A Novel Control Strategy for Superconducting Magnetic Energy Storage Unit to Improve Power System Stability

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ABSTRACT

In this paper a simple but novel control strategy is developed for Superconducting Magnetic Energy Storage (SMES) unit. The SMES unit is used to improve the dynamic performance of power system. The gain of the controller is determined depending on the power system and the capacity of the SMES unit. A simple delayed function is used to determine the desired power from the SMES unit. Eigenvalue analysis and computer simulation results show that the proposed controller is very robust in dealing different types of disturbances.

1. INTRODUCTION

During the past decade SMES Unit has attracted much attention from the researchers. Especially high temperature superconductor makes the SMES unit very attractive to the utility engineers. SMES systems have the capability of storing energy in their low resistance coils. This energy can be supplied to the power system by the SMES or received by it can be controlled by controlling the voltage across the inductor which eventually controls by the firing angles of the 12-pulse converter.

SMES has been used for different applications in power systems [1-12]. Some researchers have used the SMES unit for the improvement in power system dynamic performance[1-5]. It has also been used for the improvement in damping of subsynchronous oscillations[6-9]. Effect of SMES on Automatic Generation Control has also been investigated[10-12]. However, most of the SMES controllers fall under the following two categories:

- Proportional Integral (PI) / Proportional Integral Derivative (PID) controller
- Intelligent such as Fuzzy and Neural Network based controllers

The parameters of the PI or PID controllers are obtained by pole placement method. In case of intelligent controllers, most of the parameters are obtained on-line.

This paper introduces a novel idea of generating the compensating power from SMES unit by using a simple delay network. Pole placement technique is used to determine the gain of the controller. The controller is tested on a power system model and the results are compared to that of a PI controller.

2. SYSTEM MODEL

The power system shown in Fig. 1 comprises a synchronous generator connected to the infinite bus system through transmission line and a SMES unit at this generator terminal. The placement of the SMES unit is selected to achieve the best performance from it while improving the power system stabilization[2]. The power system is equipped with a governor and a static excitation system[2]. Without the SMES unit, there are 10 system state variables. The system is described by two-axis model[13]. Some important equations are given below:

\[ \dot{E}_d = \left[ -E_d^' - (X_q - X_d^') I_q \right] / T_d^\phi \]  
\[ \dot{E}_q = \left[ E_{FD} - E_q^' + (X_q - X_d^') I_d \right] / T_q^\theta \]  

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

\[ \dot{\phi} = \left[ P_m - D_\phi \dot{\phi} - P_e - P_{sm} \right] / M_\phi \]  
\[ \dot{\delta} = \omega - 1 \]

where \( P_{sm} \), \( D_\phi \), and \( M_\phi \) are the output power of the reheat steam turbine, damping coefficient and moment constant. \( P_e \) is the electromagnetic power transferred in the air gap. \( P_{sm} \) is stored power into the SMES. The terminal voltage which describe the relation between transmission line and generator are

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where \( V_t \) and \( V_e \) represent terminal voltage of the synchronous generator and infinite bus voltage respectively.

3. THE SMES UNIT AND ITS CONTROL STRATEGY

The SMES inductor-converter unit consists of a dc superconducting inductor, a 12-pulse cascaded bridge type ac/dc converter and a Y-Y/Δ step down transformer as shown in Fig. 2. Control of the converter firing angle (\( \alpha \)), provides the means for continuous variation of the bridge voltage \( V_{sm} \) over a wide range of positive and negative values. If losses are assumed negligible, then, in per unit [10],

\[
V_{sm} = \frac{V_{sm0}}{V_e} \cos \alpha - \frac{I_{sm}}{R_c} \quad \text{(8)}
\]

where \( \alpha \) is the delay angle

- \( V_{sm} \) is the per unit bridge voltage
- \( V_{sm0} \) is the no load per unit bridge voltage
- \( I_{sm} \) is the per unit bridge current, and
- \( R_c \) is the per unit commutating resistance

For this lossless case the current \( I_{sm} \) can be expressed as

\[
I_{sm} \frac{dI_{sm}}{dt} = V_{sm} \quad \text{(9)}
\]

![Schematic diagram of the SMES unit](image)

**Fig. 2**: Schematic diagram of the SMES unit

For “charging” at the maximum rate, \( V_{sm} \) should be held at its maximum value, which corresponds to rectifier operation with \( \alpha = 0 \). The current then builds up nearly as linear function of time until base current \( I_{sm} = 1.0 \) p.u. is reached. Then \( \alpha \) must be adjusted so that this normal or rated current is held constant. From (8), this corresponds to \( \alpha = 90^\circ \) for the normal operating conditions. At any time during the charging period, the stored energy is

\[
W_t = \frac{1}{2} L_{sm} I_{sm}^2 \quad \text{p.u.} \quad \text{(10)}
\]

With constant \( V_{sm} \), the inductor current \( I_{sm} \) can be expressed as

\[
I_{sm} = \frac{V_{sm}}{L_{sm}} t \quad \text{p.u.} \quad \text{(11)}
\]

which shows that the time variation of load current is linear for a superconductive load.

