# Linearization of Generator Power Swing Property by Controlling Power Output of SMES for Enhancement of Power System Stability

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***Abstract*—This paper proposes a control scheme to achieve a robust power system stabilization by a Superconducting Magnetic Energy Storage (SMES). The control applied in this study is to linearize the power swing property by the active power control of SMES. The control is robust in the sense that the effect is not affected by the changes of the power system configuration, the operating condition and so on. As a result the power system stability in the transient state as well as in the steady state is significantly improved. Some numerical studies demonstrate the distinguished effect of the SMES using the proposed control scheme on the power system stabilization in comparison with the SMES using the conventional feedback control of generator speed deviation.**

## I. Introduction

Development of effective ways to utilize transmission systems to the maximum thermal capacities has attracted much attention from power system engineers in recent years. Superconducting Magnetic Energy Storage (SMES) has been expected to be a significantly effective tool to enhance the power system stability since the SMES is capable of providing the active and reactive power simultaneously and quickly for the power system[1]–[3]. In most control schemes the feedback control of the generator speed or frequency deviation is used to damp the power swing of generator, where the controller is designed using a power system model linearized around an operating point. However, there arises a problem that the effect diminishes with the changes of the power system configuration, the operating condition and so on[4], [5]. Tan *et al.* [1] developed an adaptive control taking account of the power system nonlinearities, which is based on the nonlinear control theory.

In this paper a more straightforward strategy with robustness has been developed using the real and reactive power control ability of the SMES. It is well known that the SMES is capable of controlling the active power flow into power systems. By substituting the control objective it is expected that the generator power is directly controlled to follow the specified reference signal. According to this scenario the power swing property of generator is virtually linearized by giving a reference signal to achieve a linear aspect independent of the power system condition. As a result the controller is designed from the viewpoint of eigenvalue assignment. First, the capability of direct generator power control by the SMES has been numerically confirmed by giving a sinusoidal reference. The direct power control is applied to linearization of power swing property. Thus, the power system stabilizing control based on the eigenvalue assignment is designed. Some numerical studies demonstrate the significant effect of the SMES with the proposed control scheme on the power system stabilization in comparison with the SMES using the feedback control of generator speed deviation[3].

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## II. Feasibility Study for Controller Design

Fig.1 shows the typical configuration of the SMES, which is composed of a twelve pulse thyristor bridge and a superconducting magnet. By controlling the firing angles properly, the active and reactive power output can be adjusted simultaneously. The use of self-commutated devices like GTOs guarantees wide range of active and reactive power control. Development of a PWM control with a self-commutated inverter has built up simultaneous control of the active and reactive power at high MVA levels with less harmonics. In this paper it is assumed that the SMES is capable of controlling the active and reactive power independently.

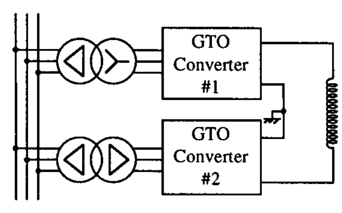


Fig. 1. Typical configuration of the SMES.

Consider a single-machine-infinite-bus system with a SMES located at the generator terminal shown in Fig.2. The swing equations of generator are represented by (1), (2) and (3), where the resistance is ignored for the sake of brevity. Note that the nonlinearity due to a trigonometric function appears only in (3).

$$\frac{M}{\omega_0}\frac{d^2\delta}{dt^2}+\frac{D}{\omega_0}\frac{d\delta}{dt} = P_m - P_e \qquad (1)$$

$$P_e = P_L - P_{SM} \qquad (2)$$

$$P_L = \frac{V_t V_b}{X_L}\sin\delta_t \qquad (3)$$

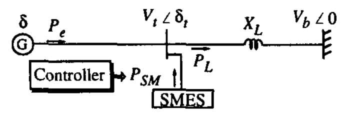


Fig. 2. Generator power control by SMES.

Transient stability of power system is often discussed on the power angle curve. Here, the control effect of the SMES is evaluated in the power angle curve. Fig.3 shows an example of power angle curve shifted by the SMES active power $P_{SM}$ within the controllable boundary $-P_{SMmax} \leq P_{SM} \leq P_{SMmax}$. Since the speed of power control by the SMES is much faster than the movement of the generator rotor $\delta$ during power swing, the generator output power $P_e$ may be adjustable for every $\delta$ by the SMES within the hatched region in Fig.3. Thus, it is expected that the generator power is directly controlled during the power swing after some disturbance.

