Transmission Power Quality Benefits Realized by a SMES-FACTS Controller

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Abstract. This paper discusses the power quality benefits for transmission systems by integrating flexible ac transmission system (FACTS) controller with superconducting magnetic energy storage. The paper discusses the incorporation of a Superconducting Magnetic Energy Storage (SMES) coil into a voltage source inverter based static synchronous compensator (STATCOM) in damping dynamic oscillations in power systems. A 100 MJ 96 MW (peak) SMES coil is attached to the voltage source inverter front end of a 160 MVA STATCOM via a dc-dc chopper. The performance of the STATCOM, a self-commutated solid-state voltage converter, can be improved with the addition of energy storage. The real and reactive power responses of the integrated system to system oscillations are studied using an electromagnetic transient program PSCAD/EMTDC, and the findings are presented. The results show that, depending on the location of the STATCOM-SMES combination, simultaneous control of real and reactive power can improve system stability and power quality of a transmission grid.

INTRODUCTION

SMES systems have received considerable attention for power utility applications due to its characteristics such as rapid response (milli-second), high power (multi-MW), high efficiency, and four-quadrant control. Advances in both superconducting technologies and the necessary power electronics interface have made SMES a viable technology that can offer flexible, reliable, and fast acting power compensation. SMES systems can provide improved system reliability, dynamic stability, enhanced power quality and area protection [1-7], as its potential applications are summarized in Fig.1 [7]. The squared area indicates the possible cost effective SMES applications.

A SMES coil requires an ac/dc power conversion unit to be connected to an ac system. This unit could be either a current source inverter (CSI) or a voltage source inverter (VSI) together with a dc-dc chopper.

A STATCOM, however, 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 storage allows the STATCOM to inject and/or absorb active and reactive power simultaneously, and therefore provides additional benefits and improvements in the system. The voltage source inverter front-end of a STATCOM can be easily interconnected with an energy storage source such as a superconducting magnetic energy storage (SMES) coil via a dc-dc chopper.

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.

![Fig. 1. SMES Power and Energy Requirements for Potential Electric Utility Applications](image)

As expected and demonstrated in the past [3], modulation of real power can have a more significant influence on damping power swings than can reactive power alone [11]. Even without much energy storage, static compensators with the ability to control both reactive and real power can enhance the performance of a transmission grid.

This work shows modeling and simulation results of the dynamics of the integration of a ±160 MVAR STATCOM and 100 MJ SMES coil (96 MW peak power and 24 kV dc interface) which has been designed for a utility application. The impact of the combined compensator on dynamic system response and power quality is discussed.

THE NEW POWER QUALITY ENVIRONMENT

Power utilities around the world are in the process of redefining their strategies in terms of planning and operating their transmission and distribution system. Disturbances such as voltage sags, impulsive transients, and harmonics, which
were always present to some degree, have become increasingly more disruptive to the operation of certain types of loads. In addition to 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 a major industrial load 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 service. This is the new electrical/electronics - power context/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.

IMPACT OF DEREGULATION

Increased interest and applications for more advanced power solutions will be engendered by deregulation of the utility industry. Among the results of the deregulation will be greater dependence on existing transmission and distribution assets.

Deregulation will no doubt facilitate and advance utility / customers relations besides providing customers with the option of power providers and that is the provision of higher power quality to customers. The new sensitive electronic equipment which has become part of our daily life requires cleaner waveforms. Utilities will have an opportunity to offer such services even to residential customers. The technology to guarantee such quality is available and has not been fully utilized because the regulated structure does not encourage such initiatives. FACTS, Custom Power and Power Quality devices will enable increased utilization of transmission and distribution systems with increased reliability. A deregulated environment will allow utilities to provide premium power to customers with sensitive loads improving the total quality of the electricity service.

FACTS PLUS SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Short-term energy can be stored in several different ways, and one additional form of energy storage is electromagnetic. If current is built up in a large inductor, the energy storage potential is a function of amperes (squared) and inductance. To avoid losses, the current is circulated in a low temperature superconductor.

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. The basic message is that customers have changed in the way they utilize electric power, and utilities have the opportunity to increase their competitiveness (in a free market economy) by offering/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 power environment, the concept of Flexible AC Transmission Systems (FACTS) and Custom Power were introduced with the purpose to allow a more flexible and optimized operation of transmission and distribution system 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. However, FACTS and Custom Power devices can only utilize and/or re-direct the power/energy available on the ac system and consequently are limited to the degree of freedom and sustained action in which they can help the power grid. In contrast, the SMES ability of rapid active power injection or absorption, and which still provides other FACTS type benefits, definitely increases the effectiveness of the overall control. Thus, functions such as system stability, transmission capacity, and the overall supply quality provided by general 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.

