An Overview of SMES Applications in Power and Energy Systems

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***Abstract*— Superconducting magnetic energy storage (SMES) is known to be a very good energy storage device. This article provides an overview and potential applications of the SMES technology in electrical power and energy systems. SMES is categorized into three main groups depending on its power conditioning system (PCS), namely, the thyristor-based SMES, voltage source converter (VCS) based SMES, and current source converter (CSC) based SMES. An extensive bibliography is presented on the applications of these three types of SMES. Also, a comparison is made among these three types of SMES. This study provides a basic guideline to investigate further technological development and new applications of SMES, and thus benefits the readers, researchers, engineers, and academicians who deal with the research works in the area of SMES.**

***Index Terms*-- current source converter (CSC), electrical power and energy systems, superconducting magnetic energy storage (SMES), thyristor, voltage source converter (VSC).**

I. Introduction

A variety of storage technologies are in the market but the most viable are battery energy storage systems (BESS), pumped storage hydroelectric systems, and superconducting magnetic energy storage (SMES) system. Some of the disadvantages of BESS include limited life cycle, voltage & current limitations and potential environmental hazards. Again, some of the disadvantages of pumped hydro electric are large unit sizes, topographic and environmental limitations. SMES is a large superconducting coil capable of storing electric energy in the magnetic field generated by DC current flowing through it [1]. The real power as well as the reactive power can be absorbed by or released from the SMES coil according to system power requirements. Although superconductivity was discovered in 1911, SMES has been under study for electric utility energy storage application since the early 1970s [2]. SMES systems have attracted the attention of both electric utilities and the military due to their fast response and high efficiency (a charge–discharge efficiency over 95%). Possible applications include load leveling, dynamic stability, transient stability, voltage stability, frequency regulation, transmission capability enhancement, power quality improvement, automatic generation control, uninterruptible power supplies, etc.. The one major advantage of the SMES coil is that it can discharge large amounts of power for a small period of time. Also, unlimited number of charging and discharging cycles can be carried out [3-8].

In SMES systems, it is the power conditioning system (PCS) that handles the power transfer between the superconducting coil and the ac system. According to topology configuration, there are three kinds of PCSs for SMES, namely, the thyristor based PCS [9-18], voltage source converter (VSC) based PCS [19-28], and current source converter (CSC) based PCS [29-38]. The thyristor based SMES can control mainly the active power, and has a little ability to control the reactive power, also the controls of active and reactive powers are not independent [39-42]. On the other hand, both the VSC and CSC based SMES can control both active and reactive powers independently and simultaneously. Therefore, the applications in which mainly the active power control is required, the thyristor based SMES is used [43-52], while the applications in which reactive power or both active and reactive powers controls are required, the VSC [53-62] or CSC based SMES [63-70] is used.

This paper attempts to present an overview and a bibliography on the SMES technology. A comprehensive set of references mainly published in archival journals and international conferences starting from the early 1970's to till now on the above-mentioned three types of SMES applications are presented. To the best of our knowledge, it is the most up-to-date information on the bibliography of the SMES applications in power and energy systems. The potential applications and cost-effectiveness of SMES are discussed in this context. Moreover, a comparison is made among these three types of SMES. It is hoped this study would serve as a basic guideline to investigate further technological development and new applications of SMES, and thus benefits the readers, researchers, engineers, and academicians who deal with the research works in the area of SMES.

The organization of this paper is as follows: Section II describes the overview of SMES technology. Section III describes the applications of SMES in power and energy

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systems. In Section IV, the cost-effectiveness of SMES is discussed. Section V provides some conclusions regarding this work.

II. Overview of SMES Technology and Controls

An SMES device is a DC current device that stores energy in the magnetic field. The DC current flowing through a superconducting wire in a large magnet creates the magnetic field. Since energy is stored as circulating current, energy can be drawn from an SMES unit with almost instantaneous response with energy stored or delivered over periods ranging from a fraction of a second to several hours.

An SMES unit consists of a large superconducting coil at the cryogenic temperature. This temperature is maintained by a cryostat or dewar that contains helium or nitrogen liquid vessels. A bypass switch is used to reduce energy losses when the coil is on standby. And it also serves other purposes such as bypassing DC coil current if utility tie is lost, removing converter from service, or protecting the coil if cooling is lost [71].