While in power system stabilization, the compensation \( P_{sm} \) provided by the SMES is continuously controlled depending on the sensed frequency deviation signal \( \Delta f \). The incremental change in the SMES power is given by

\[
P'_{sm} = \frac{K_{sm} \Delta f}{1 + sT_{dc}} \quad \text{(12)}
\]

where \( K_{sm} \) is gain of the control loop and \( T_{dc} \) is converter time delay.

The proposed control strategy is shown in Fig. 3. The gain of the controller \( K_{sm} \) can be determined by simulating a very large disturbance in the system. The maximum deviation in the system frequency can be obtained by two ways:

(i) if the system is unstable, then observe the maximum deviation before the system becomes unstable.

(ii) if the system is stable, then observe the maximum deviation in the simulation process.

Once the maximum value of the frequency deviation \( \Delta f_{\text{max}} \) is selected, the gain of the SMES controller can be calculated as

\[
K_{sm} = \frac{V_{sm, \text{max}} I_{sm, \text{max}}}{\Delta f_{\text{max}}} \quad \text{(13)}
\]

In the present study, the value of \( K_{sm} \) is found to be 172.5. When the system load increases the bus frequency falls. Consequently, a negative power \( P'_{sm} \), shown in equation (12) is consumed by the SMES unit.

![Superconducting magnetic energy storage unit control system](image)

**Fig. 3**: Superconducting magnetic energy storage unit control system

This means that a negative voltage is impressed across the inductor. The inductor current being unidirectional,
application of negative voltage across it results in withdrawal of energy.

Since the amount of stored energy is finite, the inductor current falls. In actual practice, the inductor current should not be allowed to reach zero to prevent the possibility of discontinuous conduction in the present of large disturbance[2,10]. To avoid such problems, the lower limit to the inductor current is set to 30% of $I_{sm0}$. It is desirable to set the rated inductor current $I_{sm0}$ such that the maximum allowable energy absorption equals the maximum allowable energy discharge. This makes the SMES equally effective in damping swings caused by sudden increase as well as decrease in load. Thus, if the lower current limit is chosen at 0.3 $I_{sm0}$, the upper inductor current limit, based on the equal energy absorption/discharge criterion becomes 1.38 $I_{sm0}$ [10] when $L = 0.5$ H and $W_{sm} = 4$ MJ. When the inductor current reaches either of these limits, the dc voltage has to be brought to zero.

4. DETERMINATION OF $K_P$ AND $K_I$

$$Y= CX$$

Where

$$X = \begin{bmatrix} \Delta \delta \Delta E_{d0} \Delta V_{st} \Delta E'_{d} \Delta E'_{q} \Delta P_m \Delta P_e \Delta P_h \\
\Delta P_0 \Delta U_{sm} \Delta V_{sm} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\
0 \\
0 \\
-38.46 \end{bmatrix}$$

$$U = V_{sm}$$

$$Y = \Delta \delta$$

$$C = \begin{bmatrix} 1 & 0 & \ldots & \ldots \end{bmatrix}$$

$$Y(s) = CX(s)$$

$$X^* = AX + BU$$

$$SX(s) = AX(s) + BU(s)$$

$$X(s) = (SI - A)^{-1}BU(S) = \frac{ST_u}{1 + ST_w} \begin{bmatrix} K_p & K_i \\
0 & S \end{bmatrix} Y(s)$$

$$\therefore X(s) = (SI - A)^{-1}B H(s) CX(S)$$

$$[I-C(SI-A)^{-1}BH(s)]X(s) = 0$$

The characteristic equation is

$$1-C(SI-A)^{-1}BH(s)=0$$

Substitution of $\lambda_i$

$$H(\lambda_i) = \frac{1}{C(\lambda_i I-A)B} = \frac{\lambda_i T_w}{1 + \lambda_i T_w} \begin{bmatrix} K_p & K_i \\
0 & \lambda_i \end{bmatrix}$$

$$I = C(\lambda_i I-A)^{-1}B \frac{\lambda_i T_w}{1 + \lambda_i T_w} \begin{bmatrix} K_p & K_i \\
0 & \lambda_i \end{bmatrix}$$

$$0 = \text{Imag}(XX)K_p + \text{Imag}(YY)K_i$$

$$\begin{bmatrix} 1 & \text{Real}(XX) & \text{Real}(YY) & K_p \\
0 & \text{Imag}(XX) & \text{Imag}(YY) & K_i \end{bmatrix}$$

