Superconducting Magnetic Energy Storage (SMES) System

By

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ABSTRACT- Superconducting magnetic energy storage (SMES) is an energy storage technology 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. The overall technology of cryogenics and superconductivity today is such that the components of a SMES device are defined and can be constructed. The integrated unit appears to be feasible for some utility applications at a cost that is competitive with other technologies. SMES is the only technology based on superconductivity that is applicable to the electric utilities and is commercially available today. In addition to today's power quality application, the historical development of SMES starting with the concept of very large plants that would store hundreds of megawatt hours of energy and were intended for diurnal load leveling are described.

This paper presents a detailed model for simulation of a Superconducting Magnetic Energy Storage (SMES) system. SMES technology has the potential to bring real power storage characteristic to the utility transmission and distribution systems. The principle of SMES system operation is reviewed in this paper. To understand transient and dynamic performance of a SMES system, a detailed SMES system benchmark model is given with extensive simulation results. This system is demonstrated using an electromagnetic transient program PSCAD/EMTD

I. INTRODUCTION

A 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. Generally it consists of the superconducting coil, the cryogenic system,and the Power Conversion/Conditioning System (PCS) with control and protection functions

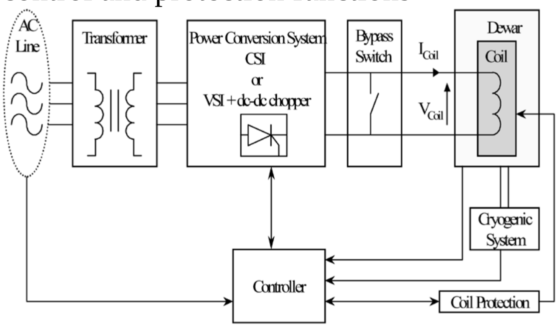

Figure 1 Components of a typical SMES system. CSI: current source inverter. VSI: voltage source inverter.

The total efficiency of a SMES system can be very high since it does not require energy conversion from electrical to mechanical or chemical energy. Depending on the control loop of its power conversion unit and switching characteristics, the SMES system can respond very rapidly (MWs/milliseconds). The ability of injecting/ absorbing real or reactive power can increase the effectiveness of the control, and enhance system reliability and availability. Consequently, SMES has inherently high storage efficiency, about 90% or greater round trip efficiency. Comparing with other storage technologies, the SMES technology has a unique advantage in two types of applications: Power system transmission control and stabilization, and power quality improvement. For instance, SMES can be configured to provide energy storage for FACTS controllers at the transmission level, or custom power devices at the distribution level.

The efficiency and fast response capability of a SMES can be further exploited in different applications in all levels of electric power systems.

In order to achieve the best system configuration possible, the design of the SMES system needs to take into account many factors. The performance evaluation of a SMES system also requires extensive knowledge about the SMES and the associated power systems. Computer aided simulation is one of the cost effective ways to carry out. This paper intends to provide a detailed model of the SMES system for the SMES related power system computer simulation. The benchmark system will provide the basis for the comparison of the different simulation tools, control strategies and algorithms related to SMES systems. The proposed SMES system will utilize parameters from BWX Technologies, Inc. for the SMES coil modelling

II. SMES SYSTEM OVERVIEW

As can be seen from Fig. 1, a SMES system consists of several sub-systems. A large superconducting coil is the heart of a SMES system, which is contained in a cryostat or dewar consisting of a vacuum vessel and a liquid vessel that cools the coil. A cryogenic system is also used to keep the temperature well below the critical temperature of the superconductor. An ac/dc PCS is used for two purposes: One is to convert electrical energy from dc to ac, and the other is to charge and discharge the coil. Finally, a transformer provides the connection to the power system and reduces the operating voltage to acceptable levels for the PCS.

For a SMES system, the inductively stored energy (E in Joule) and the rated power (P in Watt) are commonly the given specifications for SMES devices, and can be expressed as follows:

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$$E = \frac{1}{2}LI^2 \quad P = \frac{dE}{dt} = LI\frac{dI}{dt} = VI \qquad (1)$$

where is the inductance of the coil, is the dc current flowing through the coil, and is the voltage across the coil.

