SMES For Power Utility Applications:
A Review of Technical and Cost Considerations

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Abstract - Advances in both superconducting technologies and the necessary power electronics interface have made SMES a viable technology for high power utility and defense applications. The power industry’s demands for more flexible, reliable and fast active power compensation devices make the ideal opportunity for SMES applications. However, in order to make this technology attractive to the deregulated utility market, it is necessary for industry to provide cost-effective systems. The information presented herein is taken from results to date of a DARPA Technology Reinvestment Program SMES Commercialization Demonstration. This program is currently in the design and risk reduction phase. Completion is expected in 2001. This system will provide +/- 100MW peak and +/- 50MW oscillatory power with 100MJ of stored energy. The base line for the coil design assumes a cable-in-conduit conductor (CICC), with rated voltage of 24 kV, and operating at nominal temperature of 4.5 K.

This paper reviews the possible utility industry applications and discusses a number of technical issues and trade-offs resulting from the design optimization process for SMES utility applications.

The conductor design options, system configuration, current/voltage levels and insulation issues for a low temperature superconducting coil are discussed. The power electronics interfaces (system configuration, circuit topology and devices and switching technologies) are also discussed. Finally, consideration is given to the impact of the new business environment, potential markets and overall cost.

I. INTRODUCTION AND DESIGN CHALLENGES

The characteristics of a SMES system: rapid response (milli-second), high power (multi-MW), high efficiency, and four-quadrant control offer very desirable benefits to the deregulated power utility industry. As the utilization of transmission line assets becomes a substantial contribution to utility income and as significant power transfer variations may occur at short time notice in a deregulated environment, SMES applications will become very attractive. Among the potential performance benefits are improved system reliability, dynamic stability; enhanced power quality, transmission capacity enhancement; and area protection. A SMES device can also have a positive cost and environmental impact by reducing fuel consumption and emissions through reduced line losses and reduced generation availability for frequency stabilization.

FACTS (Flexible AC Transmission Systems) devices which handle both real and reactive power to achieve improved transmission system performance are multi-MW proven electronic devices now being introduced in the utility industry. In this environment, SMES is a logical addition to the expanding family of FACTS devices. SMES as a FACTS device is discussed in detail in the section entitled “Utility Applications.” Short term spinning reserve and other non-transmission related SMES applications such as load following are also possible but limited to only a few locations. Consequently the power and energy ratings in which SMES technology is attractive to the utility industry resides in the range of 50 to 200 MW and 50 to 3000 MJ.

The design of the SMES coil and power conversion system are very much dependent on the application. Although coil refrigeration and thermal insulation at low temperature present design challenges, the cryogenic system comprised of a refrigerator and cryostat-storage vessel is a function primarily of the coil refrigeration requirements and consequently are sized for each application. For this reason, the cryogenic system is not discussed in this paper.

Designing the SMES to operate at the voltages used by utilities can reduce the cost of the power conversion system and related interfaces that tend to dominate the cost of mid-sized SMES systems.

The cumulative effect of good thermal insulation to minimize heat load on refrigerator, mechanical structure to cope with the electromagnetic forces and strong insulation to withstand the high voltage stresses makes the BWXT SMES a valuable demonstration with direct commercialization application. An overall system architecture for utility applications is shown in Figure 1.

II. SMES COIL

In the process of optimizing the design of the SMES coil for a power utility application, BWXT designers have
started with the duty cycle in which the coil exchanges energy with the electric grid. The transmission stability application, which requires the coil to rapidly and cyclically discharge and absorb power, is a major challenge since the operation results in high AC losses. Typical frequencies in which significant amounts of energy are exchanged with the electrical grid are in the range of 0.3 to 3 Hz. In addition, both low frequency pulsed demands and higher frequency duty cycles are required. The high AC losses drive the design towards the CICC approach that minimizes the conductor mass subjected to eddy currents. High stability in the presence of thermal disturbances and the ability to withstand large magnetic forces also favor a CICC approach. See Fig. 2 for an illustration of a CICC configuration approach.

![Figure 1 - Overall System Architecture](image1)

- Less supporting structure, and
- Lower cost

The high external magnetic field of a solenoid can be tolerated if the magnet is located one hundred feet (5 Gauss fringe field) or more from the substation equipment. In an urban setting, where space is at a premium, the more expensive toroid with lower external field may be required. See Figure 3 for an illustration of a solenoid configuration considered.

