Power System Applications of Superconducting Magnetic Energy Storage Systems

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***Abstract* –This study overviewed current researches on power system applications of SMES systems. Some key schematic diagrams of applications were given, too. Furthermore, the authors tried to present a few valuable suggestions for future studies of SMES applications to power systems.**

***Index Terms* – Power systems, superconducting magnetic energy storage (SMES),**

I. Introduction

Since the discovery of superconductivity, people have expected a revolution to occur in the field of electrical engineering. Superconducting magnetic energy storage (SMES) is one of superconductivity applications. SMES is an energy storage device that stores energy in the form of dc electricity that is the source of a dc magnetic field. The conductor for carrying the current operates at cryogenic temperatures where it is a superconductor and thus has virtually no resistive losses as it produces the magnetic field. Consequently, the energy can be stored in a persistent mode, until required.

The overall technology of cryogenics and superconductivity today is such that the components of an SMES device are defined and can be constructed. In general, an SMES system is composed of four parts, which are the superconducting coil with the magnet (SCM), the power conditioning system (PCS), cryogenics system (CS), and controller, as shown in Fig. 1. The functions of each part can be described briefly as follows. a) The SCM is used to store the dc electrical energy. b) The PCS is the interface between the ac utility and the SCM. Through the PCS, the ac electrical energy can be converted into the dc electrical energy stored in the SCM. Inversely, the latter also can be converted into the former fed back to the ac utility. c) The CS is required to cool the SCM and keep it at the operating temperature. d) The controller is the essential part of SMES systems. No matter what purposes the SMES systems are expected to implement, they primarily depend on the controller to perform various functions.

Due to advantages in both superconducting technologies and power electronics, SMES systems have some excellent performances, such as rapid response (milli-second), high power (multi-power), high efficiency, and four-quadrant control. Thus, SMES systems can offer flexible, reliable, and fast acting power compensation. Consequently, SMES systems will be able to store energy more efficiency than any conventional energy storage systems such as chemical batteries or hydro-pumped storage. Furthermore, the integrated unit appears to be feasible for some utility applications at a cost that is competitive with other technologies. Therefore, SMES is expected to become the next generation technology for storing electrical energy.

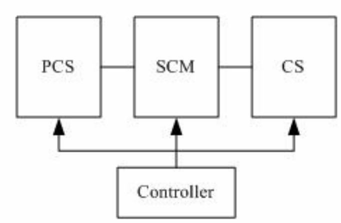

Fig. 1. Block diagram of SMES systems

Researches on SMES are focused on three aspects: (a) PCS, (b) applications of SMES, and (c) SCM. The researches on the PCS mainly include circuit topologies and control techniques. The researches on applications are to explore feasible applications and control strategies. The researches on the SCM are concerned on design and optimization of the SCM. This study is focused on the power system applications of SMES. The authors attempt to give a full overview of current researches on SMES applications to power systems and to suggest future studies.

II. Applications of SMES

Modern power systems rely strongly on stabilizing devices to maintain reliable and stable operation. These devices should provide adequate damping in the system, during the transient period following a system disturbance, such as line switching, load changes and fault clearance. To prevent collapse of the system due to loss of synchronism or voltage instability, countermeasures such as power system stabilizers,

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optimal turbine governor control systems and phase shifters have been used.

SMES systems convert the ac current from a utility system into the dc current flowing in the superconducting coil and store the energy in the form of magnetic field. The stored energy can be released to the ac system when necessary. The aforementioned excellent performances of SMES offer very desirable benefits to power system applications. The application of the SMES to a power system was first proposed in 1969 [7]. This idea is to charge the superconducting magnet with the surplus generation of the basic load units during off-peak time, and discharge to the ac power system during peak time. The first superconducting power-grid application to achieve full commercial status is SMES in 1981, which is American Superconductor's SMES system for power quality and grid stability and was located along the 500 kV Pacific Intertie that interconnects California and the Northwest [24]. This application of SMES demonstrated the feasibility of SMES to improve transmission capacity by damping inter-area modal oscillations. Since that time many studies have been performed and prototypes were developed for installing SMES.