Several factors are taken into account in the design of the coil to achieve the best possible performance of an SMES system at the least cost [5]. These factors may include coil configuration, energy capability, structure, and operating temperature. A compromise is made between each factor considering the parameters of energy/mass ratio, Lorentz forces, stray magnetic field, and minimizing the losses for a reliable, stable, and economic SMES system. The coil can be configured as a solenoid or a toroid. The solenoid type [56]) has been used widely due to its simplicity and cost effectiveness. 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 an SMES coil. The ratings of these parameters depend on the application type of SMES. The operating temperature used for a superconducting device is a compromise between cost and the operational requirements. Low temperature superconductor devices (LTS) are available now, while high temperature superconductor devices are currently in the development stage.

Different types of SMES technologies and their control methodologies are described below.

A. Thyristor Based SMES

Fig. 1 shows the basic configuration of a thyristor based SMES unit, which consists of a Wye-Delta transformer, an AC/DC thyristor controlled bridge converter, and a superconducting coil or inductor.

The converter impresses positive or negative voltage on the superconducting coil. Charge and discharge are easily controlled by simply changing the delay angle α that controls the sequential firing of the thyristors [72-81]. If α is less than 90°, the converter operates in the rectifier mode (charging). If α is greater than 90°, the converter operates in the inverter mode (discharging). As a result, power can be absorbed from or released to the power system according to requirement. At the steady state, SMES should not consume any real or reactive power [82-91].

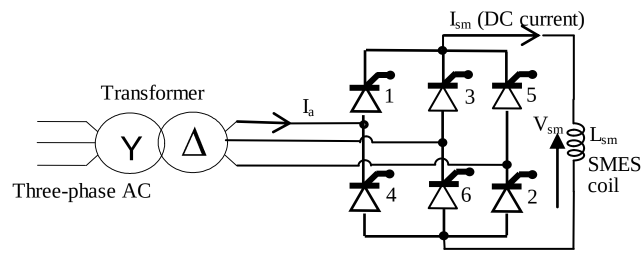

Fig. 1. SMES unit with 6-pulse bridge AC/DC thyristor controlled converter.

The voltage V_{sm} of the DC side of the converter is expressed by

$$V_{sm} = V_{sm0} \cos\alpha \tag{1}$$

where V_{sm0} is the ideal no-load maximum DC voltage of the bridge. The current and voltage of superconducting inductor are related as

$$I_{sm} = \frac{1}{L_{sm}} \int_{t_0}^{t} V_{sm} d\tau + I_{sm0} \tag{2}$$

where I_{sm0} is the initial current of the inductor. The real power P_{sm} absorbed or delivered by the SMES can be given by

$$P_{sm} = V_{sm} I_{sm} \tag{3}$$

Since the bridge current I_{sm} is not reversible, the bridge output power P_{sm} is uniquely a function of α, which can be positive or negative depending on V_{sm}. If V_{sm} is positive, power is transferred from the power system to the SMES unit. While if V_{sm} is negative, power is released from the SMES unit [92-101]. The energy stored in the superconducting inductor is

$$W_{sm} = W_{sm0} + \int_{t_0}^{t} P_{sm} d\tau \tag{4}$$

where $W_{sm0} = \frac{1}{2} L_{sm} I^2_{sm0}$ is the initial energy in the inductor.

B. VSC Based SMES

Fig. 2 shows the basic configuration of the VSC based SMES unit [102-111], which consists of a Wye-Delta transformer, a 6-pulse PWM rectifier/inverter using IGBT, a two quadrant DC-DC chopper using IGBT, and a superconducting coil or inductor. The PWM converter and the DC-DC chopper are linked by a dc link capacitor.

The PWM VSC provides a power electronic interface between AC power system and superconducting coil. The control system of the VSC is shown in Fig. 3. The PI controllers determine the reference d- and q-axis currents by using the difference between the DC link voltage E_{DC} and reference value $E_{DC\text{-}ref}$, and the difference between terminal voltage V_G and reference value $V_{G\text{-}ref}$, respectively. The reference signal for VSC is determined by converting d- and q-axis voltages which are determined by the difference between reference d-q axes currents and their detected values. The PWM signal is generated for IGBT switching by comparing the reference signal which is converted to 3-phase sinusoidal wave with the triangular carrier signal. The DC voltage across the capacitor is kept constant throughout by the 6-pulse PWM converter [112-121].