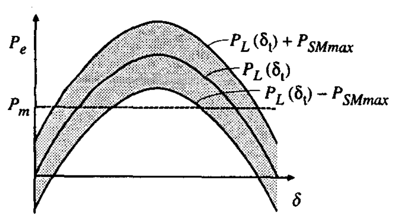


Fig. 3. Power angle curves shifted by the SMES active power.

## III. Control Scheme for Linearization of Power Swing

The swing equation (1) is rewritten with the accerelating power $P_a$ which represents $P_m - P_e$.

$$\frac{M}{\omega_0}\frac{d^2\delta}{dt^2}+\frac{D}{\omega_0}\frac{d\delta}{dt} = P_a \qquad (4)$$

The nonlinearity of power system is included only in $P_a$. Here, suppose that $P_a$ in (4) is directly controlled by the SMES and the reference signal $P_a^*$ for $P_a$ is given by

$$P_a^* = \frac{M}{\omega_0}\beta_1(\delta-\delta_0) + (\frac{M}{\omega_0}\beta_2 + \frac{D}{\omega_0})\frac{d\delta}{dt} \qquad (5)$$

where $\delta_0$ is $\delta$ at the operating point.

Ignoring the time delay between $P_a$ and $P_a^*$, which implies that $P_a = P_a^*$, (4) is linearized as

$$\frac{d^2\delta}{dt^2} - \beta_2\frac{d\delta}{dt} - \beta_1(\delta-\delta_0) = 0 \qquad (6)$$

The control gains $\beta_1$ and $\beta_2$ can be specified according to the eigenvalue assignment method based on the linear second order differential equation (6).

Here, two important issues are still unsolved. 1) How to observe the signal $P_a$ which includes the variation of mechanical power $P_m$, some uncertain DC bias due to the change of operating condition and some uncertain dynamics due to electrical responses of armature winding, damper winding and so on. 2) How to realize the direct power controller for $P_a$ to follow $P_a^*$ during the transient status of power system after some disturbance. The first issue can be solved by using a band pass filter to obtain the power swing signal whose frequency is around 1 [Hz] since the dynamics of $P_m$ controlled by governor systems are slower and the oscillations due to the response of armature winding and damper winding have much higher frequencies than that of power swing. As a result the control object for the direct power control is produced by

$$\tilde{P}_a = -\frac{1}{1+0.0265s}\frac{1.59s}{1+1.59s}P_e. \qquad (7)$$

The second issue is realized by the proportional feedback control

$$P_{SM} = -K_{PL}(\tilde{P}_a - P_a^*) \qquad (8)$$

because it is qualitatively explained that the generator power $P_e$ is increased and decreased by absorbing and supplying the SMES power $P_{SM}$, respectively (See Fig.3).

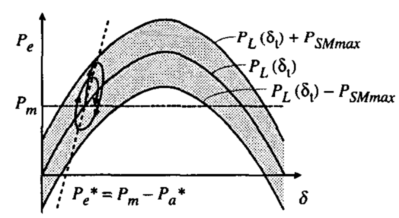


Fig. 4. Schematic image of linearizing control in power angle curve.

The effect of the proposed control can be schematically explained in the power angle curve shown in Fig.4. The generator power is fundamentally controlled to follow the linear $P_e - \delta$ line depicted as $P_e^*$. The power system has a sufficient damping specified by the $\beta_1$ and $\beta_2$ in (6) after the proposed control is applied. Therefore, the locus in the power angle curve becomes a clockwise spiral around $P_e^*$ and finally converges into the equilibrium point with stable dynamics specified by the eigenvalues. Since the generator power is regulated to follow the linear line $P_e^*$ whose gradient is larger than that of $P_e$ at the operating point, the power system gains a large amount of decelerating energy just after a large disturbance which is effective to enhance the transient stability. Thus the proposed control should be effective for the transient stability as well as steady state stability.

In the control of the SMES the reactive power is still available. Here the reactive power $Q_{SM}$ is applied to the

TABLE I
SYSTEM CONSTANTS.

| |
|---|
| Generator (Park's 5-th order model, 1,170 MVA base) |
| $X_d = 1.60$ $X_{ad} = 1.35$ $X_{ffd} = 1.44$ $X_{kkd} = 1.38$ |
| $X_q = 1.60$ $X_{aq} = 1.35$ $X_{kkq} = 1.37$ |
| $R_a = 0.00181$ $R_{kd} = 0.00620$ $R_{kq} = 0.0124$ $R_{fd} = 0.0006$ |
| $M = 7.78$ s $D = 2.00$ |
| Transmission system (5,850 MVA base) |
| $X_t = 0.197$ $X_L = 0.449$ $R_L = 0.0463$ $X_s = 0.193$ |

constant voltage control according to the control scheme

$$Q_{SM} = -K_V \Delta V_t. \tag{9}$$

## IV. Simulation Results

The configuration of a model power transmission system used for simulation study is shown in Fig.5. The details of control schemes are also shown in Fig.5. The power plant with five identical 1,170 MVA generators is represented as a single 5,850 MVA machine with an AVR. The Park's model including an armature winding, damper windings in d and q axes, a field winding and a set of swing equation are used to describe the dynamics. The generator is connected to a large power system through a 500 kV and 100 km double circuit transmission line. System constants are shown in Table I.

