considering the four-quadrant operation, SMES can deal with the primary problems of the black start process, which are over-voltage, voltage drop, and power oscillation [66].

3.14 Load leveling

Load leveling is a concept that helps with having a balanced power profile by decreasing demand at peak times and filling the valleys (**Figure 2**). Due to the principles of load leveling, SMES has two advantages: High storage efficiency of 90% and no site limitation. In low demand time, SMES is recharged, and thus the generator operates in its optimal range (filling the valley), and at the peak-demand time, the SMES is discharged. The difference between the demanded and generated power (in the optimal range) is compensated by discharging its power in the network [171, 179, 180].

On the other hand, every generator has an optimum work point, achieving that, parameters such as generator lifetime, total loss, and system overall performance would be at the prime mode. On the other hand, consumption would not be monotonic and uniform, and the profile consists of peaks and valleys. Concerning the discrepancy between generation and consumption curves, a SMES unit could be utilized to preserve the optimum system performance and prevent waste of energy. Receiving energy during the underload situation and releasing it during the overload situation, the SMES charged and discharged respectively; hence the power would have a smooth curve. Having a large capacity and fast response time, SMES is capable of rapid load following to develop the invariant outage for the generating unit [119].

3.15 Spinning reserve

Spinning reserve is defined as the dormant capacity that the system operator could employ. Considering the capacity and response time, a SMES unit represents a significant spinning reserve capacity that could quickly be activated by Primary Frequency Control (PFC) and improve system parameters [10, 181].

3.16 Transportation

The transportation application can be investigated from three points of view. First, considering the required power while charging, electric vehicles draw significant

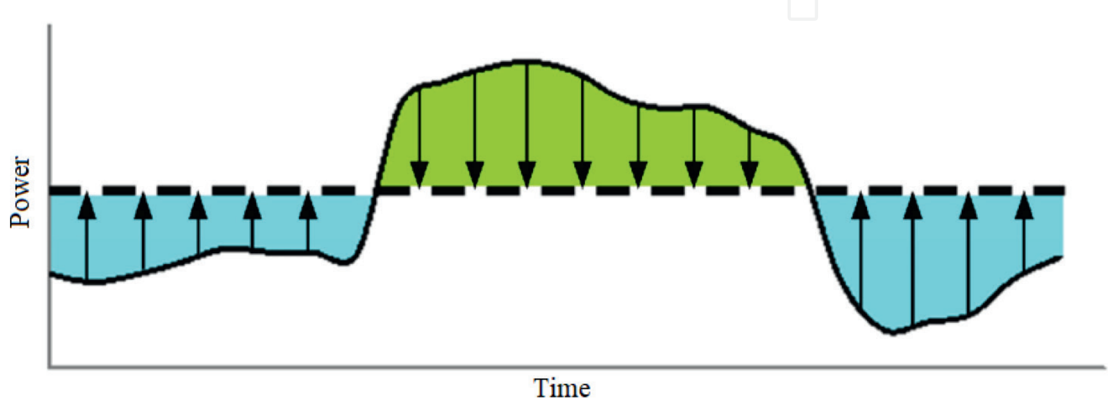

Figure 2.
Load leveling in the power profile.

current from the power system, which causes instability and following complications. The primary role of stationary SMES in road vehicles and railway transportation systems is to supply a high-frequency component [105, 106]. Second, as an ESS, the SMES is an auxiliary unit causing more contribution of Renewable Energy Resources (RES) as the energy supplier for electrical transportation, whether rail or road. Although renewable power stations such as wind farms or PV cells can provide the necessary power to run mentioned transportation systems, due to variations of output power subordinate to weather conditions, an energy storage system is required to supply the load with standard quality. During low-demand periods and peak times, if power generation cannot support all the consumers, a previously stored amount of power is released into the grid, which is feasible by utilizing an ESS with a fast response [121, 123]. Third, in railway systems, a tremendous amount of energy is wasted during deceleration in the form of thermal energy. Retrieving and returning this energy to be used in the system saves energy and reduces costs in the long term. Large capacity and fast response make SMES an excellent candidate for absorbing energy during acceleration and releasing it during deceleration [182–187].

3.17 P & Q control

SMES can absorb or deliver active and reactive powers independently and simultaneously. Although the output of active power from SMES relies on the energy stored in the coil, SMES can uninterruptedly function throughout its reactive power range to regulate the voltage of the common coupling point. The converter firing angle controls the domains of active and reactive power [188–192].

3.18 Reliability

To strengthen the reliability of the power systems, storage systems should cope with electrical outages caused by natural events and support demands when power system failures arise accordingly. The power and energy capacity of SMES provide reliability for the system by ensuring the power supply for a given load while observing the standard range for different parameters [55, 107, 108, 120].

3.19 Uninterruptable power supplies

Widespread usage of electric devices from domestic consumers to industry consumers emphasizes the continuous quality of supply. Some equipment demands an uninterrupted electricity supply among all facilities due to high prices or high-performance sensitivity. With high energy density and fast response, SMES can be a promising candidate to supply these loads for up to several hours [3, 10, 193].

4. Conclusion

In this chapter, based on previously published articles on the technology of SMES, the potential usages of this technology have been reviewed. Considering the application this storage system is used for, the type and the control strategy should be selected. This storage system has been proven effective for many industrial applications, such as active and reactive power control, system stability, and power quality.

Given its technology advancement, price reduction, and the required room, it is anticipated that the SMES has a clear horizon to be more involved in areas like reliability and the transportation industry. Due to the exhaustiveness of the study, this article can be used as an acceptable guideline for researchers, engineers, readers, and academicians working in the fields related to this technology.

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