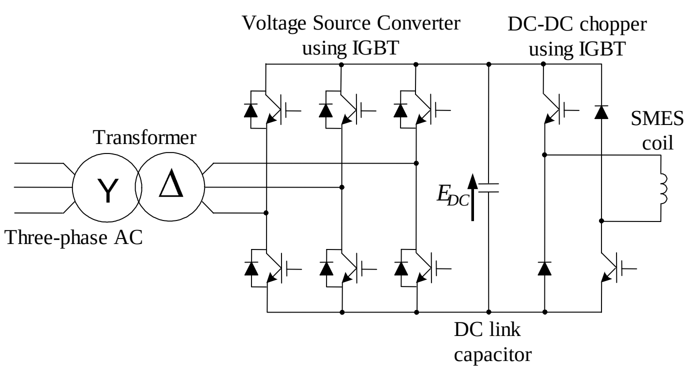

Fig. 2. Basic configuration of VSC based SMES system.

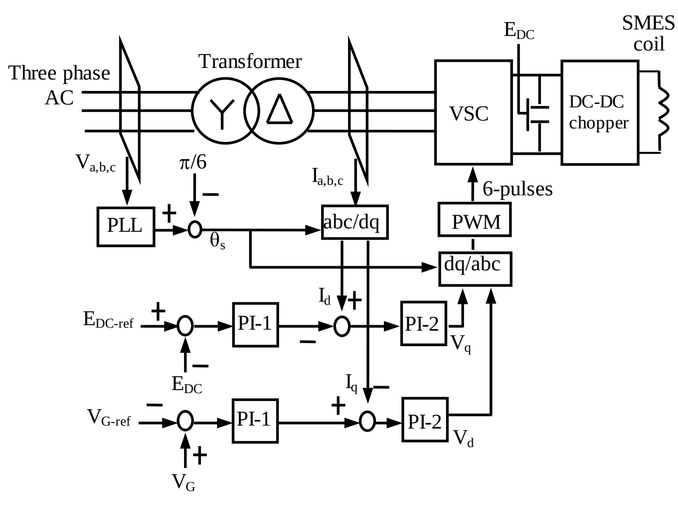

Fig. 3. Control system of the VSC.

The superconducting coil is charged or discharged by a two quadrant DC-DC chopper. The DC-DC chopper is controlled to supply positive (IGBT is turned on) or negative (IGBT is turned off) voltage V_{sm} to SMES coil and then the stored energy can be charged or discharged. Therefore, the superconducting coil is charged or discharged by adjusting the average voltage, $V_{sm\text{-}av}$, across the coil which is determined by the duty cycle of the two quadrant DC-DC chopper. When the duty cycle is larger than 0.5 or less than 0.5, the stored energy of the coil is either charging or discharging. In order to generate the PWM gate signals for the IGBT of the chopper, the reference signal is compared with the triangular signal [122].

C. CSC Based SMES

Fig. 4 shows the basic configuration of the CSC based SMES unit. The dc side of CSC is directly connected with the superconducting coil, and its ac side is connected to the power line. A bank of capacitors connected to a CSC input terminal is utilized to buffer the energy stored in line inductances in the process of commutating direction of ac line current. Furthermore, the capacitors can filter the high-order harmonics of the ac line current. In CSC, through regulating the trigger signals of the switching devices, the current in the superconducting coil can be modulated to generate controllable three-phase pulse width modulation (PWM) current at the ac side. As the SMES system is inherently a current system, the transfer of both active and reactive powers between the CSC and power network is very fast [36].

In case of 12-pulse CSC based SMES, to improve the Total Harmonics Distortion (THD) of the AC source currents, an optimal PWM switching strategy is used to minimize the 5th, 7th, 11th, and 13th harmonics. It has been proved that the 5th, 7th, 11th and 13th harmonics can be minimized to zero with the modulation index M ranging from 0.2 to 1 [37]. Compared to a 6-pulse CSC, the 12-pulse CSC has smaller voltage ripples on the DC side, which means a further reduction of the AC losses in the SMES coil.