The SMES unit located at the generator terminal is modeled as active and reactive sources with delays represented by the first order time lags

$$P_{SMo} = 1/(1 + 0.01s)P_{SM} \tag{10}$$
$$Q_{SMo} = 1/(1 + 0.01s)Q_{SM} \tag{11}$$

where $P_{SMo}$ and $Q_{SMo}$ are the actually controlled active and reactive power.

First, the capability of direct control of generator power by the SMES is confirmed. A sinusoidal variation has been

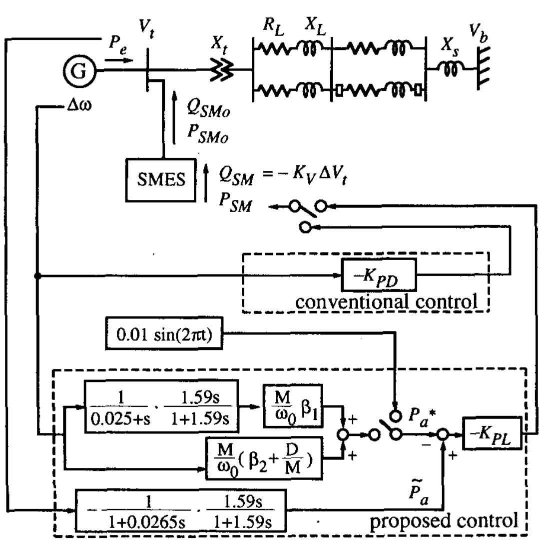


Fig. 5. Long distance bulk power transmission system with SMES.

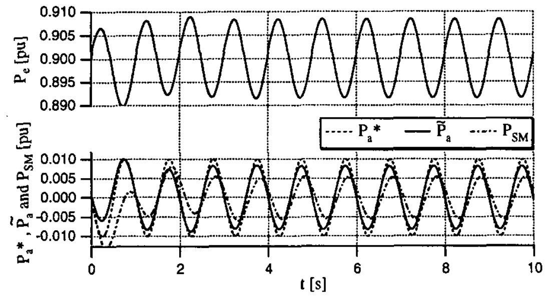


Fig. 6. Result of generator power control by the SMES.

given as a power control reference $P_a^*$, that is

$$P_a^* = 0.01\sin(2\pi t) \tag{12}$$

which has the frequency corresponding to the power swing. The result of control is shown in Fig.6, where $K_{PL} = 3.0$ and the gain $K_V$ of voltage control by reactive power control is 2.0. The generator power is effectively controlled to follow the specified sinusoidal waveform.

The relation $\tilde{P}_a \approx P_a^*$ is confirmed by this investigation and it is ready to carry out the linearizing control by substituting the sinusoidal signal with (5) as the reference $P_a^*$, where $(\delta - \delta_0)$ in (5) is substituted by

$$\delta - \delta_0 = \frac{1}{0.025 + s}\frac{1.59s}{1 + 1.59s}\Delta\omega \tag{13}$$

to eliminate the DC bias component and to produce $\Delta\delta$ approximately from $\Delta\omega$. As a result, $P_a^*$ given here is represented by

$$P_a^* = \frac{M}{\omega_0}\{\beta_1\frac{1}{0.025 + s}\frac{1.59s}{1 + 1.59s} + (\beta_2 + \frac{D}{M})\}\Delta\omega \tag{14}$$

The control gains $\beta_1$ and $\beta_2$ have been determined in such a way to assign the eigenvalues in (6) at $-1.0[1/s] \pm j2\pi[rad/s]$. The imaginary part is specified so as to enhance the synchronizing torque. As a result the control gains $\beta_1$ and $\beta_2$ are calculated as $-40.5$ and $-2.0$, respectively. A voltage drop from 1.0 [pu] to 0.8 [pu] during 4 [cycles] at the infinite bus is given as a system disturbance. The control is activated right after the fault. In Fig.7 $\tilde{P}_a$ and $P_a^*$ are compared, where both signals coincide with each other. Fig.8 shows the effectiveness of the proposed control. A control scheme by the conventional feedback control represented by

$$P_{SM} = -K_{PD}\Delta\omega, \quad K_{PD} = 20.0 \tag{15}$$
$$Q_{SM} = -K_V\Delta V_t, \quad K_V = 2.0 \tag{16}$$

has been applied for comparison.