Up to now, reported applications of SMES can be classified into two kinds, which are power system applications and pulse power application [13]. In [7] (Hsu and Lee, 1992), a survey of the technology of SMES was made. The authors of [7] also proposed some power system applications of SMES. Luongo (1996) reviewed a history of SMES development in the U. S. and summarized ongoing SMES developments in U. S., Europe, and Japan. Furthermore, that paper gave the cost estimation of SMES systems and discussed markets of SMES [18]. Later, Karasik, et al (1999) gave a review of technical and cost consideration for SMES applications to power utility [16]. The Buckles and Hassenzal's studies (2000) overviewed historical perspective and technology status of SMES in the whole world, and described practical applications of SMES systems to power systems. SMES systems developed and being developed in some countries also were listed [3]. Torre and Eckroad (2001) summarized the studies results of SMES to improve transmission system performance [24]. The interest of this paper is also concerned on power system applications of SMES. A number of reported studies explored and investigated feasible applications of SMES to power systems. These applications include basically two aspects. One of which is the enhanced system stability and the other is the power quality improvement.

III. Applications of SMES to Power Systems

A. Enhanced Power System Stability

1) Damping system oscillations

Power system stability limitations are often characterized by low frequency oscillations (0.5—1 Hz) following a major system disturbance. Power transfers are often limited to prevent growing oscillations from occurring, following the loss of a single major transmission line or generator. When limited by long term stability the transmission capacity can be increased by providing active damping of these oscillations. SMES can actively damp these system oscillations through modulation of both real and reactive power. Because SMES can modulate real power, as well as reactive power, it can be much more effective, and smaller in size, than other technologies. Fig. 2 illustrates the schematic diagram of the typical power transmission system with a SMES unit for damping system oscillations.

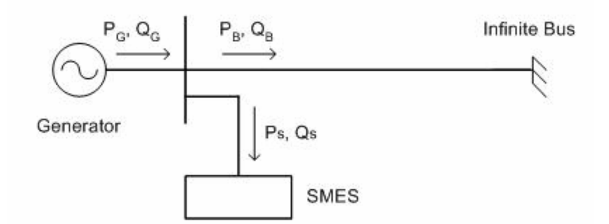

Fig. 2. Schematic diagram of an SMES unit for damping system oscillations

Ise, et al (1987) performed active and reactive power control in the model power transmission system successfully, and verified the effect of power system stabilizing control by SMES. Furthermore, they developed the active filter to compensate for the harmonics generated by the PCS of SMES [11]. Jiang and Conlon (1996) tested an optimized PWM type SMES unit for the power system stabilization, in real time. They demonstrated successfully the real and reactive power compensation by SMES [12]. The Rabbani, et al's studies (1998) presented a fuzzy control strategy for the SMES unit to damp any kind of disturbance in power system. The proposed scheme made effective use of both active and reactive power modulation of the SMES unit [20]. Kamolyabutra, et al (1999) presented a control scheme for the power system stabilization, considering the combination of a SMES and high speed phase shifter to be a unified power system controller. Their experiment demonstrated that the proposed apparatus with the proposed control scheme is significantly effective for the stabilization of a long distance bulk power transmission system even through it is located far from the generator [15]. Arsoy, et al (2000) proposed a strategy of the StatCom-SMES combination. Their studies found that the location where the combined StatCom compensator is connected is important for improvement of the overall system dynamic performance. The StatCom-SMES controller can damp the power system oscillations more effectively than a reactive power controller, and therefore stabilize the system faster if the StatCom-SMES controller is located near a generation area rather than a load area [1].

2) Improving voltage stability

Dynamic voltage instability can occur when there is a major loss of generation or heavily loaded transmission line and there is insufficient dynamic reactive power to support voltages. Voltages will degrade slowly over time in the 5 - 15 minute time frame (sometimes faster) and can result in a voltage collapse. SMES is effective in mitigating dynamic voltage instability by supplying real and reactive power simultaneously supplanting loss of generation or a major transmission line. Depending on the energy storage capability and the reactive power rating of the converter, SMES can stabilize the system long enough to allow generators or other reactive power sources to come on line and prevent voltage instability. On the other hand, a transient voltage dip lasting for 10-20 cycles can result when a major disturbance on the power system occurs. SMES is also effective for providing voltage support. The schematic diagram of the power control system with the SMES unit for improving voltage stability is similar to Fig. 2.

B. Power Quality Improvement

1) Spinning reserve

In case a major generating unit or major transmission line is forced out of service a certain amount of generation must be kept unloaded as “spinning reserve”. Most operating guidelines require that this spinning reserve be as much as 7% of the system load or largest single contingency. Since SMES can store a significant amount of energy it is possible to rely on SMES to provide enough “spinning reserve” to meet the requirement until gas turbine generators can be brought on-line. Providing “spinning reserve” with SMES is much more efficient since it is a virtually lossless form of storage, whereas providing spinning reserve with generation has significant losses and high operating costs [24].