While each system will be tailored to individual utility needs, 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 devices like SVCs, FACTS, etc., that do not provide the full range of services that a SMES provides.

MODELING AND CONTROL DESCRIPTION

A typical ac system equivalent was used in this study to show the dynamic performance of the STATCOM with a SMES coil. The circuitry simulated representing this integration is shown in Fig. 2. The detailed representation of the STATCOM, dc-dc chopper, and SMES coil is depicted in Fig. 3.

The ac system equivalent used in this study corresponds to a two machine system where one machine is dynamically modeled (including generator, exciter and governor) to be able to demonstrate dynamic oscillations. Dynamic oscillations are simulated by creating a three phase fault in the middle of one of the parallel lines at Bus D (Refer to Fig. 2). A bus that connects the STATCOM-SMES to the ac power system is named a STATCOM terminal bus. The location of this bus is selected to be either Bus A or Bus B.

As can be seen from Fig. 3, two-GTO based six-pulse voltage source inverters represent the STATCOM used in this particular study. The voltage source inverters are connected to the ac system through two 80 MVA coupling transformers, and linked to a dc capacitor in the dc side. The value of the dc link capacitor has been selected as 10mF in order to obtain smooth voltage at the STATCOM terminal bus.
As stated in [12, 13], a GTO based inverter connected to a transmission line acts as an alternating voltage source in phase with the line voltage, and, depending on the voltage produced by the inverter, an operation of inductive or capacitive mode can be achieved. It has also been emphasized that a dc link capacitor establishes equilibrium between the instantaneous output and input power of the inverter.

The primary function of the STATCOM is to control reactive power/voltage at the point of connection to the ac system [12-14]. The control inputs are the measured STATCOM injected reactive power ($S_{stat}$) and the three-phase ac voltages ($V_a, V_b$ and $V_c$) and their per unit values measured at the STATCOM terminal bus. The per unit voltage is compared with base per-unit voltage value (1pu). The error is amplified to obtain reference reactive current which is translated to the reference reactive power to be compared with $S_{stat}$. The amplified reactive power error-signal and phase difference signal between measured and fed three phase system voltages are passed through a phase locked loop control. The resultant phase angle is used to create synchronized square waves.

![Fig. 2. AC System Equivalent](image1)

![Fig. 3. Detailed Representation of the STATCOM, dc-dc Chopper, and SMES Coil](image2)

To generate the gating signals for the inverters, line to ground voltages are used for the inverter connected to the Y-Y transformer, whereas line to line voltages are utilized for the inverter connected to the Y-Δ transformer. This model and control scheme is partly based on the example case given in the EMTDC™/PSCAD™ simulation package, though some modifications have been made to meet the system characteristics. These modifications include change in transformer ratings and dc capacitor rating, tuning in control parameters and adding voltage loop control to obtain reference reactive power. It should be noted that the STATCOM control does not make use of signals such as deviation in speed or power to damp oscillations, rather it maintains a desired voltage level at the terminal bus that the STATCOM is connected to.

A SMES coil is connected to a voltage source inverter through a dc-dc chopper. It controls dc current and voltage levels by converting the inverter dc output voltage to the adjustable voltage required across the SMES coil terminal. The purpose of having inter-phase inductors is to allow balanced current sharing for each chopper phase.

A two-level three-phase dc-dc chopper used in the simulation has been modeled and controlled according to [15]. The phase delay was kept 180 degrees to reduce the transient overvoltages. The chopper's GTO gate signals are square waveforms with a controlled duty cycle. The average
voltage of the SMES coil is related to the STATCOM output dc voltage with the following equation [16]:

\[ V_{\text{SMES-dc}} = (1-2d)V_{\text{dc-av}} \]

where \( V_{\text{SMES-dc}} \) is the average voltage across the SMES coil, \( V_{\text{dc-av}} \) is the average STATCOM output dc voltage, and \( d \) is duty cycle of the chopper (GTO conduction time/period of one switching cycle).

This relationship states that there is no energy transferring (standby mode) at a duty cycle of 0.5, where the average SMES coil voltage is equal to zero and the SMES coil current is constant. It is also apparent that the coil enters in charging (absorbing) or discharging (injecting) mode when the duty cycle is larger or less than 0.5, respectively. Adjusting the duty cycle of the GTO firing signals controls the rate of charging/discharging.

The duty cycle is controlled in two ways: Three measurements are used in this chopper-SMES control: SMES coil current; ac real power measured at the STATCOM terminal bus; and dc voltage measured across the dc link capacitor. The SMES coil is initially charged with the first control scheme, and the duty cycle is set to 0.5 after reaching the desired charging level. The second control is basic to a stabilizer control that orders the SMES power according to the changes that may happen in the ac real power. This order is translated into a new duty cycle that controls the voltage across the SMES coil, and therefore the real power is exchanged through the STATCOM.

