A DYNAMIC MODEL OF THE D-SMES DEVICE FOR POWER SYSTEM PERFORMANCE STUDIES

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Abstract – This paper presents a dynamic model of the D-SMES (distributed SMES) device developed for power system performance studies. A D-SMES device, the combination of a SMES system with a voltage-source IGBT converter, is modeled as a controllable energy source. The model is designed to accurately reproduce processes in the electromechanical frequency range in accordance with the basic principles of modeling FACTS devices. Shown are model diagrams for the active and reactive power paths. The model is provided with two numerical solution modes for short-term and long-term dynamical simulations. Given are examples of using the model in voltage and angular stability studies of actual power systems.

Keywords: SMES, FACTS, dynamic model, power system, simulation

1 INTRODUCTION

The SMES (Superconducting Magnetic Energy Storage) is well known to be a system where energy is stored within a magnet that is capable of quickly releasing megawatt amounts of power. SMES applications have been considered as new options to solve a variety of transmission, generation, and distribution system problems, including improvement of voltage and angular stability, increasing power transfer capability of existing grids, damping subsynchronous oscillations, damping inter-area oscillations, load leveling, etc. [1-7]. Using SMES devices substantially enhances the controllability and provides operation flexibility to a power system and is therefore a prospective option in building a FACTS (Flexible AC Transmission System).

The D-SMES (distributed SMES) is a set of SMES devices connected to different buses in a transmission system [8]. Each device, a combination of a SMES system with a voltage-source IGBT converter, is capable of effectively controlling and near-instantaneously injecting both active and reactive power into the power system. Obviously, it is reasonable to consider a power system with a D-SMES as a multi-device FACTS in terms used in [7,9,10]. The general issues associated with the utilization of a D-SMES system are optimizing location, size, and control of the devices.

To evaluate the effectiveness of SMES systems with respect to power applications, different techniques have been used and many variants of mathematical description have been developed. In many papers, the eigenvalue analysis, followed by digital simulation of the dynamics, is applied. Usually, simplified device controls and small (like IEEE benchmark network models) or middle size power systems are studied. However, in practical applications it is necessary to evaluate the impact of a D-SMES on electromechanical processes of large actual power systems and to analyze the effectiveness of complex control schemes with their non-linear elements and delays adequately represented.

Described in this paper is a dynamic model of the D-SMES device developed for power system performance studies. To reproduce processes in the electromechanical frequency range accurately, the device is considered as a controllable energy source in accordance with the basic principles of modeling FACTS in these applications. The device is modeled as a non-linear system that contains both continuous and discrete elements, including parameter and power output limitations of different physical nature. Shown are model diagrams for the active and reactive power paths responsible for injecting power into or consuming power from the power system. Given are examples of using the model in voltage and angular stability studies of actual power systems.

Originally developed as a user-written for the PSS/E (Power System Simulator) software, the D-SMES model has been included in the PSS/E standard dynamic library. The model is provided with two numerical solution modes for short-term and long-term dynamical simulations.

2 DESCRIPTION OF THE D-SMES DEVICE PERFORMANCE

Figure 1 schematically shows the principal components of the D-SMES device as well as the way it is connected to the power system.

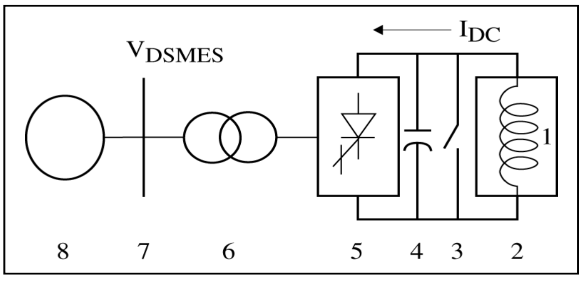

Figure 1. Schematic diagram of the D-SMES device: 1 – coil, 2 – superconducting magnet, 3 – controlled bypass switch, 4 – DC capacitor, 5 – IGBT

converter, 6 – step-up transformer, 7 – D-SMES terminal bus, 8 – power system.