During SMES operation, the magnet coils have to remain in the superconducting status.

A refrigerator in the cryogenic system maintains the required temperature for proper superconducting operation. Since the refrigeration load can affect the overall efficiency and cost of a SMES system, the refrigeration load that has loss components (such as, cold to warm current leads, ac current, conduction and radiation, etc) should be minimized to achieve a higher efficient and less costly SMES system.

A PCS provides a power electronic interface between ac power system and superconducting coil. It allows the SMES system to respond within tens of milliseconds to power demands that could include a change from maximum charge rate to maximum discharge rate of power. This rapid response allows a diurnal storage unit to provide spinning reserve and improve system stability. Converters may produce harmonics on the ac bus and in the terminal voltage of the coil. Using higher pulse converters can reduce these harmonics. A PCS could be either a current source inverter or a voltage source inverter with a dc–dc chopper interface. 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. The superconducting coil is charged or discharged by adjusting the average (i.e., dc) voltage across the coil to be positive or negative values by means of a dc–dc chopper. When the unit is on standby, the coil current is kept constant, independent of the storage level, by adjusting the chopper duty cycle to 50%, resulting in the net voltage across the superconducting winding to be zero.

III) DETAILED SMES MODEL SYSTEM

3.1. SMES Coil

The SMES Coil modeling is based on a 50 MW, 100 MJ SMES coil built by BWX Technologies, Inc. for a FACTS/energy storage application. The entire SMES coil has a width/height ratio of 3.66 m (144 in)/1.53 m (60 in) made of 48 Double Pancakes (DP). Each double pancake has 40 turns.

The calculated series and shunt capacitances for each turn have been lumped to represent capacitances for a double pancake, and lumped further to obtain the equivalent capacitances for the entire coil for simulation of the dynamic operation as showed in Table I.

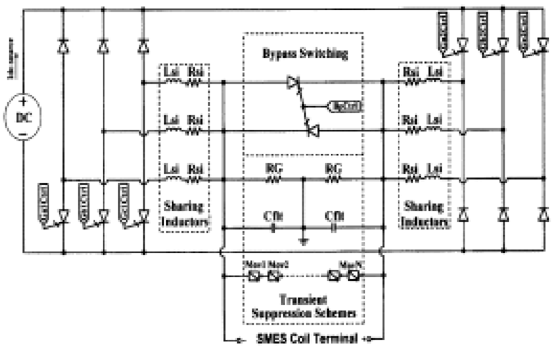

Figure 2 Structure of a GTO-based chopper

The self and mutual inductances for each turn also have been lumped to obtain the equivalent self and mutual inductances for each double pancake. The total inductance is 12.5 H.

In order to reduce the computational burden, an equivalent circuit of the coil is represented by a 6-segment model comprised of self inductances, mutual couplings, ac loss resistances, and series and shunt capacitances, as shown in Fig. , including the mutual couplings between segments to obtain more accurate frequency and voltage response .

The inductance and capacitance values for segments are based on the previous design of the SMES coil provided by BWX Technologies. When calculating the parameters of the 6-segment model, the following steps are used: 1). Turn to turn values are lumped to obtain the parameters of a double pancake, 2). These lumped values are used to calculate the parameters of the entire coil, 3). The entire coil parameters are evenly distributed into 6 segments.