![Figure 2 SMES CICC](image2)

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The characteristics of cable-in-conduit conductor that seem to satisfy the power utility application are listed below:
-Multi-strands, multi stage cable twisted from composite wires with copper matrix containing superconducting filaments
-Cable enclosed in a stainless steel jacket, which is a basic magnet structural component
-Cooled in closed loop circuit by helium flow originated by helium refrigerator
-Operating current range 4,000-50,000 A
-Operating voltage up to 30kV
-Stored magnetic energy up to 3000 MJ

Two basic coil geometries are possible: solenoid and toroid configurations. The solenoid configuration with low aspect ratio is preferred for rural utility applications because it offers:
- Less conductor amount,

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III. OPERATING VOLTAGE

Superconducting magnets for scientific applications have generally been designed to work with high current and low voltages (<8kV). Typical utility transmission applications demand the use of higher voltages in the range of 13 to 24 kV to minimize cost of power electronics. Although most of the time the SMES coil will be quiescent at negligible voltage, during power exchange with the electrical system, the voltage can momentarily reach its rated voltage value. Also since the higher voltages reduce the current level, the refrigeration costs may go down.

Turn-to-turn and layer-to-layer operating voltages will be low in comparison to those of the coil to ground. Insulation selection in the majority of these areas is dominated by thermal and mechanical considerations.
However, the insulation must address the higher electrical stresses due to the transient voltages near the coil terminations.

During charge and discharge, voltage transients can be applied to the coil terminals, including ripple produced by the chopper and surges from the network passed through the inverter. These higher frequency disturbances could excite coil resonances whose frequencies are determined by the distributed capacitance and inductance of the coil. Harmonic filters, surge capacitors, MOVs or semiconductor over-voltage protection devices are required to protect the coil against surge voltages.

At higher voltage levels, especially where localized heat can build between conductors at liquid helium temperatures, an all-solid insulation is typically used in coils made of CICC. The use of liquid helium as a dielectric is not practical since it is difficult to avoid helium gas bubbles in which the breakdown voltage may be an order of magnitude lower than in liquid. With the exception of the helium lines, the high voltages between the coil, its leads, and the grounded parts of the cryostat could theoretically be provided by vacuum alone. However, this is also not practical due to the likelihood of helium leaks and the possible breakdown in low-pressure vapor.

Solid insulating systems for CICC usually include epoxies that are coupled with fibers to provide mechanical strength and are vacuum-pressure impregnated to minimize voids which lower the onset of partial discharges. These fibers can be oriented to minimize the thermal stresses incurred during cool-down. Plastic films having high dielectric strengths are sometimes used as additional barriers to safeguard against breakdown associated with the cracking of the epoxy.

IV. POWER ELECTRONICS INTERFACE

In SMES, the power electronics converter or conditioner is the interface between the storage source and the utility bus. By adjusting a thyristor’s delay angle, changes of charge and discharge rate can be performed within one half-cycle of a power system frequency. The specification of a power conversion system requires a comprehensive understanding of power semiconductor devices, circuit configurations and topologies, control technologies, and system integration. In general, power conditioners are intended to condition the voltage or power so that power is conveniently and efficiently utilized and deviations from a desirable or acceptable voltage waveform are minimized.

The converter can be either line-commutated or forced-commutated. Although line-commutation presents some benefits (low risk of commutation failure), it has shortcomings which limit the effectiveness of SMES for power stabilization applications. An illustration of a SMES system and associated voltage source GTO-based power conversion system is shown in Fig. 4. In the process of determining the specific power systems performance and requirements, integrated electrical systems analytical software tools such as EMTP, PSSE are extensively used.

In the specification process of a SMES power conversion system for a high power utility application, the designer is confronted with several alternatives regarding system circuit topology, devices and switching technologies. For example, with respect to circuit topology, the reactive power requirements of utility applications tend to give preference to voltage source inverter configurations (instead of a current source). This is particularly true in situations where voltage/frequency stabilization rather than energy balance is the dominant requirement. However, even in cases like spinning reserve applications where a current source inverter can be utilized, utilities may prefer a voltage source interface since the continuous voltage control provided by a voltage source topology may become a major component in the cost-benefit equation.