2.1 Controlled Voltage and Voltage Thresholds

The D-SMES device is capable of controlling or supporting the voltage at either its terminal bus (V_{DSMES}) or a remote bus (V_{remote}). The voltage sensor is located at the high voltage bus of the step-up transformer or, alternatively, at the remote bus. Also the step-up transformer's low voltage is monitored. If this voltage reaches a threshold, usually about ten percent above the rated voltage, the remote voltage control is abandoned.

The D-SMES operation depends on four voltage thresholds V_i (i = 1,2,3,4) that define voltage ranges with different functions and operational conditions of the device ($V_{i+1}<V_i$, some typical values of the thresholds are given in Section 7). The voltage at a controlled bus V_{contr} is monitored and compared against the four values V_i to determine whether it is necessary to inject active and/or reactive power.

2.2 Active Power Operation

The D-SMES device starts injecting active power into the system if the controlled voltage is deemed to be low. The injection needed is provided by discharging the D-SMES magnet that is activated when a voltage drop occurs. Currently, the magnet is not able to absorb active power from the power system. In the future the device, following a damping signal P_{aux} , will also be able to absorb active power from the system and dissipate it in resistor banks. This capability of the device is being under development, therefore only its simplified representation is provided in the present model.

The device starts injecting active power into the system if V_4 =<V_{contr}<V_3. The injection is also enabled immediately after V_{contr} quickly crosses this voltage range. If the controlled voltage is beyond this range and V_3 =<V_{contr}<V_2 or V_{contr}<V_4, the device is able to absorb active power from the power system based on a P_{aux} signal.

Note that such absorption may take place only if the magnet has been activated longer than a given time interval T_{off} (see Section 4.2); otherwise, it will continue its discharge injecting power to the system until T_{off} is reached.

2.3 Reactive Power Operation

The D-SMES device can inject or consume reactive power when the controlled voltage V_{contr} is within any voltage range. This reactive power is provided by the IGBT voltage-source converter in the amount determined by an AVR (Automatic Voltage Regulator), depending on an input error signal that is the difference between the voltage reference V_{ref} and V_{contr}.

The device is capable of temporarily boosting the reactive power output. For boosting, the reference voltage V_{ref} is raised by a given step for a short time interval of about a second. After this interval, V_{ref} returns to its original value.

2.4 Overload Capability

When the voltage at the controlled bus is below a specified threshold (V_{contr}<V_3), a thermal overload capability of the IGBT converter is available in existing D-SMES devices. This overload capability is especially important for improving the first-swing stability and for damping power system oscillations. Since the converter has a finite thermal capability, there is a choice in sharing it among active and reactive power. Priority is given to active power, since its injecting is the primary purpose of the device.

3 GENERAL APPROACH TO THE MODELING OF THE D-SMES DEVICE

The general approach to modeling the D-SMES device is based on the principles applied in the modeling of FACTS devices in power system performance studies. The D-SMES device is considered as a controllable energy source, capable of simultaneous injection of active and reactive power in all four quadrants. Because electromechanical processes are to be reproduced, accurately modeling only the phenomena in the corresponding frequency range is required.

The device's converter is built of IGB transistors. Since the control of such high-speed electronic switches is beyond the frequency bandwidth typical for system dynamic performance studies, it need not be modeled in detail. Therefore the device's representation needed for such studies substantially differs from SMES representations in electromagnetic transient simulations as well as from small signal models in analyses of other SMES applications.

The D-SMES model layout basically contains two power paths responsible for active P_{out} and reactive Q_{out} injections along with constraints reflecting actual limitations and delays in operational conditions and controls (see Figure 2).

The ADSOC (Analyzing the D-SMES Operation Conditions) block determines the branch of the active and reactive power paths (algorithms) that corresponds to the present combination of operational conditions. The ADSOC logic takes into account within which voltage range [V_i,V_{i+1}), characterized by variable M_v, the controlled voltage V_{contr} is and, consequently, whether the device's capability of injecting/consuming power to the system is enabled/disabled (see Sections 2.2-2.4). At the same time, the ADSOC reflects the delays in the controls, such as the time intervals during which the state of the magnet cannot be abruptly changed even though the controlled voltage variation requires a new control action.