For the magnet training, a DC current (I_d) control algorithm is applied [37]. The block diagram is shown in Fig. 5, where I_{dref} is the reference value of I_d, PI is a proportional-integral regulator, L is the inductance of the SMES coil, R_d is the resistance in the DC circuit, and V_d is the DC voltage. With the phase angle *a* being fixed to zero, the DC voltage is proportional to the modulation index M, which determines the charging rate.

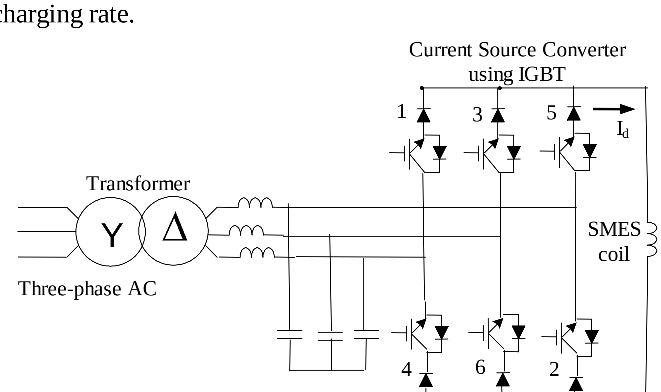

Fig. 4. SMES sy[illegible] CSC.

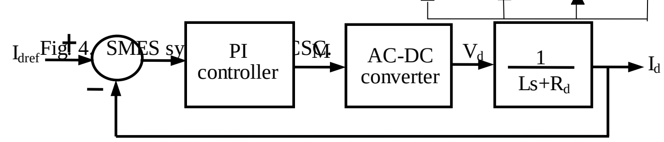

Fig. 5. Block diagram of the DC current control algorithm.

D. Comparison of Thyristor Based, VSC Based, and CSC Based SMES

Table I shows a comparison of the thyristor-based, VSC-based, and CSC-based SMES. The comparison is done in terms of real and reactive powers control ability, control structure, total harmonic distortion (THD), and SMES coil voltage ripple.

TABLE I
COMPARISON OF SMES TECHNOLOGIES

Criteria	SMES topologies		
	Thyristor based SMES	**VSC based SMES**	**CSC based SMES**
Real and reactive powers control ability	The thyristor based SMES exhibits a lagging power factor to the power system network at all times, and significant low order harmonics caused by the thyristor firing pattern. Thus, the thyristor based SMES can control mainly the active power, and has a little ability to control the reactive power, also the controls of active and reactive powers are not independent.	The VSC based SMES allows an independent control of the real and reactive power flowing between the superconducting coil and the power system network. Also, VSC based SMES can provide continuous rated capacity VAR support even at low or no coil current.	The CSC based SMES allows an independent control of the real and reactive power flowing between the superconducting coil and the power system network. However, the CSC topology is able to supply a high level of capacitive reactive power. Also, CSC based SMES is dependent of coil in providing VAR support.
Control structure	Having only one AC/DC module, the thyristor based SMES is easier to control.	The VSC based SMES includes not only an AC/DC circuit but also a DC/DC chopper, thus the control is complicated compared to both the thyristor based SMES and CSC based SMES.	Having only one AC/DC module, the CSC based SMES is easier to control. Also, in the application of high power, the CSC has an additional advantage, that is, being easily paralleled of multiple bridges.
Total harmonic distortion (THD)	The total harmonic distortion is much higher than that of both the VSC and CSC topologies.	A low total harmonic distortion can be obtained in VSC topology.	A low total harmonic distortion can be obtained in CSC topology.
Coil voltage ripple	There appears ripple in the coil voltage when using the thyristor based SMES topology.	There appears ripple in the coil voltage when using the VSC based SMES topology.	The superconducting coil voltage ripple is much smaller when using the CSC based topology, especially the twelve-pulse one. This implies a reduction in the superconducting coil ac losses.

III. APPLICATIONS OF SMES IN POWER AND ENERGY SYSTEMS

It is the fast response that makes SMES able to provide benefit to a lot of potential utility applications. The applications of SMES are described in the following.

1) **Energy storage -** An SMES unit could provide the potential for energy storage of up to 5000 MWh with a high return efficiency (up to 95% for a large unit) and a rapid response time for dynamic change of energy flow (milliseconds) [123-131]. This aspect makes it ideal for large variations in energy requirements between daytime peak demand and off-peak back-down as well as large amounts of energy available for replacement of major unit trips. This may provide for the potential reduction of spinning reserve requirements.