It is assumed that inductance and capacitance values are equal for each segment, and PI model is adopted. The parameters for 6 segments are used throughout the voltage distribution and transient analysis studies. The inductance matrix used in the simulation is as follows:

$$L_{Coil\_6segment} = \begin{bmatrix} 0.5806 & & & & & \\ 0.4308 & 0.5806 & & & & \\ 0.3064 & 0.4308 & 0.5806 & & & \\ 0.2360 & 0.3064 & 0.4308 & 0.5806 & & \\ 0.1885 & 0.2360 & 0.3064 & 0.4368 & 0.5806 & \\ 0.1539 & 0.1885 & 0.2360 & 0.3064 & 0.4368 & 0.5806 \end{bmatrix}.$$

3.2. The Power Conversion System—a GTO-Based Chopper

A multiphase GTO-based chopper is modeled as shown in Fig. . Components in dashed rectangles are for bypass switching and transient suppression purposes. A constant 24 kV dc voltage source represents the dc side of the chopper. In FACTS/SMES applications, the dc–dc chopper is connected to a FACTS device through a dc link capacitor maintaining amconstant dc voltage. Operation principles of the multiphase dc chopper can be explained with the help of a single-phase dc chopper. In a Singlephase dc chopper, the GTO firing signal is a square wave with a specified duty cycle. The average voltage and current of the SMES coil are related to the dc source voltage and average current by the duty cycle applied . These relationships can be expressed as

$$V_{smes\_av} = [1-2d]V_{dc\_av}$$
$$I_{dc\_av} = [1-2d]I_{smes\_av}.$$

Where $V_{smes\text{-}av}$ is the average voltage across the SMES coil, $I_{smes\text{-}av}$ is the average current through the SMES coil, $V_{dc\text{-}av}$ - is the average dc source voltage, $I_{dc\text{-}av}$ - is the average dc source current, and d is the duty cycle of the chopper (d=GTO conduction time/period of one switching cycle).

There is no energy transferring at a duty cycle of 0.5, wherethe average voltage of the coil is zero and the average coil current is constant. In the cases of duty, when cycle being larger than 0.5 or less than 0.5, the coil is either charging or discharging respectively. Adjusting the duty cycle of the GTO firing signals controls the rate of charging/discharging. For a n-phase dc chopper, the duty cycle of firing signals of each phase is 1/ηof the total duty cycle. In the 3-phase chopper used, the duty cycle of each phase changes from 0 to 1/3, and the frequencies of the GTO firing signals are 100 Hz.

In Fig. , small inductors L_{si} are placed at the output of each chopper phase for the purpose of current sharing, and resistors represent the resistances R_{si} of these inductors and the leads.

IV) STACOM–SMES COMBINATION SYSTEM

4.1. STACOM–SMES Experiment System Setup

To utilize and verify the SMES model, an integrated system of a Static Synchronous Compensator (StatCom) with a SMES system is simulated for testing. A 100 MJ 96MW(peak) SMES coil is attached to the voltage source inverter front end of a StatCom via the dc–dc chopper. The real and reactive power responses of the integrated system-to-system oscillations are studied using the electromagnetic transient program (PSCAD/EMTDC).

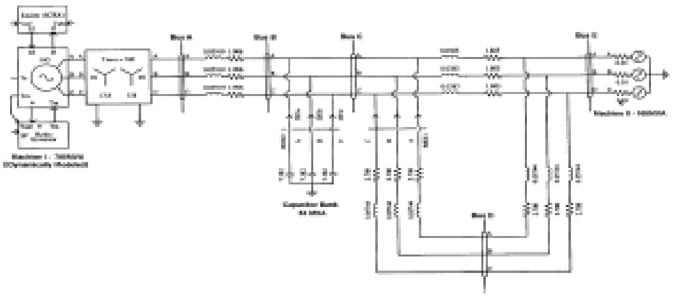

Figure 3 AC system equivalent

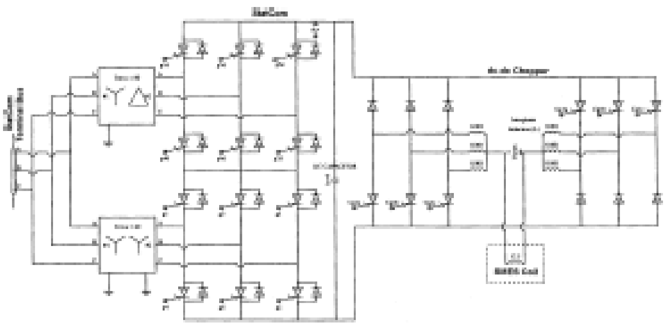

Figure 4 Detailed representation of statcom, dc–dc chopper and SMES coil.