Besides those shown in Figure 2, there are other control flags that are reflected in the ADSCOC algorithm to include/exclude some control operations. Examples are the flags used to switch off either active or reactive power injections or flags to make the injections independent of the voltage thresholds. The corresponding sub-algorithms of the ADSOC block add more simulation flexibility, especially with respect to

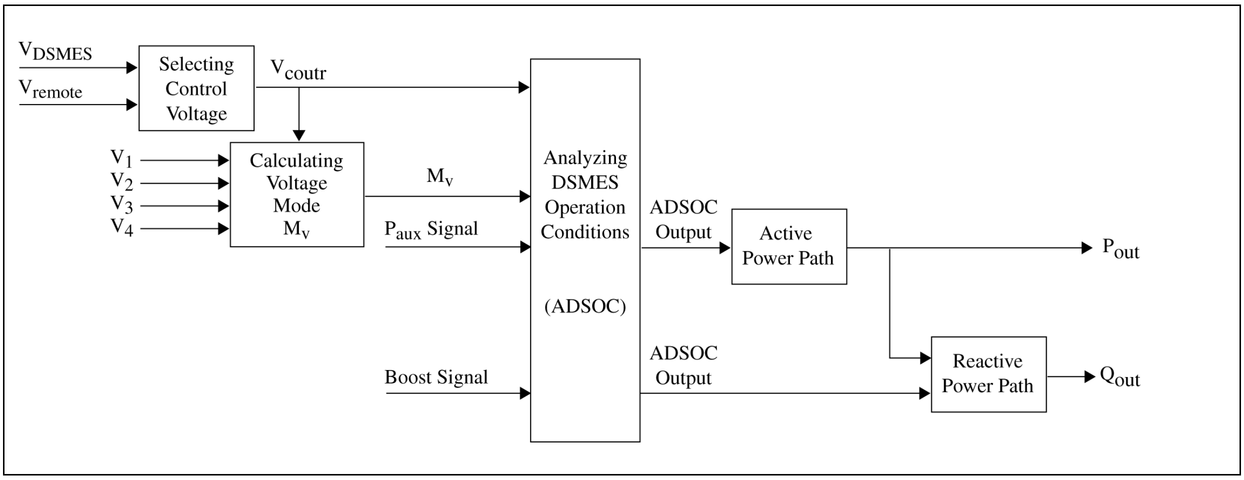

Figure 2. General model diagram.

the device's behavior when absorbing active power is required.

4 MODEL REPRESENTATION OF THE D-SMES DEVICE

As is usual in electromechanical simulations, calculations for the network are performed on the system apparent power base SBASE (typically 100 MVA). For the internal D-SMES device model calculations, except those for the DC side, it is reasonable to use another power base (MBASE) and to set this base equal to the device's rated value S_{rated}. For the DC side calculations, the actual physical units are most suitable.

4.1 Model Active Power Path

When the magnet is being discharged, the output active power of the device P_{out} as a function of time t is calculated as

$$P_{out}(t)=V_{DC}(t)I_{DC}(t),$$

subject to the limits shown in Figure 3.Here $I_{DC}(t)$ is the DC side current: $I_{DC}(t)$ is equal to the coil current $I_L(t)$ when the magnet is activated, otherwise $I_{DC}(t)=0$. The voltage across the DC side capacitor $V_{DC}(t)$ is assumed to be constant during the magnet discharge interval, therefore the form of the active power output $P_{out}(t)$ is the same as that of $I_{DC}(t)$.

When the D-SMES absorbs active power from the system, $P_{out}(t)= P_{aux}(t)$.

The limit P_{max} changes (increases) the reactive power available when the active power is at a high level. The $I_{ACmax}V_{DSMES}$ limit reflects AC current limitations of the IGBT converter and step-up transformer.