2) **Load following** - An SMES unit has the ability to follow system load changes almost instantaneously which provides for conventional generating units to operate at constant output [123], [126].

2) **System stability -** An SMES unit has the capability to dampen out low frequency power oscillations and to stabilize system frequency as a result of system transients [42], [74], [96], [120], [123-124].

4) **Automatic Generation Control -** An SMES unit can be the controlling function in an AGC system to provide for a minimum of area control error [123].

5) **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". A SMES unit can represent a tremendous amount of spinning reserve capacity when in the charged mode. This lowers the costs for spinning reserve requirements over comparable values and methods of maintaining spinning reserve [123-124], [126].

6) **VAR control and power factor correction -** An SMES unit can increase the stability and power carrying capacity of a transmission system [123].

7) **Black start capability -** An SMES unit can provide power to start a generating unit without power from the grid. This provides for grid restoration when area failures have occurred [123].

8) **Bulk energy management -** An SMES unit has the ability to store large quantities of energy, and thus can act as a storage and transfer point for bulk quantities of energy based on the economics, potentially lowering the cost of electricity [123].

9) **Transient voltage dip improvement** - A transient voltage dip lasting for 10-20 cycles can result when a major disturbance on the power system occurs. SMES and associated converter equipment has been shown to be effective for providing voltage support which can result in increasing the power transfer limitations on the transmission system [127].

10) **Dynamic 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. SMES has been shown to be effective in mitigating dynamic voltage instability by supplying real and reactive power simultaneously supplanting loss of generation or a major transmission line [126-127].

11) **Tie line control -** 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 [127].

12) **Underfrequency load shedding reduction -** When the power system suffers the loss of a major resource such as a generating plant or major importing transmission lines the system frequency will drop and continue to decline until the generating resource – load balance is restored. Because SMES can inject real power rapidly into the system it is an effective method to offset, or reduce, underfrequency load shedding because it reduces the mismatch between load and supply capability of the system disturbance [127].

13) **Circuit breaker reclosing -** Following clearance of a fault, circuit breakers attempt to reclose and return the affected transmission line to service. This is accomplished routinely whenever the power angle difference across the circuit breaker is within acceptable limits. However, protective relays prevent the circuit breaker from reclosing if the angle difference is too large. By briefly supplying some fraction of the power normally transmitted by the transmission line, SMES can reduce the power angle difference across a circuit breaker and allow reclosure of the circuit breaker. This allows restoration of the system power transfers quickly following outages of major transmission lines [127].

14) **Power quality improvement -** 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 [127].

15) **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. Studies have shown SMES can be sized with the appropriate energy storage and capacity to provide back up through most disturbances and be cost effective [126-127].

16) **Sub-synchronous resonance damping -** Generators which are connected to transmission lines which have high levels of series compensation (series capacitors) can be exposed to a phenomenon called Sub-Synchronous Resonance (SSR) which can result in serious damage to the generator. SMES as an active device can be designed to provide mitigation of SSR and allow higher levels of series compensation to be installed [12], [75-76], [78], [111], [127].

17) **Electromagnetic launcher** – An electromagnetic launcher requiring high power pulse sources has been developed as a railgun for military applications. A railgun can launch projectiles at velocities higher than 2000 m/s, surpassing the conventional possibilities. Due to its high power density, SMES is a very interesting energy storage device for an electromagnetic launcher [132].

18) **Wind generator stabilization -** Wind generators have transient stability problems during network disturbances. An SMES unit based on a self-commutated inverter using insulated-gate-bipolar-transistor (IGBT) or gate-turn off (GTO) thyristor is capable of controlling both the active and reactive powers simultaneously. Therefore, it can act as a good tool to stabilize the wind generator system considerably [112], [117].

19) **Minimization of power and voltage fluctuations of wind generator -** Due to random variations of wind speed, output power and voltage of wind generator fluctuate randomly. These fluctuations pose serious problems on the system, for example, lamp flicker and inaccuracy in the timing devices. Since an SMES unit is capable of controlling both the active and reactive powers simultaneously, it can act as a good tool to decrease voltage and power fluctuations of the wind generator system considerably [102], [114], [118], [133].