2) Improving FACTS performances

SMES systems can be configured to provide energy storage for FACTS (Flexible AC Transmission System) devices. FACTS inverters and PCS of SMES systems are configured in very similar ways. FACTS devices, however, operate with the energy available in the electric grid. SMES can improve FACTS performance by providing greater real power in addition to reactive power control enhancing system reliability and availability. A static synchronous compensator (StatCom) can only absorb/inject reactive power, and consequently is limited in the degree of freedom and sustained action in which it can help the power grid. The addition of energy from SMES allows the StatCom to inject and/or absorb active and reactive power simultaneously, and therefore provides additional benefits and improvements in the system.

The Ribeiro, et al’s paper (2000) discussed the power quality benefits for transmission systems by integrating FACTS controller with SMES. A SMES coil is incorporated into a voltage source inverter based on StatCom in damping dynamic oscillations in power systems. Their studies showed that, depending on the location of the StatCom-SMES, simultaneous control of real and reactive power can improve system stability and power quality of a transmission grid. Furthermore, the StatCom-SMES connected to a bus near the generator (such as the location of Bus A shown in Fig. 3) shows very effective results in damping electromechanical transient oscillations caused by a three-phase fault [21].

3) Compensation of fluctuating loads

SMES is a promising device for compensation of fluctuating active and reactive power from various loads such as industrial manufacturing plants, nuclear fusion power plants, and substations of high speed railway system. Fig. 4 depicts a typical power control system located close to the customer end.

Tay and Conlon (1998) proposed two control strategies of the SMES system to suppress voltage fluctuation caused by disturbing loads. One of which, named as the direct strategy, is based on equal and opposite compensation of the active and reactive power components of the fluctuating load. The other, named as the optimized strategy, maximizes the usage of the limited capacity of the SMES device [22]. In Funabiki, et al’s studies (1998), the simulation and experiment demonstrated that an SMES system installed close to the power consumer end can be used to level load power fluctuations by using the fuzzy control strategy. The active power on the source side is well leveled while the reactive power on the source side is compensated to almost 0 var [6]. Chu, et al (2001) investigated the performance of SMES systems as fluctuating load compensator and developed the control algorithm for load fluctuating leveling. Furthermore, these were tested successfully through the simulation and experiment [5]. Ise (2001) proposed a SMES system for compensation of power required to control unstable plasma in International Thermonuclear Experimental Reactor system [8]. Next, Ise, et al (2003) proposed a power supply using

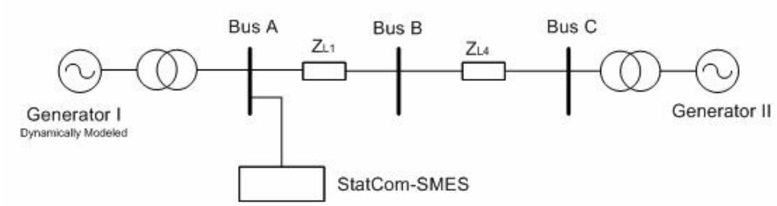

Fig. 3. Schematic improving FACTS performances using SMES

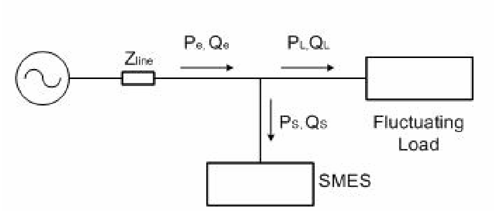

Fig. 4. Schematic diagram to compensate for fluctuating load

SMES to compensate for fluctuating power from high intensity synchrotron. It can absorb the fluctuation of active and reactive power caused by charging and discharging the synchrotron magnet [9].

Without this power compensating system, power fluctuations will exist in the source line. With this system, however, the fluctuating component of the active power P_e on the source side can be compensated by releasing or absorbing energy from the SMES, and the fluctuating component of the reactive power Q_e on the source side can be compensated, too.

4) Reducing area control error

When power is scheduled between utility control areas it is important that the actual net power matches closely with the scheduled power. Unfortunately when generators are ramped up in one control area and down in the receiving control area to send power, the system load can change causing an error in the actual power delivered. This area control error (ACE) can result in inefficient use of generation. SMES can be designed with appropriate controls to inject power to virtually eliminate this error and insure that generation is efficiently used and power schedules are met.

Tripathy and Juengst (1997) studied a small-capacity SMES system to supply sudden power requirements of real power load. The ACE is used to control the SMES, when both load and SMES are connected in parallel at the generator terminal [25].