4.2 Magnet Discharge Representation

Positive active power injection is effected by discharging the D-SMES magnet. The process of discharge can be either continuous or in discrete steps, however, in any case the total discharge time (the sum of intervals Δt_i when the magnet is activated) is the same: $T_{dis}=\Delta t_1+\Delta t_2+\Delta t_3$, see Figure 4. During any discharging interval the coil current $I_L(t)$ ramps down linearly with a given slope under the constant voltage V_{DC} across the DC side capacitor.

The D-SMES magnet cannot be activated or deactivated by the controls instantaneously. To represent the device's performance more accurately, in the model there are two special time constants. These constants are defined by the minimum time intervals needed to activate (T_{on}) the magnet and to shut it down (T_{off}) after the previous switching operation. Both the constants reflect delays in the control software and hardware, critical for reproducing the device's performance during and/or immediately after a fault in the power system area close to the D-SMES bus.

4.3 Model Reactive Power Path

The output reactive power of the device is approximated as

$$Q_{out}(t)= V_{DSMES}(t)I_Q(t),$$

where $I_Q(t)$ is the current with the following Laplace transform:

$$I_Q(s)=\frac{G(s)}{1+G(s)H(s)}(V_{ref}-V_{contr}),$$

$$G(s)=\frac{(1+sT_1)(1+sT_2)}{(1+sT_3)(1+sT_4)}\bullet\frac{k_{AVR}}{s},$$

$$H(s)= k_d$$

Here T_1, T_2, T_3, and T_4 are time constants, k_{AVR} is gain, k_d is droop element. The value of $Q_{out}(t)$ is calculated with respect to limits shown in Figure 5. Thus, the reactive power path is actually a kind of AVR whose dynamic behavior significantly depends on the limits shown.

The principal elements of this AVR are a double lead/lag element and an integrator, provided with a feed back. The lead/lag elements can reduce the AVR high-frequency gain to avoid control instability in case of a weak power system or of interaction with other fast control devices. A pure integrator k_{AVR}/s causes reac-

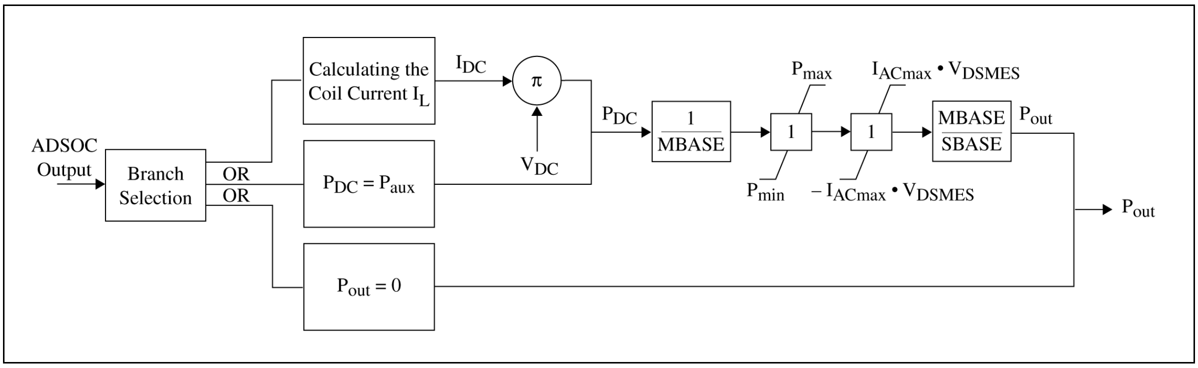

Figure 3. Model active power path**.**

tive current I_Q to continue increasing or decreasing as long as there is a non-zero input signal. The feedback provided by the droop element k_d limits the increase of $I_Q(t)$ and determines the steady state AVR gain.