$$K_p = \begin{bmatrix} \text{Real}(XX) \text{ Real}(YY) \end{bmatrix}^{-1} 1$$

$$K_i = \begin{bmatrix} \text{Imag}(XX) \text{ Imag}(YY) \end{bmatrix} 0$$

$$\because K_p = 45.99 \text{ and, } K_i = 376.4$$

5. EIGENVALUE ANALYSIS

Table 1 shows the system eigenvalues for two initial operating conditions. It can be seen that for $P_0 = 1.0$ p.u., the real part of the oscillatory mode is very small. The system has positive real parts with $P_0 = 1.2$ unit. However, the overall performance is improved with SMES unit. For both initial operating conditions, the real part of the electromechanical mode has been shifted significantly to a safe negative value when SMES unit is added. In order to examine the stability of the proposed controller at any other load conditions, the real part of the eigenvalues of the electromechanical mode is also studied. It is seen that the system is stable up to $P_0 = 1.128$ p.u., without the SMES unit. With the SMES unit, the system is highly stable even at $P_0 = 1.7$ p.u. The proposed controller extends the stability margin considerably.

6. COMPUTER SIMULATION AND PERFORMANCE ANALYSIS

In order to demonstrate the beneficial damping effect of the proposed controller, computer simulations based on system non-linear differential equations are carried out for different load conditions. Both small and large disturbances are considered. The differential equations are solved under MATLAB environment. All the non-linearities such as exciter ceiling voltage, SMES voltage limits, inductor current limits have been included.

The use of SMES unit for small disturbance has been studied. The disturbance considered is a three phase symmetrical fault near the infinite bus cleared after 0.1 sec with the post fault transfer impedance increased by 50%. It reflects a reduction in power transfer capability due to isolation of part of transmission circuitry. Figure 4 shows the system performance without SMES unit. We see that the system is oscillatory in nature without SMES unit. For comparison purposes, the performance of the traditional PI controller and the proposed controller is shown in fig.5. Figure 5 shows the system performances with the SMES unit following the large disturbance ($P_0 = 1.0$ p.u) with the proposed mode of control and that with the conventional PI controller. The damping of the system frequency is not satisfactory without the SMES unit. With the addition of SMES, the damping is improved significantly. At the initial period, the frequency deviation with PI and proposed controller are almost same. It is due to the delay time $T_{ds}$ which is accounted for the SMES power transfer to the system.

Table 1: System Eigenvalue
However, as the time increases, the proposed controller shows a clear edge over PI controller. Though both the controllers make use of the same maximum SMES power, but due to the efficient harnessing of the SMES power $P_{sm}$ by proposed one, a better performance is obtained. It is evident from the Fig. 5 that the settling time of the speed reduced substantially when the proposed controller is used.

In this paper, the SMES unit is applied for the improvement of power system damping. A simple control strategy for the SMES unit is applied. The damping of the synchronous generator is greatly improved by the SMES unit with proposed mode of control system. The simulation results show that the SMES performs better when equipped with the proposed controller. The power compensation of the SMES unit is directly obtained depending on the speed deviation, which makes it more sensitive to the disturbance. The scheme proposed in the present paper makes effective use of active power modulation of the SMES unit. Hence, its economic advantage is expected to be stronger than that of earlier schemes. The control strategy is simple and does not require heavy computation, therefore, implementation is feasible.

7. CONCLUSION

In this paper, the SMES unit is applied for the improvement of power system damping. A simple control strategy for the SMES unit is applied. The damping of the synchronous generator is greatly improved by the SMES unit with proposed mode of control system. The simulation results show that the SMES performs better when equipped with the proposed controller. The power compensation of the SMES unit is directly obtained depending on the speed deviation, which makes it more sensitive to the disturbance. The scheme proposed in the present paper makes effective use of active power modulation of the SMES unit. Hence, its economic advantage is expected to be stronger than that of earlier schemes. The control strategy is simple and does not require heavy computation, therefore, implementation is feasible.

REFERENCES:


APPENDIX

System data and initial conditions[2,13]
All parameters are expressed in p.u. unless stated otherwise.

Generator and transmission line
Base 160 MVA, 15 kV.   Generator 160 MVA, 15 kV, 0.85 p.f. Exciter 375 V, 926 A
\[
\begin{align*}
X_d & = 0.245  \quad X_q = 1.64  \\
X_d & = 1.70  \quad X_q = 1.64  \\
R_a & = 0.001096  \quad M_g = 4.74  \\
D_g & = 0  \quad R_e = 0.02  \\
T_{q0} & = 0.075 s  \quad T_{d0} = 5.9 s
\end{align*}
\]

SMES Unit [6]
\[
\begin{align*}
I_{sm0} & = 0.6495 \text{ p.u}  \quad V_{sm0} = 0 \text{ p.u}  \quad L_{sm} = 0.5 \text{ H} \\
W_{sm0} & = 6.0 \text{ MJ}  \quad T_{dc} = 0.026 \text{ secs}
\end{align*}
\]