In addition to direct applications and benefits from the SMES technology, the following are additional secondary benefits that could be derived [123]:

1) **Lower use of oil and gas -** An SMES unit can be charged by the more efficient units in a system, thereby lessening the need for the lower efficiency units to operate during peak periods.

2) **Increased efficiency and reduced maintenance of generating units -** Because an SMES unit can absorb the fluctuations in demand and ramp at extremely rapid rates, generating units can be operated and maintained at their most efficient set points, thereby increasing efficiency, reducing maintenance, and extending operability.

3) **Deferral of new conventional capacity -** An SMES unit has the ability to receive credit that would otherwise go to additional intermediate load and peak load generating units. It may also serve to reduce the calculated avoided cost.

4) **Deferral of new transmission capacity -** An SMES unit, if strategically placed, can defer the need for new transmission to high load centers by loading existing transmission systems during off-peak periods.

5) **Increased availability of generating units -** An SMES unit provides for the back-up of additional generating units which were previously needed only during peak periods, thus increasing the overall capacity of the system.

6) **Environmentally sound -** The clean and efficient storage of electricity by SMES from conventional units operating more efficiently at their set points will displace inefficient fossil-fueled units, conserve premium fuels, and reduce air pollutants. SMES may provide for some emissions credit. SMES has no emissions and its electromagnetic field is confined to an area comparable to generating technologies.

IV. COST-EFFECTIVENESS OF SMES

The cost of an SMES system can be separated into two independent components where one is the cost of the energy storage capacity and the other one is the cost of the power handling capability [129], [134-143]. Storage related cost includes the capital and construction costs of conductor, coil structure components, cryogenic vessel, refrigeration, protection, and control equipment. Power related cost has the capital and construction costs of the power conditioning system. According to [56], the cost of storage system is within the range of $ 85-125K per MJ, while the cost of the power conversion system is in the range of $150 to $250 per kW. The reason for the wide variation in the cost of the power conversion system is its dependence on the configuration of the system. For example, if an SMES is connected to an ac system, a dc-dc chopper and a voltage source converter or a current source converter is needed, but if the SMES is connected to an existing FACTS device with a dc bus, only the dc-dc chopper is required.

However, although it appears that SMES systems are costly [144-152], due to its salient properties such as very fast response, high efficiency, capability of control of real power and reactive power, etc., SMES system is getting increasing interest in the field of power and energy systems. It is hoped that its potential advantages and environmental benefits will make SMES units a viable alternative for energy storage and management devices in the future [84], [123].

Some recommendations on how the cost of SMES might be reduced are as follows.

a)Using high-temperature superconducting coil, the SMES cost might be reduced.

b) Reduction of costs on conductor material and refrigeration system might reduce the SMES energy storage cost.

c)Reducing the cost on the power conditioning unit might also considerably reduce the overall SMES cost.

d) Continued research and development is likely to bring the price down and make the technology appear even more attractive.

V. CONCLUSION

This paper provides an overview and potential applications of the SMES technology in electrical power and energy systems. An extensive bibliography is presented on the applications of thyristor based, VSC based and CSC based SMES. Also, a comparison is made among these three types of SMES. Since the up-to-date SMES references and applications are provided in this article, this would serve as a basic guideline to investigate further technological development and new applications of SMES, and thus benefits the readers, researchers, engineers, and academicians who deal with the research works in the area of SMES.

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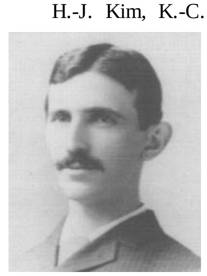

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VI. Biographies

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Roger A. Dougal (SM'94) received his Ph.D. in electrical engineering from Texas Tech. University, Lubbock, in 1983. He is currently the *Thomas Gregory Professor* of Electrical Engineering at the University of South Carolina, where he leads the Power and Energy Systems group. He is a Director of the Electric Ship R&D Consortium, which is developing electric power technologies for the next generation of electric ships, he is co-director of the [illegible]y Cooperative Research Center for Grid-connected Advanced Power Electronic Systems, and he leads development of the Virtual Test Bed --- a computational environment for simulation-based-design and virtual prototyping of dynamic, multidisciplinary systems. His research interests include power electronics, hybrid power sources, and simulation methods.