Figure 4 - SMES Overview

Recent technological advances in semiconductor switching devices have created highly flexible and efficient systems. When four-quadrant independent control is required, the designer can choose fundamentally between GTOs, IGCTs and IGBTs. Because of their higher voltage and current ratings, GTOs have been preferred for high power utility applications. However, recently IGCTs and IGBTs have reached levels comparable to GTOs with the advantages of higher switching frequencies, lower operating losses and lower costs. IGCTs and IGBTs also offer simplified gate drive circuitry, and higher tolerance to fault conditions, which makes it easier to meet power quality requirements and easier to manage thermal problems in a cost-effective system.

Other recent power electronics technologies and techniques such as multi-level topology and soft-switching techniques which can improve the efficiency, response time, power quality, and cost-effectiveness of the power
 conversion system, can be easily implemented with the new class of semiconductor devices. These devices have become accepted for utility operation over the last five years.

Figure 5 illustrates the decision-tree and the ranges of possibilities in terms of system configuration, commutation technology, transition approach, and circuit topology and device type.

V. UTILITY APPLICATIONS

SMES systems can be configured to provide energy storage for Flexible AC Transmission System (FACTS) devices. FACTS inverters and SMES inverters 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. Figure 6 illustrates a case of frequency stabilization provided by a FACTS-SMES device on a typical transmission system. Frequency and voltage are stabilized following a three-phase fault.

Utilities around the US are in the process of redefining their strategy in terms of planning and operating their transmission and distribution systems. Deregulation of the utility industry and environmental restrictions on new transmission line construction have brought this about. Disturbances such as voltage sags, transients, and harmonics, which were always present to some degree, have become increasingly more disruptive to the operation of certain types of loads. Instead of just continuity of service, compatibility between the electric system and sensitive electronic loads is now required. A voltage sag of a few milli-seconds might trip an electronic controller and put out of operation a major industrial load for several hours. Continuity of the electrical supply is maintained, but the load is unable to utilize the power service. This is the new electrical/electronics utility systems environment. Reliability plus the overall quality of the supply, both at transmission and distribution levels, should indeed be an essential component of the adequacy of the transmission / distribution equation.

Although many voltage quality problems can be resolved locally (at the end-user side - including use of small SMES units), it should be of great interest for the utility to solve the problem up-stream and consequently add value to its service by reducing the risk of outage. The basic message is that customers have changed the way they utilize electric power, and utilities have the opportunity to increase their competitiveness (in a free market economy) by providing better electricity with value-added services regarding the total quality of the supply. Integrated SMES devices appear to be a competitive technology for addressing the total supply quality problem.

In this context, FACTS and Custom Power were introduced with the purpose of allowing a more flexible and optimized operation of transmission and distribution systems through the utilization of power electronics devices. By using reliable, high speed power electronic controllers, utilities may increase control of power flow, secure loading of transmission lines to levels near their thermal limits, increase ability to transfer power between areas reducing generation reserve margin, prevent cascading outages by limiting the effects of faults, damping power system oscillations, and increasing the overall reliability and power quality of the system.

![Decision Tree for Power Electronics](image)

However, FACTS and Custom Power devices can only utilize and/or re-direct the power and energy available on the ac system and consequently are limited in the degree of freedom and sustained action in which they can help the power grid. In contrast, the SMES ability to rapidly inject or absorb active or reactive power and still provide other FACTS benefits, increases the effectiveness of the overall control. Thus, functions such as system stability, transmission capacity, and the overall supply quality provided by power electronics devices, including FACTS and Custom Power devices, can be significantly enhanced by the ability of the SMES to sustain the actions associated with active power control.

VI. SYSTEM COSTS

SMES system costs for a transmission application are driven by the operational requirements. The costs of the system can be broken into three main components: SMES Coil (including containment, leads and bus and external supports), Cryogenic System (including Refrigerator and Vacuum Vessel) and Power Conversion System (including voltage source inverter plus chopper, monitoring and
controls). See Figure 7.