It is assumed that the PCS of the SMES consists of the chopper voltage source converter (CVSC). The change in the ACE is sensed and used to control the SMES voltage by altering the duty cycle of the chopper. During sudden loading of the system, the generator cannot pick up the load due to its inertia so that the ACE will be negative, and the SMES will discharge.

5) Load leveling

The highest cost energy is produced at peak load conditions. Load leveling is performed by storing energy during off-peak periods and returning energy and capacity on peak. This benefit is realized when SMES gains credit for both converting low-cost energy into higher value energy and its ability to defer the acquisition of high-cost generating resources. SMES can have a large net present worth when it can replace the need to acquire combustion turbine units of similar capacity. The idea of SMES for load leveling of a power system was first proposed by Ferrier (1969) [7].

6) Protection of critical loads

SMES can provide ride through capability and smooth out disturbances on power systems that would otherwise interrupt sensitive customer loads. When momentary disturbances such as transmission line flashovers or lightning strikes occur, power can be lost if the transmission line trips, or voltages can dip low. SMES has very fast response can inject real power in less than one power cycle preventing important customers from losing power. Hence, SMES systems can provide area protections.

Lamoree, et al (1994) developed a successful commercial application of Micro-SMES technology to improve power quality for critical loads. The most important characteristic of the developed Micro-SMES system is its ability to completely supply any load connected to it during a short system disturbance such as a voltage sag caused by a remote fault, a momentary interruption caused by lighting or a tree climb, or any supply discontinuity during a load transfer between two available power sources. In an occurrence of such a disturbance, the Micro-SMES will operate by isolating the load from the power system supplying the load from the energy stored in it [17]. Kalafala, et al (1996) proposed a SMES system to protect critical industrial and military loads against voltage sags and interruptions, as well as to provide continuous power conditioning [14]. Parizh, et al (1997) investigated SMES systems for 15 kV substation applications. Their studies indicated that a SMES system with the ride through capacity of 1 second may be used for protection of all critical loads connected to 15 kV class utility bus and a SMES system with a ride through capacity of at least 2 seconds is suitable for protection of distributed critical loads connected to the customer's 15 kV load bus [19]. Protection of distributed critical loads by using SMES was also proposed in Aware and Sutanto's study (2004). In the same time, they also suggested the two-stage dc bus voltage operation by using the hysteresis control to regulate the SMES discharge to extend the support time to critical loads during a short-term disturbance in the distribution network

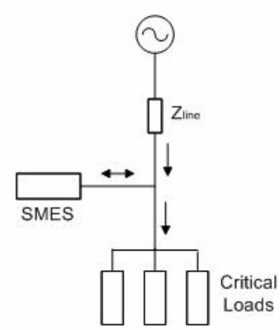

Fig. 5. SMES system for protection of distributed critical loads

[2]. Fig. 5 illustrates the SMES configuration for protection of distributed critical loads.

7) Backup power supply

The energy storage capacity of SMES can be used as a back up power supply for large industrial customers in case of loss of the utility main power supply. SMES systems can be sized with the appropriate energy storage and capacity to provide back up through most disturbances and be cost effective.

Chu, et al (2001) investigated the performances of SMES systems as a UPS. They developed the control algorithm for the UPS application. These have been successfully tested through both the simulation and experiment [5].

8) Improving power system symmetry

In the operation of power systems, voltage asymmetry is very common because asymmetrical fault, single-phase load, unequal capacitor between line and ground, asymmetrical loads, and incomplete transposition of transmission line are unavoidable. Asymmetrical voltages will increase the loss of transformer and transmission line, decrease the output power of transformer, reduce the efficiency of motors, affect the operation of critical load, and even endanger the safety of equipments. SMES systems can be used to compensate for asymmetrical loads and voltages. Fig. 6 shows a typical configuration of the compensation system with the SMES system. The harmonic current produced by the non-linear load and unbalanced current, which is negative sequence current, produced by the single phase load, are compensated by I_S from the SMES unit. The harmonic voltage and unbalanced voltage, which is negative sequence voltage

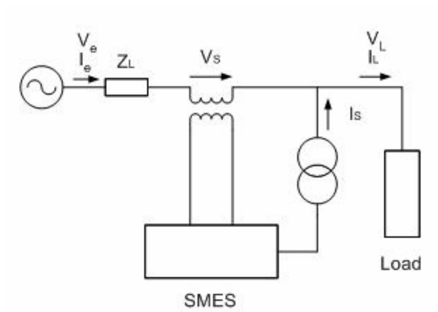

Fig. 6. Configuration of an asymmetrical compensation system with SMES

contained in source voltage, are compensated by V_S from the SMES unit.

