# Power Control by Superconducting Magnetic Energy Storage for Load Change Compensation and Power System Stabilization in Interconnected Power System

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***Abstract*—This paper describes a load change compensation by a superconducting magnetic energy storage (SMES) which is assumed to be installed in a power system for power system stabilization. A simultaneous control strategy of SMES for load change compensation as well as for power system stabilization in a longitudinally interconnected power system is derived. Several numerical examples demonstrate the significant effectiveness of the SMES.**

## I. Introduction

A typical configuration of superconducting magnetic energy storage(SMES) consists of a superconducting magnet and a set of power converters. The SMES connected to an appropriate bus in a power system through the power converters is capable of controlling active and reactive power simultaneously at the bus[1]. This control capability has been applied to power system controls; power system stabilization[2], [3], load frequency control[4], the load leveling[5] and so on.

On the other hand, in a longitudinally interconnected power system, it is a problem that long term and undamped power oscillations tend to occur due to the power swings between some groups of generators. In addition to the stability problem, various kinds of apparatus with large and pulsive power consumptions are increasing in the power system; for typical examples, a magnetic levitation transportation, a testing plant for nuclear fusion, a steel manufacturing plant and so on. Under the situation, it may be difficult for governor systems to absorb the frequency deviation. Moreover, as the frequency of load change becomes higher it approaches to the natural frequency of power swing mode. As a result, the mode resonating to the load change may cause a large power oscillation.

SMES is an apparatus which is capable of solving these problems. However, simultaneous effectiveness for different purposes of power system controls by SMES has not been clear since the effectiveness depends on its location in the power system. In this study, a control strategy for load change compensation by a SMES located at the end bus of an interconnected power system for the stabilization of long term power swing, is derived. The control scheme of the SMES and the effect of the distance between changing load and the SMES are evaluated in detail for the different values of load change frequency.

Numerical studies using a longitudinally interconnected power system model with six identical generators demonstrate the significant effectiveness for load change compensation and for power system stabilization by the SMES.

## II. Power System Modes and Dynamic Characteristic of Power System

Fig.1 shows a longitudinally interconnected power system model with six identical generators. Each generator corresponds to a 10,000MVA power system. Fig.2 shows the characteristics of an automatic voltage regulator (AVR) and a governor system. In general the governor model for the analysis of load control is described more in detail. However, the characteristic of the governor used here is simply represented by a first order time lag, since the load change compensation by the SMES aims at a quick load change which is difficult to be followed by the governor system.

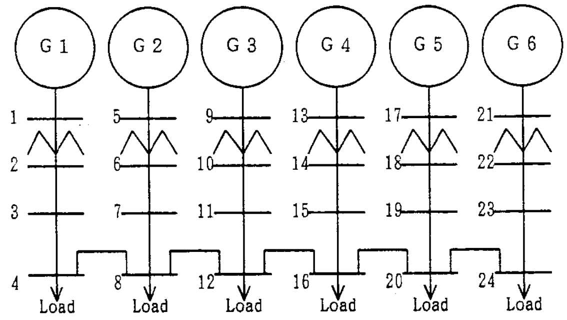

Fig. 1. Model power system.

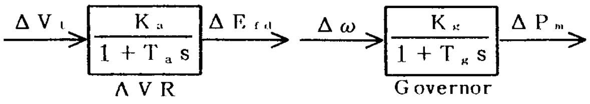

Fig. 2. Block diagrams of AVR and governor.

Manuscript received October 16, 1994

TABLE I

Behavior of eigenvalues for two different power flow conditions.

| Light flow case | Heavy flow case |
|---|---|
| -0.331 + j7.56 | 0.025 + j5.72 |
| -0.532 + j8.91 | -0.312 + j7.38 |
| -0.577 + j9.21 | -0.381 + j7.79 |
| -0.593 + j9.31 | -0.407 + j7.94 |
| -0.599 + j9.35 | -0.417 + j8.00 |

Dynamic characteristics of the power system are evaluated for the following two different power flow conditions:

1) output power of each generator and consumed power of each load are equal to 1.0[pu] (heavy flow case).
2) output power of each generator and consumed power of each load are equal to 0.5[pu] (light flow case).