The lead/lag limits $V_{Q\ max}$ and $V_{Q\ min}$ reflect voltage restrictions in an analog implementation of the AVR or allow non-windup in a digital implementation. The variable $I_{Q\ max}(t)$ reflects AC current limitations of the IGBT converter and step-up transformer that are especially significant because of the voltage-source type of the converter. During a fault or a post-fault regime of the power system the controlled voltage V_{contr} may be very low, and the converter raises the AC current, therefore the power output $Q_{out}(t)$ should be limited in accordance with the maximum continuous AC current capability:

$$I_{Q\,max} = \sqrt{(I_{AC\,max})^2 - (P_{out}\ / V_{DSMES})^2}\ .$$

Note that both the limit $I_{Q\ max}$ and limit Q_{lim} (see Section 4.4) are functions of the active power output P_{out} that has priority over Q_{out}.

4.4 Overload Capability Representation

The normal upper limitation on the device's apparent power output **S**$=P_{out}+jQ_{out}$ is determined by the rating S_{rated}. To have active power output P_{out} at maximum when needed, reactive power output Q_{out} should be limited by Q_{lim} as

$$Q_{lim} = \sqrt{S^2{}_{lim} - P^2{}_{out}}\,.$$

The overload capability of the D-SMES device is activated when $V_{contr} < V_3$, if the device is required to inject or consume apparent power with the phasor **S** modulus exceeding S_{rated}. If this takes place (at time t= t^*), the limit Q_{lim} is temporarily changed according to a cycle defined by the overload diagram of Figure 6. During this cycle, the limit S_{lim} rises to $S_{lim\ max} = k_{ol}$ $*S_{rated}$ and this increased value is kept constant for T_{ol} seconds, then S_{lim} is linearly ramped back to its original value of S_{rated} in T_{back} seconds. Once in the overload mode, the device should stay in it for the complete overload cycle shown in Figure 6, regardless of how the controlled voltage V_{contr} changes. However, this only means increasing the upper limit, whereas the actual output power as determined by the AVR operation may be far less than the limit.

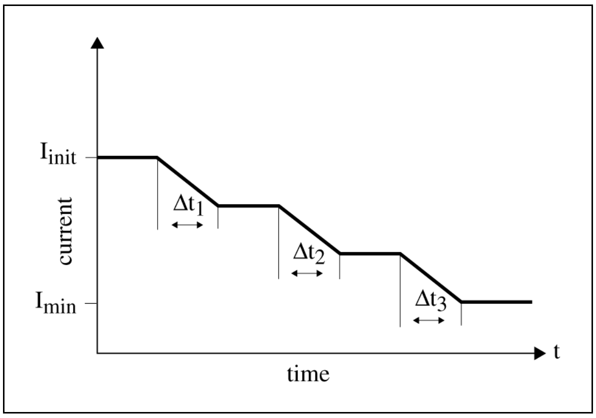

Figure 4. Magnet discharge curve.

5 INCORPORATING THE MODEL INTO A POWER SYSTEM SIMULATOR

The D-SMES representation described allows building a model that is supposed to be incorporated into a general power system simulator. The particular digital model based on the description of Sections 3 and 4 was to be included into the PSS/E dynamic model library and therefore was designed in accordance with the general PSS/E model-writing style and simulation algorithms.

5.1 D-SMES Current Injection to the Power System

The PSS/E as a simulator of electromechanical processes is based on a set of algebraic nodal equations for the network. In this set each D-SMES device is represented as a current injection (phasor $\mathbf{I}_{DSMES}$) through the system bus to which the device is connected. The conjugate of this phasor is determined by the phasor **S**$=P_{out}+jQ_{out}$ of apparent power injected or consumed by the device:

$$\mathbf{I}^*_{DSMES} = \frac{P_{out} + jQ_{out}}{\mathbf{V}_{DSMES}}$$

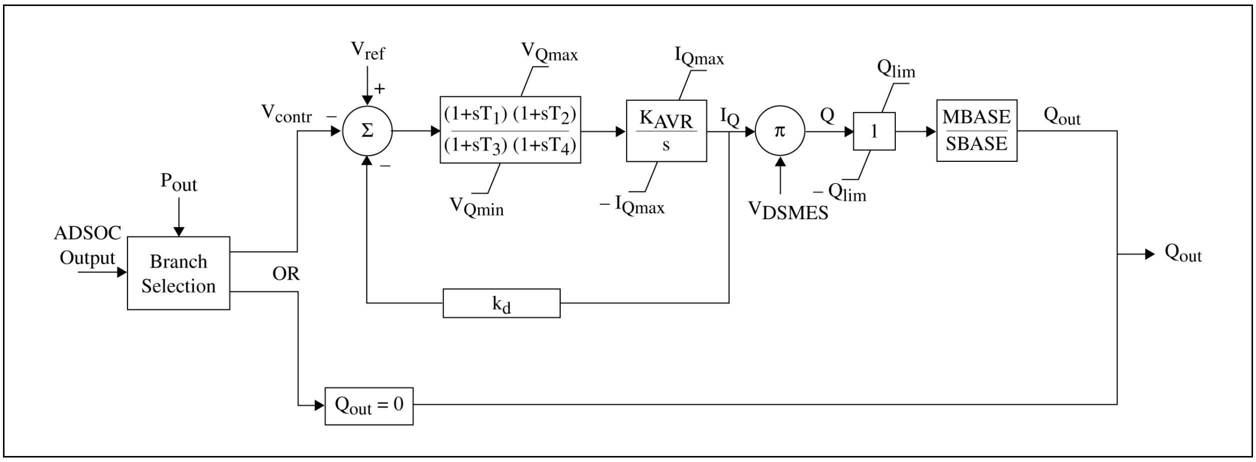

Figure 5. Model reactive power path

With respect to the current injection of the model it is worth noting how a D-SMES device is treated in fault calculations. In PSS/E when calculating faults on a network with a D-SMES, each device is represented by its Thevenin equivalent. Care should be taken of reasonably setting the device's equivalent source impedance to a reasonably large value, which allows avoiding an inadequate model's contribution to short circuit currents in the power system.

5.2 Numerical Solution of the Model Equations

Since the device's power output depends on its terminal voltage $\mathbf{S}=\mathbf{S}(\mathbf{V}_{DSMES})$, iterations are needed at each simulation time step until the nodal equations are solved to acceptable mismatch tolerance.

At each time step the phasor $\mathbf{S}= P_{out}+jQ_{out}$ is calculated based on the model's state space variables. Since the model is developed for a particular software package – PSS/E, its generic numerical algorithms have been used. The model is provided with two modes of numerical integration corresponding to those of PSS/E. In the mode for short-term dynamical simulations the two-step explicit Adams-Bashforth method is used, while for long-term simulations a special algorithm approximating the trapezoidal rule is applied.

Examining the model diagrams, one can easily see that each D-SMES device adds only three differential equations of its AVR to the mathematical description of the whole power system. The simulation time step size should be considerably less than the smallest model time constants to be reflected (such as magnet software delays T_{on} and T_{off}). For the typical D-SMES parameter range, analysis shows and simulation practice confirms that incorporating D-SMES models into a power system model usually neither introduces difficulties in numerical integration nor worsens the convergence for the network algebraic equations.

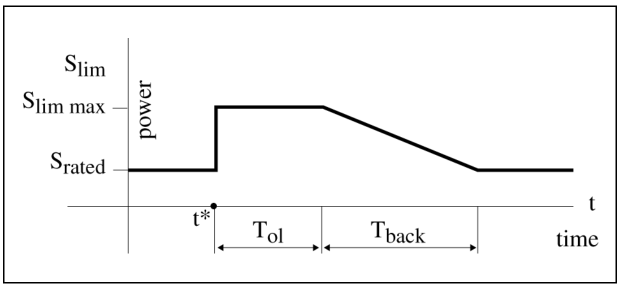

Figure 6. Overload diagram

5.3 Initialization of the Model

When initializing the model for a dynamic simulation, both components of the phasor $\mathbf{S}=P_{out}+jQ_{out}$ should be defined as well as the values for the state variables. In a normal steady state operation, the controlled voltage V_{contr} is assumed be about 1 p.u., therefore there should be no active power output. The reactive power output is determined by the load flow of the power system and may differ from zero. If the initial value of Q_{out} does not match the existing AVR limits (see Figure 5), specifically, the $I_{Q\ max}$ limit, a weak transient at the beginning of a simulation run may occur. Setting initial values for the three state variables and other model dynamic parameters is trivial.