Ise, et al (1999) investigated the compensation of harmonics and negative sequence components in line current and voltage by the SMES system. The SMES system provides sinusoidal and balanced voltage and eliminates current harmonics and unbalanced in three phase lines of the distribution system [10]. Casadei, et al (1999) analyzed the behaviour of the SMES system under unbalance supply voltages and unbalanced loads and developed two control strategies. One of which is based on keeping the source current vector in phase with the positive sequence component of the supply voltages. It determines sinusoidal and balanced source currents. The other is based on keeping the source current vector in phase with the source voltage vector, and with a magnitude proportional to that of the source voltage vector. This strategy determines sinusoidal source currents with the same unbalanced of the source voltages [4]. In Tay and Conlon's study (2000), independent control of the active and reactive power flows and independent control of the positive and negative sequence current flows for SMES were achieved. Thus, the SMES system can be used to compensate for unbalanced loads [23]. Yu, et al's paper (2002) proposed a control method of the SMES system under asymmetrical voltage, which is named as the zero negative sequence current control method and used to reduce the relative error of average value of active power supplied by SMES and to limit the relative error of 2^{nd} harmonic component of active power supplied by SMES effectively [26].

Overall, it can be seen from the above overview that the SMES systems have found a number of power system applications. These applications are demonstrated not only by simulations fully but also by experiments partially. Fig. 7

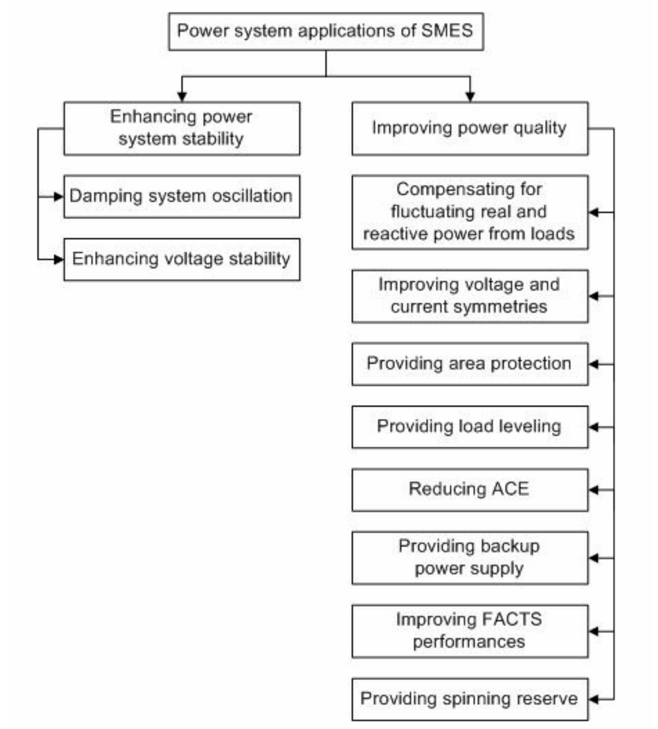

Fig. 7. Classification of SMES applications to power systems

provides a fast view of SMES applications to power systems.

IV. Discussions and Suggestions

SMES is the only technology based on superconductivity that is applicable to the electric utilities and is commercially available today. However, because of large cost and large invest of SMES systems, most of reported studies are implemented through computer simulations or in laboratories. There are only few practical application cases. Therefore, with advancements in technology and reductions in cost of superconductivities and power components, it is suggested that more efforts should be launched into practical applications of SMES to power systems.

Generally, small ratings of SMES systems are applied to compensate for fluctuating loads, to provide protections of critical loads, to provide backup power supply, to compensate for asymmetries of currents and voltages from loads, and to improve FACTS performances. Whereas, large ratings of SMES systems are used to damp system oscillations, to enhance voltage stability, to reduce ACE, to provide load leveling, and to provide spinning reserve.

Based on the current technology, SMES systems are small ratings of ones. Hence, it is suggested to develop efficient control strategies that are used to reasonably arrange small ratings of SMES systems at various locations or to optimize allocations of these small ratings of SMES systems, to enhance whole power system stability and to improve power quality of whole system.

In addition, large ratings and low harmonics of the PCS should be developed through changing circuit topologies and control methods of the PCS for large ratings of SMES systems, in the further studies.

It is also suggested to develop SMES systems with many purposes to power systems, through the integration of various control strategies and the optimization of PCS configurations. This will enhance ratio of performances versus cost for SMES systems, consequently, accelerate practical applications of SMES to power systems.

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