In each case the eigenvalues of the linearized system are evaluated. The result is shown in TableI. This system has a power swing mode with a long period which becomes unstable as the power flow becomes heavier. This mode is the cause of the oscillation between both ends of the power system, which is well-known in a longitudinal power system. According to [6] it is effective to locate a SMES at the end of longitudinal structure for the purpose of stabilization. Therefore, it is assumed in this study that the SMES has been located at the bus 24 for the purpose of power system stabilization. The SMES is modeled as an apparatus which is able to control active and reactive power simultaneously. According to [1] the SMES can be represented by a model with first order time lags, where the time constants are set at 0.03(s). Equations (1) and (2) are used as a power system control scheme by the SMES where$\Delta P_s$ and $\Delta Q_s$ are the specified active and reactive power.

$$\Delta P_s = -K_{PD}\Delta\omega - \Delta P_L \qquad (1)$$

$$\Delta Q_s = -K_{QD}\Delta V_S \qquad (2)$$

Equation (1) consists of two types of controls. The first term is applied for power system stabilization using the deviation of angular velocity of generator 6 ($\Delta\omega$). The second term is applied for load change compensation using the deviation of load change ($\Delta P_L$ ). Equation (2) is applied for voltage control using the deviation of the bus voltage where the SMES is located($\Delta V_S$ ). $K_{PD}$ and $K_{QD}$ are the control gains. The effect of the distance between the changing load and the SMES on load change compensation is evaluated for different locations of the load at the bus 24, 20, 16 and 4 while the location of the SMES is fixed at the bus 24. The load change is represented by the following time function with a single frequency,

$$P_L = P_A \sin(2\pi f t) \qquad (3)$$

where the frequency of load change f and the magnitude $P_A$ are set as parameters.

## III. Load Change Compensation by The SMES

Here the effectiveness of only the load change compensation by SMES, is evaluated for the different locations of changing load. The control scheme of the SMES used here is represented by (1) and (2), where both $K_{PD}$ and $K_{QD}$ are set at 0. The light flow case is assumed in order to evaluate the effectiveness of load change compensation under the condition that the power system is stable.

The maximum magnitude of the oscillation of generator angular velocity caused by the load change is calculated in each case of load locations, that is, the correlation between the effectiveness of load change compensation and the distance from the SMES, is evaluated.

### *A. In The Case of Load Change Frequency Below The Natural Frequency of Power System*

It is assumed here that the load change frequency is below the natural frequency of the power system. Parameters of the changing load in (3) are set as $P_A$ =0.015(pu) and $2\pi$f=0.8(rad/s). Fig.3 summarizes the results of calculating maximum magnitudes of the oscillations of generator angular velocities caused by the load change.

Concerning the case without the SMES, only the result that the changing load is located at bus 24 is shown in Fig.3 since the other results are quite similar to each other independent of the location of changing load. In the case with the SMES, the effectiveness is also independent of the location, and the oscillation of the power system becomes much smaller even if for the case where the changing load is located at bus 4 which is most distant from the SMES. An example of simulated swing curves is shown in Fig.4, where the changing load is located at bus 16.

In the case without SMES, all the generators are oscillated in phase with the load change. Note that the result is independent of load location. Similarly the control with SMES is always effective for suppressing the power oscillation independent of the load location.

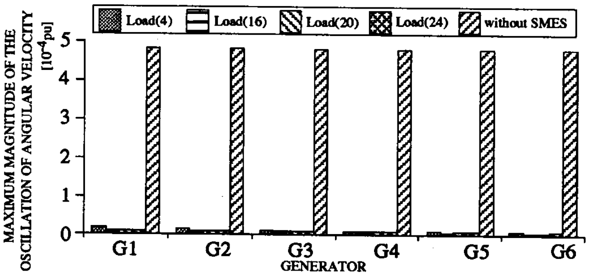

Fig. 3. Maximum magnitudes of the oscillations of generator angular velocities caused by load change for different locations of load change.

(Load(n) denotes that the changing load is located at the bus n.)

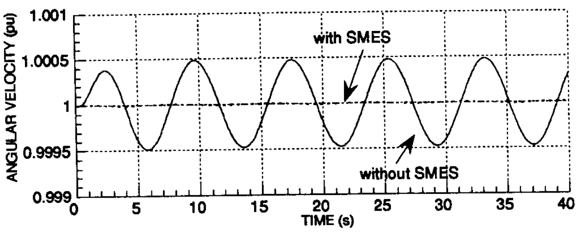

Fig. 4. Simulated wave forms.