CASE STUDIES

In order to demonstrate the effectiveness of the STATCOM-SMES combination, several cases are simulated. These cases are given as subsections here. A three-phase fault is created at Bus D of Fig.2 to generate dynamic oscillations in each case. The plot time step is 0.001 sec for all the figures given in these cases.

A two-machine ac system is simulated. The inertia of the machine I was adjusted to obtain approximately 3 Hz oscillations from a three phase fault created at time=3.1 sec and cleared at time=3.25sec. When there is no STATCOM-SMES connected to the ac power system, the system response is depicted in the first column of Fig. 6 in the interval of 3 to 5 sec where first and second rows correspond to the speed of Machine 1 and ac voltage at Bus B, respectively. When a STATCOM-only is connected, the response is given in the second column of Fig.4. Since the STATCOM is used for voltage support, it may not be as effective in damping oscillations.

Now, the 100MVAR-96MW SMES coil is attached to a 160MVAR STATCOM through a dc-dc chopper at Bus B. The SMES coil is charged by making the voltage across its terminal positive until the coil current becomes 3.5kA. Once it reaches this charging level, it is set at the standby mode. In order to see the effectiveness of the STATCOM-SMES combination, the SMES activates right after the three-phase fault is cleared to 3.25sec. The dynamic response of the combined device to ac system oscillation is depicted in the third column of Fig. 6. The first plot shows the machine frequency, the next two gives the real and reactive power injected or absorbed by the STATCOM-SMES device, and the fourth one gives the STATCOM terminal voltage in pu. In these figures, negative real and/or reactive power values represent the injected power from the device to the ac system. When compared to no compensation and STATCOM-only, both frequency and voltage oscillations were damped out faster.

The STATCOM-SMES combination is now connected to the ac power system at a bus near the generator bus. Compared to other two cases, STATCOM-SMES connected to a bus near the generator shows very effective results in damping electromechanical transient oscillations caused by a three-phase fault.

Fig. 4. Dynamic Response to AC System Oscillations
While keeping the compensator location at Bus B, the performance of STATCOM-only at full rating is compared to the performance of STATCOM-SMES at reduced rating. The power rating of the SMES and STATCOM was reduced to half of its original ratings (80MVAR, 50MW peak). The energy level of SMES was kept the same, however the real power capability of SMES was decreased. The SMES coil was charged until it reaches the desired charging current level, which took twice the time since the terminal voltage was lower. A three-phase fault is created at 5.6sec for .15 sec, and the responses of the STATCOM-SMES versus STATCOM-only to the power swings are compared in Fig. 5.

This comparison shows that STATCOM-SMES at the reduced rating can be as effective as a STATCOM at the full rating in damping oscillations. On the other hand, the terminal voltage has not been improved. This requires higher reactive power support, but not as high as the full rating. Adding energy storage therefore can reduce the MVA rating requirements of the STATCOM operating alone.

Low frequency oscillations following disturbances in the ac system can be damped by either reactive power or real power injection/absorption. However, the reactive power injected to the system is dependent on the STATCOM terminal voltage. On the other hand, the SMES is ordered according to the variation of the real power flow in the system. Damping power oscillations with real power is more effective than reactive power since it does not effect the voltage quality of the system. Better damping dynamic performance may be obtained if SMES is connected to the ac system through a series connected voltage source inverter (Static Synchronous Series Compensator) [11] rather than a shunt connected voltage source inverter. However, this is not a justifiable solution since it involves more cost.

**Fig. 5. 160 MVA STATCOM vs. 80 MVA, 50MW STATCOM-SMES**

**SUMMARY AND CONCLUSIONS**

This paper presents the modeling and control of the integration of a STATCOM with SMES, and its dynamic response to system oscillations caused by a three-phase fault. It has been shown that the STATCOM-SMES combination can be very effective in damping power system oscillations as well as keeping its power quality.

Thus, adding energy storage enhances the performance of a STATCOM and improves its power quality. This combination can also possibly reduce the MVA ratings requirements of the STATCOM operating alone. This is important for cost/benefit analysis of flexible ac transmission system controllers on utility systems.

It should be noted that, in this study, the STATCOM provides a real power flow path for SMES, but the SMES controller is independent of the STATCOM Controller. While the STATCOM is ordered to absorb or inject reactive power, the SMES is ordered to absorb/inject real power.

It was also observed that the location where the combined compensator is connected is important for improvement of the overall system dynamic performance. Although the use of a reactive power controller seems more effective in a load area, as stated in [11], this study shows that a STATCOM with real power capability can damp the power system oscillations more effectively, and therefore stabilize the system faster if the STATCOM-SMES controller is also located near a generation area.

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