APPLICATION OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNIT TO IMPROVE THE DAMPING OF SYNCHRONOUS GENERATOR

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ABSTRACT
A systematic approach is presented to design a controller for superconducting magnetic energy storage (SMES) unit to improve the dynamic stability of a power system. The developed scheme employs a proportional-integral (PI) controller to enhance the damping of the electromechanical mode oscillation of synchronous generators. The parameters of the proposed PI controller are determined by pole assignment method based on modal control theory. Eigenvalues analysis and nonlinear computer simulations show that SMES with the PI controller can greatly improve the damping of system under various operating conditions.

Key words: SMES, PI controller, pole assignment, computer simulation

1. INTRODUCTION
Power system oscillations will occur if there are system disturbances such as load change or system fault. The damping of the system must be enough such that the synchronous generators can return to steady state after disturbances [1]. Many countermeasures have been suggested in the literatures to increase the damping such as power system stabilizers (PSS) [2-6], governor and turbine system [7], static Var compensator (SVC) [8-9], and phase shifter [10].

Due to the rapid development in the technique of high temperature superconducting material, the application of the superconducting conductor becomes an important issue in the electrical engineering [11-15]. The superconducting magnetic energy storage (SMES) unit is designed to store electric power in the low loss superconducting coil [11-12]. Power can be absorbed by or released from the coil according to system requirement. The SMES unit can also be used as a load frequency controller [16] and transmission line stabilizer [11], or increase the stability of power system [17-18].

In this paper, a systematic approach is used to design a SMES unit with proportional-integral (PI) controller for increasing the damping of synchronous generators. The PI controller is very simple in structure and had been successfully used as a power system stabilizer [5]. The parameters of the PI controller are determined using modal control theory [19] by assigning the eigenvalues of the electromechanical mode at the prespecified position. The main results obtained in this paper are:

(a) Eigenvalues analysis and computer simulation results show that the SMES unit with the proposed PI controller can greatly enhance the damping of the synchronous generator.

(b) The superconducting coil can draw or release the power during the dynamic period. The energy stored in the coil is always under its rating.

(c) Although the PI controller is designed at a special load condition, it can also provide good damping effect at other load conditions.

(d) The stability margin can be expanded by the PI controller.

(e) The PI controller is very simple in structure and easy to be implemented.

2. DESCRIPTION OF SYSTEM MODEL

Fig. 1 shows the studied system with a synchronous generator connected to the infinite bus through a transmission line and a superconducting magnetic energy storage (SMES) unit. Although the example system is a simple one, it is sufficient to demonstrate the damping effect of SMES [18]. The unit with thyristor controller is located at the generator bus terminal. The nonlinear dynamic behavior of the synchronous generator is described by two axis model [1], where the armature transient voltage of direct axis and quadrature axis are described by

\[ \frac{dE_d}{dt} = \frac{\omega}{T_d} \frac{R_d}{T_d} I_d - \frac{1}{T_d} \frac{E_d}{M} - \frac{M}{T_d} \frac{dE_d}{dt} \]

where \( E_d \) is the field excitation voltage, and \( T_d \) and \( T_q \) represent d-axis and q-axis transient time constant, respectively. The swing and rotor angle equations can be written as

\[ \delta = \omega (\omega - 1) \]

where \( P_m \), \( D_e \), and \( M_e \) are the output power of the reheat steam turbine, damping coefficient, and moment constant. \( P_e = E_d I_d + E_q I_q \) is the electromagnetic power transferred in the air gap. \( P_{SM} \) is the stored power into the SMES. The terminal voltages which describe the relation between transmission line and generator are

\[ V_d = E_d - R_a I_d - X_d I_d \]

\[ V_q = E_q - R_a I_q + X_d I_d \]

where \( V_d \) and \( V_q \) represent terminal voltage of generator and infinite bus voltage, respectively.

The static excitation control system is shown in Fig. 2, and the governor and reheat turbine is also shown in Fig. 3. They are all represented by the transfer functions in the s domain. Combining generator, exciter, and governor-turbine system, we can obtain a set of 10th order nonlinear differential equations. At the initial operating point the nonlinear differential equations can be linearized to get the linear differential equations [1].
Fig. 1 Single machine connected to infinite bus power system with SMES unit

Fig. 2 Static excitation system

Fig. 3 Steam turbine and governor system

All eigenvalues of the open loop system, that is without SMES, are shown in the first column of Table 1. From Table 1, the real part of the electromechanical mode is -0.073, which means that the damping of the synchronous generator is very bad. A SMES unit is used in this paper to improve the damping under system disturbances.