A StatCom is a second-generation flexible ac transmission system controller based on a self-commutated solid-state voltage source inverter. However, it can only absorb/inject reactive power, and consequently is limited in the degree of freedom and sustained action. The addition of energy storage will allow the StatCom to inject and/or absorb active as well as reactive power simultaneously, 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 SMES coil via a dc–dc chopper.

The characteristics of a SMES system such as rapid response (Milliseconds), high power (Multi-MW), high efficiency, and four-quadrant control can help to meet the power industry's demands for more flexible, reliable and fast active power compensation devices.

The simulation circuit representing the integrated ac system is shown in Fig. . The detailed representation of the StatCom, dc–dc chopper, and SMES coil are depicted in Fig. 14. In this figure, the units of resistance, inductance, and capacitance values are Ohm, Henry, and Microfarad, respectively.

4.2) AC Power System: The ac system equivalent used corresponds to a two-machine system where one machine is dynamically modeled (including generator, exciter and governor) to demonstrate the dynamic oscillations. Dynamic oscillations are simulated by creating a three-phase fault in the middle of one of the parallel lines at Bus D in Fig. . 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.

4.3) StatCom—SMES System:

As can be seen from Fig. , two-GTO-based six-pulse voltage source inverters represent the StatCom used. The voltage source inverters are connected to the ac system through two 80 MW coupling transformers, and linked to a dc capacitor in the dc side. The value of the dc link capacitor has been selected as 10 mF in order to obtain smooth voltage at the StatCom terminal bus.

The primary function of StatCom is to control the reactive power/voltage at the point of connection to the ac system. Basically, there are two fundamental control strategies for the dc bus voltage.

The first one is basically to keep the constant dc bus voltage, therefore operating with a variable modulation of the inverter.

The second will have the variable dc bus voltage and always operating with a modulation of near one . The second control is basically a stabilizer control that regulates the SMES power according to the changes that may happen in the ac real power. Different control schemes will certainly have different effect on the performance of the system, which is not the focus of this paper.

The SMES coil is connected to the VSI 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. A two-level three-phase dc–dc chopper used in the simulation has been modeled and controlled according to . The phase delay is kept at 180 degrees to reduce the transient over voltages.

The average voltage of the SMES coil is related to the StatCom output dc voltage with the relationship displayed by (10). Where - is the average voltage across the SMES coil, - is the average StatCom output dc voltage, and d is duty cycle of the chopper (GTO conduction time/period of one switching cycle) . Three measurements used in this Chopper-SMES control are: SMES coil current, ac real power measured at the StatCom terminal bus, and dc voltage measured across the dc link capacitor.

CONCLUSIONSThis paper provides a detailed model for the simulation of the SMES system. The model is intended to provide guidelines for a detailed SMES device simulation in the power system, as well as to provide a basis for comparison of various simulation tools, control strategies, algorithms and realization approaches.

The paper considered a transient modeling of a SMES coil and the chopper.

The SMES coil is modeled as sections where each section is represented with its series capacitance, shunt capacitance, self and mutual inductances to other sections.The computation of models is developed to represent the entire coil to reduce computational effort.

The voltage distribution and transient analysis of the SMES coil find the transient over voltages to SMES coil are generated during normal chopper operation, any open or short circuit fault on the chopper GTOs, and the bypass switch operation.

This paper also presents the modeling and control of the integration of a StatCom with SMES system, and its dynamic response to system oscillations. It has been shown that the StatCom-SMES combination can be very effective in damping power system oscillations. More effective damping and faster stabilization of the system can be obtained if StatCom-SMES is located near a generation area rather than a load area. Adding energy storage enhances the performance of a StatCom and possibly reduces the MVA ratings requirements of the StatCom operating alone. This is important for cost/benefit analysis of installing FACTS controllers on utility systems. It should be noted that, 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.

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