![Figure 6 - SMES Frequency Stabilization (Following a Three-Phase Fault)](image)

a) Frequency vs. Time (with and without SMES)
b) SMES Real Power Output vs. Time
c) SMES Reactive Power Output vs. Time

The cost of the SMES coil is primarily determined by the amount of energy to be stored. For the utility applications under consideration, estimates are in the range of $70-100K per MJ. The corresponding cost of a cryostat system is within the range of $15-25K per MJ. The power conversion system is estimated to be 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. That is, if the SMES is connected via a voltage source or current source inverter, or if the SMES is connected to an existing system, for which only a DC-DC chopper is required. The percentage in terms of relative cost of each subsystem with regard to the total cost is therefore dependent on the application. Figure 8 shows the BWXT estimate for a 100MJ / 100MW SMES system designed in conjunction with an existing FACTS device. The numbers include the cost of the power electronics inverters already installed.

In order to establish a realistic cost estimate for a SMES system, the following steps are suggested: identify the system issue(s) to be addressed; select preliminary SMES system characteristics: define basic energy storage, power, voltage and current requirements; model SMES performance in response to system demands to establish effectiveness of the device; optimize SMES system specification and determine system cost; determine utility financial benefits from SMES operation; compare SMES system's cost and utility financial benefits to determine adequacy of utility's return on investment.

While each system will be tailored to individual utility needs, BWXT targets costs for a basic SMES system on a per kilowatt basis at less than the costs on a per kilowatt basis of the lowest cost generation units. On a per unit active or reactive power basis, SMES costs will be higher than the costs for FACTS devices like SVCs, Statcoms, etc., that do not provide the full range of services that a SMES can provide.

Short-term power sales have recently risen to $7 per kWh. At this cost level, significant investments to increase utilization of transmission assets can be justified. Among the benefits that SMES can bring is an increase in power transfer by reducing thermal margin of transmission lines.

![Figure 8 - Overall System Costs](image)

Besides utility interest, the US Navy is evaluating new, less costly ship concepts. A "more electric ship" taking advantages of the efficiencies and additional improvements of electric drives and SMES for pulse power needs, takes advantages of a similar industrial infrastructure. This will result in lower costs and more rapid integration of the technology.
VII. THE NEW BUSINESS ENVIRONMENT

Deregulation will allow the utility industry to become more competitive as well as to facilitate the relations between utility and customers. By providing customers with the option of power providers and premium service, customers with sensitive equipment will have the chance to buy enhanced power quality at a competitive price.

The new sensitive electronic devices that have become part of our daily life require cleaner waveforms. As a consequence of deregulation, utilities will have an opportunity to offer higher power quality services even to residential customers. The technology to guarantee such quality is available and has not been fully utilized because the regulated structure did not encourage such initiatives. FACTS, Custom Power and Power Quality devices will enable increased utilization of transmission and distribution systems with increased reliability. The deregulated utility environment will rely heavily on existing transmission assets. This increased reliance will result in increased investment in devices that make this asset more productive. A deregulated environment will also allow utilities to provide premium power to customers with sensitive loads, improving the total quality of the electricity service. SMES Technology fits very well within the new environment by enhancing the potential application of FACTS, Custom Power and Power Quality devices.

As deregulation takes place, generation and transmission resources will be utilized at higher efficiency rates leading to tighter and moment-by-moment control of the spare capacities. SMES devices can facilitate this process, allowing the utility maximum utilization of utility resources.

VIII. CONCLUSIONS

This paper has presented a number of technical and cost issues related to the design of SMES devices for power utility applications reflecting the deregulated environment.

The characteristics of SMES technology in terms of transient response and efficiency favors applications such as power quality and dynamic stability. Large diurnal or spinning reserve applications have been found to be less cost-effective.

In the design optimization process for a power utility SMES application, BWXT has faced many technical and cost issues. The team has overcome several conductor and coil technical challenges that will bring about adequate performance at a cost competitive with other technologies.

The power electronics interface has been thoroughly investigated in order to provide an adequate interface at minimum cost. Higher magnet operating voltages will contribute significantly to overall system cost reductions.

When the deregulation process is complete, the industry will require devices with FACTS-SMES performance characteristics. As an example one can cite the recent West Coast blackouts. The lack of swing-damping control was found to be among the causes of two system failures in 1996. SMES devices either alone or in combination with FACTS devices can substantially increase power swing-damping control and consequently minimize the possibility of such events.

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EPRI has been the major motivating force behind the concept of FACTS devices for utility application. Several major multi-MW projects involving different FACTS configurations have been completed in the last five years.

REFERENCES