The proposed control stabilizes the power swing effectively as it has been expected from the control specifications given as eigenvalues. Since the synchronizing torque as well as the system damping have been specified in the case of proposed control, the peak value of $\delta$ during the

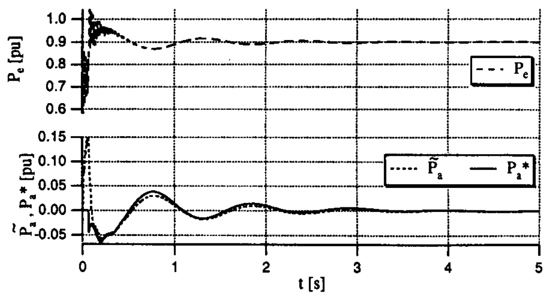


Fig. 7. Regulated generator power.

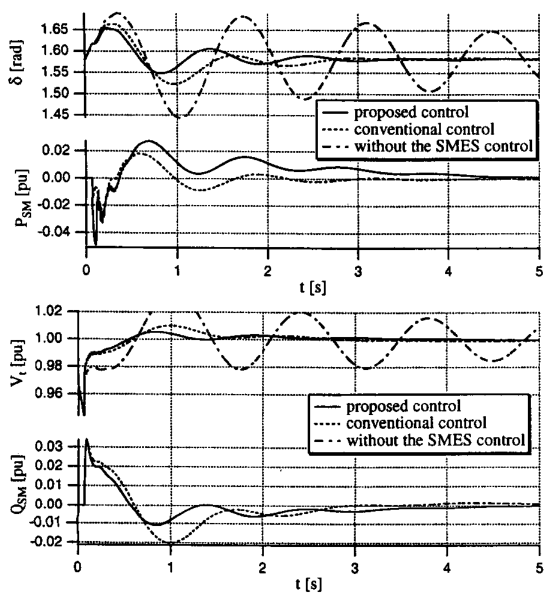


Fig. 8. Dynamic responses of the system.

initial transient is reduced more significantly than the case of conventional feedback control. The SMES with proposed control quickly absorbs the active power to follow the desired linear line $P_e^*$ (see Fig.4) after the fault, which effectively works on the transient stability. The fluctuation of generator terminal voltage is effectively suppressed by the reactive power independently of the active power control.

In a further simulation, the line reactance and resistance are 50% increased as a new operating condition in order to demonstrate the robustness of the control scheme. This operation corresponds to the case that one of double circuit is opened in a certain section of transmission line. The system disturbance is the same voltage drop at the infinite bus. The results are shown in Fig.9. The generator loses its synchronization after the disturbance without SMES. The period of power swing becomes larger, when the SMES is not installed, which implies that the synchronizing torque has decreased. The SMES with conventional feedback control gains a large damping torque and not a synchronizing torque. The SMES with proposed

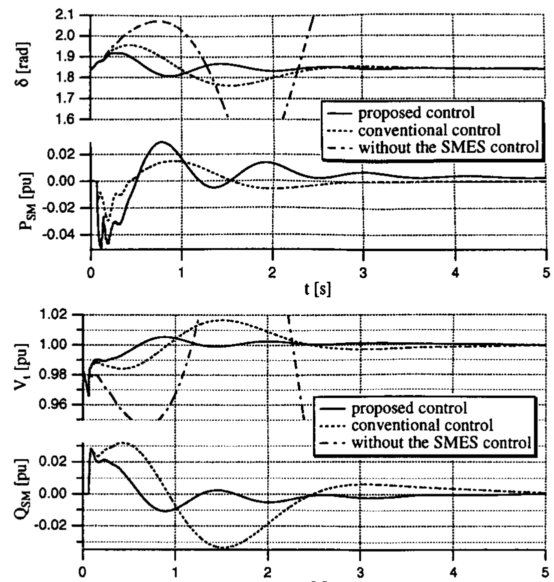


Fig. 9. Dynamic responses of the system at the heavy power flow case.

control remains very effective with specified damping and synchronizing torque.

## V. Conclusions

In this paper a robust power system control scheme by the SMES, is proposed. Since the power swing property is virtually linearized by the direct control of power flow with the active power of SMES, the control specifications are given as desired eigenvalue assignments which are independent of the power system condition. Numerical results demonstrate that the proposed control is robust in the sense that the control parameters do not have to be readjusted even if the operating condition is much changed. It has been confirmed that the transient stability as well as the steady state stability is significantly improved by the SMES with proposed control.

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