6 EXAMPLE STUDIES OF VOLTAGE AND ANGULAR STABILITY

This Section contains examples of using the model in PSS/E-based studies of actual power systems. A single modeled device is capable of injecting up to 18 MVAR and 3 MW within a half of a fundamental frequency cycle after a critical event in the system. The maximum rating can be sustained for 0.5 sec for active power and 1.0 sec for reactive. If needed, the device is also capable of injecting up to 8 MVAR continuously to assist the post-fault system for as long as necessary.

All the parameters' values and ranges used in the simulations correspond to those of existing D-SMES systems [8]. Specifically, on the DC side V_{DC}=3.0 kV, I_{init}= 1.05 kA, I_{min} = 0.4 kA, T_{dis}= 0.6 msec, $T_{on}=T_{off}$ = 100 msec. The voltage control threshold values V_i (i = 1,2,3,4) are 1.03, 0.99, 0.9, and 0.5 respectively; for the Overload Diagram k_{ol} =2.3, $T_{ol}=T_{back}$ = 1.0 sec. The AVR parameters are to be tuned to optimize the device's performance in the particular network.

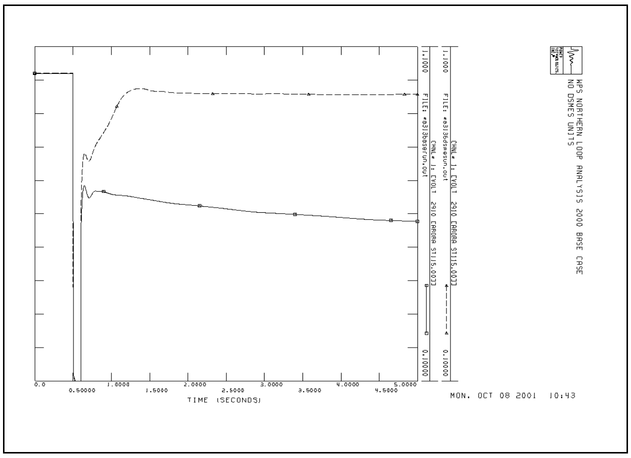

Figure 7. Voltage stability improvement.

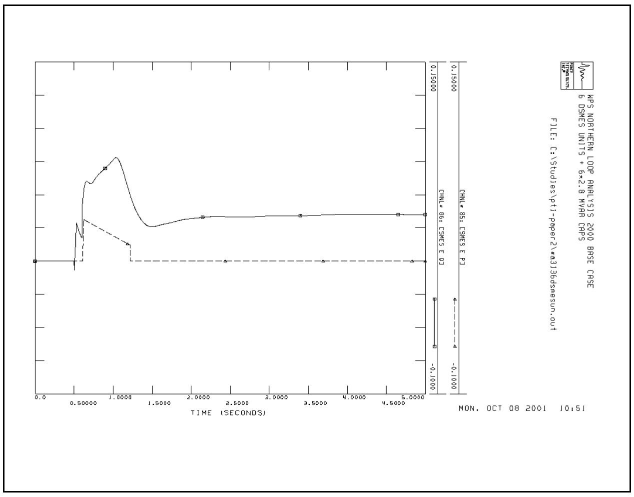

Figure 8. D-SMES active and reactive power output.

6.1 Example of Voltage Stability Improvement

This example demonstrates the voltage stability improvement as a result of a D-SMES installation in a fairly large, but remote network. The study area is a 115 kV, looped power system, with a large amount of motor loads, that serves 230 MW of load in approximately a 4000 square mile region in northern Wisconsin, USA. The D-SMES system consists of six 3 MVA D-SMES units, each with a 3 MJ magnet.

In Figure 7, the solid line depicts the voltage at an area 115 kV substation before the D-SMES installation, following a critical system fault. The very low voltages here are determined by the system particularities mentioned above. The dashed line shows the improved voltage response for the identical fault with the D-SMES in place.