Fig. 4 shows the configuration of the SMES unit, containing a Y-Δ/Y-Y connected transformer, a 12-pulse converter and a DC superconducting inductor. The converter unit is forced commutated and is the firing angle of SCR. If α < 90°, the converter works as a converter mode (charging mode). If α > 90°, the converter then works as an inverter mode (discharging mode) [17]. Real power can be absorbed from or delivered to the power system by controlling the sequential firing angle of thyristors [15]. In order to effectively control the power balance of the synchronous generator during dynamic period, the SMES is located at generator terminal bus [17]. The current and voltage of superconducting inductor are related by

\[ I_{SM} = \frac{1}{L_d} \int_{0}^{t} V_{SM} \, dt + I_{SM0} \]  

where \( I_{SM0} \) is the initial current of inductor. The real power absorbed or delivered by the SMES unit then is

\[ P_{SM} = V_{SM} I_{SM} \]  

If \( V_{SM} \) is positive, power is transferred from the power system to the SMES unit. While if the \( V_{SM} \) is negative, power is released from the SMES unit. The energy stored in the superconducting inductor is

\[ W_{SC} = W_{SCO} + \int_{0}^{t} P_{SM}(r) \, dr \]  

where \( W_{SCO} = \frac{1}{2} L_d I_{SM0}^2 \) is the initial energy in the inductor.

To use the SMES as a stabilizing control unit, the terminal voltage \( V_{SM} \) across the inductor is controlled continuously depending on the measured speed deviation of the generator rotor. That is

\[ \Delta V_{SM} = \frac{K_c}{1 + s T_{dc}} \Delta \omega \]  

where \( K_c \) is the gain of control loop, and \( T_{dc} \) is the delay time constant of the control device. Because of constraint of hardware implementation the voltage and current of the inductor all have upper limit and lower limit. Since the converter operates in continuous mode, the upper limit of the inductor current is set in 1.38 \( I_{SM0} \) (p.u.), and the lower limit is 0.31 \( I_{SM0} \) (p.u.). The limit of terminal voltage is 0.438 (p.u.). All the system datas of generator, exciter, governor system, and SMES unit are given in Appendix.

3. DESIGN OF A PI SMES CONTROLLER USING MODAL CONTROL THEORY [19]

In order to enhance the electromechanical mode damping of synchronous generator, a PI SMES controller is used to control the inductor terminal voltage shown as in Fig. 5. Although many controllers can be used, the PI controller is sufficient and simplest to provide two degrees of freedom to control the electromechanical mode in Table 1 for damping the low frequency oscillation. The parameters of the PI controller can be determined by using the modal control theory. At the initial operation point, the linearized differential equations can be expressed as

\[ X = AX + BU \]  

\[ Y = CX \]

where \( X = [\Delta \omega, \delta, \Delta E_{FD}, \Delta V_{g}, \Delta E_{Fg}, \Delta E_{r}, \Delta P_g, \Delta P_h, \Delta P_c, \Delta P_{m}, \Delta V_{SM}]^T \) is the state vector, \( Y = \Delta \omega \) is the output signal, and \( U = U_{SM} \) is the control signal. A, B, and C are all constant matrixes. \( P_g, P_h, \) and \( P_c \) are states of the governor and reheat turbine. If \( V_{SM} \) is positive, power is transferred from the power system to the SMES unit. While if the \( V_{SM} \) is negative, power is released from the SMES unit. The energy stored in the superconducting inductor is

\[ W_{SC} = W_{SCO} + \int_{0}^{t} P_{SM}(r) \, dr \]

\[ \Delta V_{SM} = \frac{K_c}{1 + s T_{dc}} \Delta \omega \]  

Taking the Laplace transformation of eqs. (12) and (13), we have

\[ sX(s) = AX(s) + BU(s) \]  

\[ Y(s) = CX(s) \]
The control signal from Fig. 5 can be represented by

\[ U(s) = H(s) Y(s) \]

where \( T_w \) is the washout time constant and \( K_p \) and \( K_I \) are the controller gains to be determined. For any closed loop system eigenvalue controller can be other types as shown in the third column of Table 1. when \( T_w \) is the washout time constant and \( K_p \) and \( K_I \) are the controller gains to be determined. Of course, the controller is replaced by an unity gain. Of course, the controller is replaced by an unity gain. Of course, the controller is replaced by an unity gain. It is noted that the eigenvalues of this mode are actually the pre-specified values. The system with SMES and with PI controller at \( P_o = 1.05 \text{ p.u.} \) and \( P_o = 1.14 \text{ p.u.} \) respectively. While the stability margin of the system with PI controller is above \( P_o = 1.6 \text{ p.u.} \). The system stability margin is greatly enlarged by the PI controller.

4. EIGENVALUE ANALYSIS

At the initial operation condition, the system eigenvalues are given in Table 1. When the system is with SMES but without PI controller, there is little improvement in the damping of the electromechanical mode. The system with SMES but without PI controller means that the controller is replaced by an unity gain. Of course, the controller can be other types as shown in the third column of Table 1. If the PI controller designed in section 3 is presented, there is great improvement in the damping of the electromechanical mode as shown in the third column of Table 1. It is noted that the eigenvalues of this mode are actually the pre-specified values. The dynamic performance of the synchronous generator can be greatly improved by the proposed PI controller.