(The power swings of all the generators are almost equal to each other.)

### *B. In The Case of Load Change Frequency in The Vicinity of The Natural Frequency of Power System*

It is assumed here that the frequency of the load change is equal to the frequency of a long term power oscillation mode. Parameters of the changing load in (3) are set as $P_A$ =0.005(pu) and $2\pi$f=7.6(rad/s). Fig.5 shows the maximum magnitude of the oscillation of generator angular velocity caused by the load change in the case without SMES.

The power oscillation mode with the longest period resonates to the load change. As a result the oscillation between the generators at the ends of the power system becomes large, and as the location of load change moves to the ends of the power system, the power swing caused by the load change grows larger.

Fig.6 shows the maximum magnitudes of the oscillations of generator angular velocities caused by the load change when the SMES is located at bus 24. The power oscillations become larger as the distance between the changing load and the SMES becomes longer. By comparing Fig.5 with Fig.6 it is clear that the oscillation of the generators located at the ends of the power system is larger in the case with SMES than without SMES, when the changing load is located at bus 16 or 4. Fig.7 shows a set of simulated swing curves in the case that the changing load is located at bus 16. An oscillation between generator 1 and generator 6 is observed in Fig.7, which is different from the result in Fig.4 where all the generators oscillate in phase following the load change. The load change compensation by the SMES causes an unnecessary oscillation between the generator 1 and 6 although the oscillation of generator 4 is suppressed.

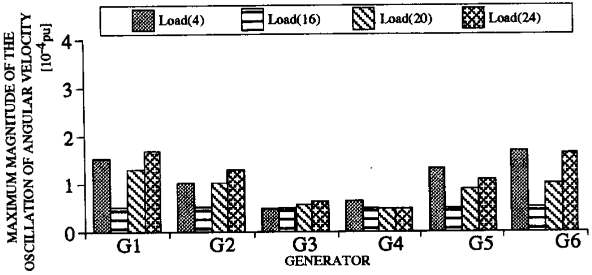

Fig. 5. Maximum magnitudes of the oscillations of generator angular velocities caused by load change for different location of load change (without SMES).

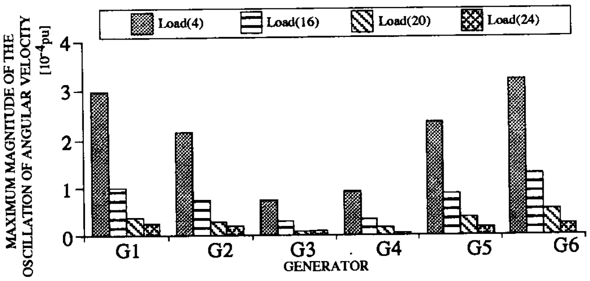

Fig. 6. Maximum magnitudes of the oscillations of generator angular velocities caused by load change for different location of load change (with SMES).

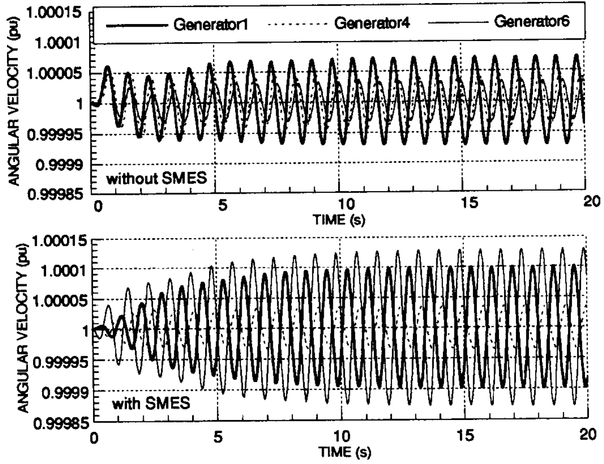

Fig. 7. Simulated wave forms.