Figure 8 shows the power outputs P_{out} and Q_{out} of one of the D-SMES units in the system discussed. Note that the solid line represents the reactive output Q_{out} of the unit which peaks at 6.9 MVAR, leading. The dashed line shows the active power output P_{out} which peaks at 3 MW.

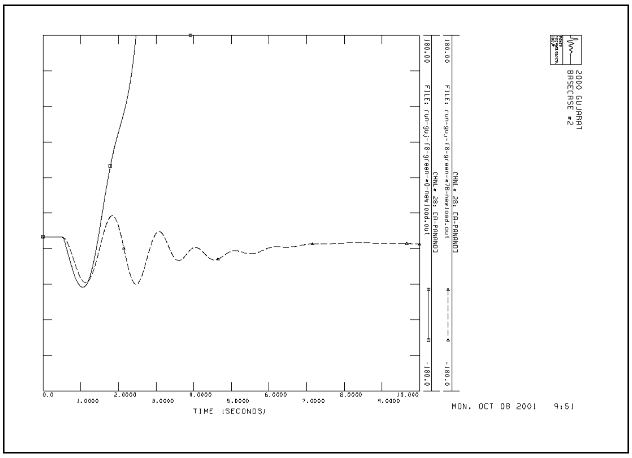

Figure 9. Angular stability improvement.

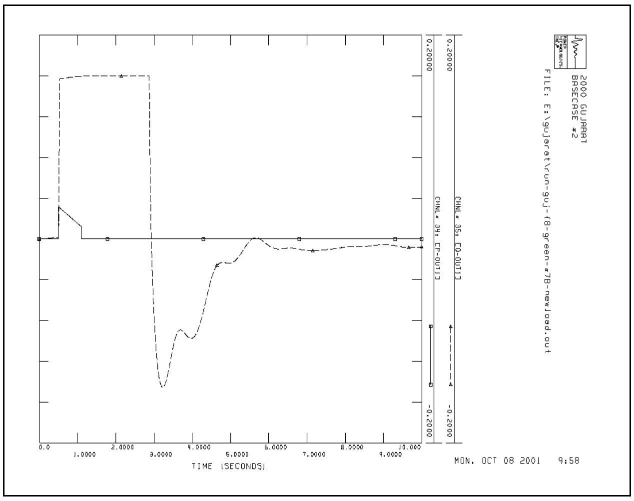

Figure 10. D-SMES active and reactive power output.

6.2 Example of Angular Stability Improvement

This example demonstrates the angular stability improvement that can be realized with the utilization of a D-SMES system. The study area in this example is a remote portion of a large interconnected area in Southeast Asia. The remote portion of the area includes about 383 MW of the 7500 MW overall load and consists mainly of 220 kV and 132 kV transmission lines with a single 172 MW generating station. Considered is a fault resulting in the loss of one of two circuits that connects the remote area with the rest of the power system. The solid line of a machine angle in Figure 9 shows the first swing instability at the 172 MW generating unit as a result of the fault. The dashed line characterizes the same scenario, but with the addition of seven 8 MVA D-SMES units, each with a 3 MJ magnet. Clearly, the D-SMES installation has solved the first swing instability problem.

Figure 10 shows the D-SMES active (solid line) and reactive (dashed line) power output for one of the D-SMES units. The output peaks at 18 MVAR of reactive power and 3 MW of active power.

The D-SMES model has been used in performance studies for transmission systems in many utilities within the US, Canada, Mexico, Brazil, and Southeast Asia. A more detailed example of the voltage stability analysis, including data and one-line diagrams of the network, is given in [11].

7 CONCLUSIONS

The D-SMES device model described is based on the general principles of FACTS devices' representation in power system performance studies. The physical phenomena that determine the device operation in the electromechanical frequency range as well as the features of the device's controls are carefully taken into account. The model has proved to be an adequate and effective simulation tool for system performance analysis and has been used in voltage and angular stability studies for actual power systems.

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