5. COMPUTER SIMULATION

In order to demonstrate the damping effect of the proposed PI controller, computer simulations based on the nonlinear differential equations are taken at various load conditions. All the nonlinearities such as exciter ceiling voltage limit and voltage limit of the inductor must be considered. Two types of system disturbances are tested. Fig. 7 shows the system responses when there is a 0.01 p.u. 4 cycles load change. This is a small disturbance, and so the speed oscillation curves certify the damping characteristics of the electromechanical mode as given in Table 1. Next we examine the dynamic performances when there is a large disturbance. A 4 cycles three phase
fault is occurred at the transmission line near the infinite bus. The system responses when there is no SMES are plotted in Fig. 8 for three different load conditions. There is almost no damping at the initial load condition $P_o = 1$. At $P_o = 1,2$, the system is unstable. Also the damping at $P_o = 0.8$ is not good enough. Fig. 9 shows the system responses when there is with SMES but without PI controller. The damping of the generator system is only a little improved, but at $P_o = 1.2$, the system is still unstable. The system responses when there is with SMES and the proposed PI controller designed in the previous section are shown in Fig. 10. Several observations can be obtained from Fig. 10:

(a) The damping of the synchronous generator can be greatly improved by the SMES with PI controller.

(b) From Fig. 10(b), the stability margin is expanded by the PI controller.

(c) During the dynamic period, the SMES unit draws power from the generator output bus or releases it to the bus. The power delivery limit is constrained by the converter voltage rating, and the size of the SMES unit. The SMES may allow the power delivery to saturate during the transient period as shown in Fig. 10, but still provide excellent damping for dynamic period. The power rating is chosen according to the size of generator and types of disturbance [20].

(d) The energy stored in the coil is always less than 6 MJ, the energy rating of the superconducting inductor.

(e) Although the PI controller is designed at a special operation point, it also can provide good damping effect at other load conditions. The controller is low sensitive to the system load.

6. CONCLUSION

In this paper, the superconducting magnetic energy storage (SMES) unit with a proportional-integral (PI) controller is proposed to enhance the damping of the synchronous generator. A systematic approach based on the modal control theory is used to determine the gain values of the PI controller by shifting the electromechanical mode to the prespecified position. Eigenvalues analysis and computer simulation results show that the damping effect of the SMES with PI controller is excellent. The dynamic performance of the generator can be greatly improved and the stability margin can be expanded. Although the PI controller is design at a special load condition, it can also provide good damping effect at other load conditions.

Application of the SMES to increase the damping of the multimachine power system can be suggested for later study. The effect of reactive power input/output of the SMES can also be considered. But this needs a different system model and is currently under study. Although the BPA has built a 30 MJ unit, the commercial devices are still not currently available. The cost of a practical SMES unit is unknown, but would more expensive than other damping devices, such as PSS and SVC. The stability improvement must be an additional benefit from the SMES but not the only one, since the unit should be used for load leveling and load management.

7. NOMENCLATURE

\[ \begin{align*}
\omega & \quad \text{angular speed} \\
\delta & \quad \text{torque angle} \\
E_d & \quad \text{d-axis transient voltage} \\
E_q & \quad \text{q-axis transient voltage} \\
E_{FD} & \quad \text{field voltage} \\
V_s & \quad \text{stabilizing transformer output voltage} \\
U_{SM} & \quad \text{SMES controller output} \\
V_b & \quad \text{infinite bus voltage} \\
V_d & \quad \text{d-axis terminal voltage} \\
V_q & \quad \text{q-axis terminal voltage}
\end{align*} \]
8. REFERENCES

(8) A.J. Ramos and H. Tyll, "Dynamic Performance of A Radial Weak Power System with Multiple Static VAR Compensator", 89 WM 183-5, PWRS.


APPENDIX SYSTEM PARAMETERS [1, 16]

Generator and transmission line
- Rated 160 MVA Rated Voltage 15 kV
- Excitation Voltage 375 V Field Current 926 A
- Power 1.0 p.u.
- \( X_d = 0.245 \) \( R_d = 0.001096 \)
- \( X_q = 1.70 \) \( X_{d0} = 1.64 \)
- \( T_{q0} = 0.075 \) s \( T_{do} = 5.9 \) s
- \( R_e = 0.020 \) \( L_e = 0.400 \)

Exciter
- \( K_{SE} = 400 \)
- \( K_{SF} = 0.025 \) s

Governor
- \( K_G = 3.5 \)
- \( T_{CH} = 0.05 \) s
- \( T_{SR} = 0.1 \) s
- \( T_{SM} = 0.2 \) s

SMES unit
- \( I_{SM0} = 0.6495 \)
- \( V_{SM0} = 0 \)
- \( L_d = 0.5 \) H
- \( K_C = 1.83 \)
- \( T_W = 0.125 \) s

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