When the load change frequency is equal to a natural frequency of the power system, the load change compensation by the SMES in which the active power is injected into the power system in reverse phase against the load change, is not always effective. Let us now consider the control scheme where $K_{PD}$ and $K_{QD}$ are not set at zero, respectively. In this scheme there is an additional feedback of the deviation of the angular velocity. This scheme should be effective for stabilization, because it enhances damping of the electoro-mechanical mode and therefore the resonance is expected to be suppressed. Here, the parameters of the control scheme in (1) and (2) are set as $K_{PD}$=50 and $K_{QD}$=1. Fig.8 shows the results of calculating the maximum magnitude of oscillation of the angular velocity of generator 6.

When the deviation of the angular velocity is used, i.e., the control scheme is represented by $\Delta P_L + \Delta\omega$ control, the load change is always compensated for more effectively than by the control using only the deviation of load change, which is represented by $\Delta P_L$ control. These result in the conclusion that the SMES suppresses the generator oscillations following the load change effectively by the

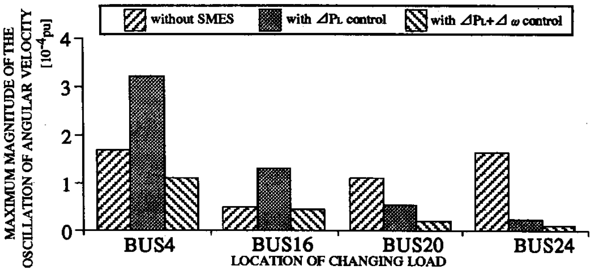

Fig. 8. Maximum magnitudes of the oscillation of angular velocity of generator 6 caused by load change for different control schemes of SMES.

addition of the $\Delta\omega$ feedback control to the load change compensation, even in the case that the SMES is located far from the load.

## IV. EFFECTIVENESS OF THE POWER SYSTEM STABILIZATION

Here, the effectiveness of the SMES for power system stabilization is to be confirmed. It is assumed that a disturbance occurs in the power system while the SMES is operating for load change compensation. The heavy flow case is used, which implies that the power system is unstable without the SMES. The changing load assumed here consists of three different components in the frequency domain, one of which has a frequency corresponding to the long-term power swing mode (see Table.I) as follows.

$$P_L = 0.015\sin(0.8t) + 0.0075\sin(2.5t) + 0.005\sin(5.7t) \tag{4}$$

The changing load is located at bus 20. The control scheme of the SMES used here is the $\Delta P_L + \Delta\omega$ control. The assumed disturbance is that one of the double circuit line 23-24 is suddenly opened. The load change starts at t=0(s). The system disturbance is applied at 15.25(s) when the angular velocity of the generator 6 reaches the maximum value for load change compensation, which is expected to give an additional disturbance to the power system. Fig.9 shows the swing curves of the angular velocity of generator 6.

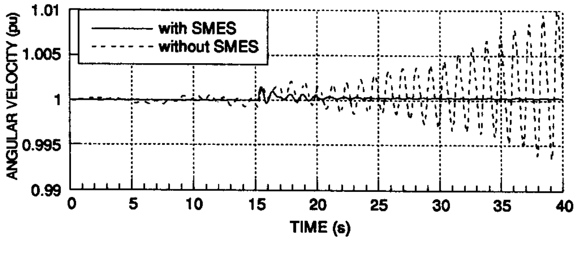

Fig. 9. Simulated wave forms.

In the case without SMES, the power oscillation caused by the load change is large and grows rapidly after the disturbance. When the control with SMES is applied, the load change is effectively compensated for in the heavy flow case and the power oscillation is effectively stabilized as well after the disturbance.

## V. CONCLUSION

In this paper a control strategy for a SMES installed for the purpose of power system stabilization in a longitudinally interconnected power system, is described. The effectiveness of the SMES for load change compensation is evaluated under the assumption that the SMES for power system stabilization is installed at the end of the power system. The SMES which has a control scheme to inject power into the power system in reverse phase against the load change, is always effective for load change compensation independently of the location of the changing load as long as the frequencies of the load change exist far below the natural frequencies of power swings. When a load change frequency is in the vicinity of the natural frequency of a power swing, however, the SMES may cause an unnecessary disturbance to the power system when the changing load is located far from the installed SMES. The problem has been solved by adding a damping control using the angular velocity of the generator located at the end of the power system. The effectiveness of the simultaneous control by the SMES with the proposed control scheme, has been demonstrated by a digital simulation using a six machine longitudinally interconnected power system model.

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