# Stabilizing Control for Power Systems by Means of Superconducting Magnetic Energy Storage

By

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**Abstract**

This paper represents the stabilizing control for electric power systems by means of the superconducting magnetic energy storage (SMES). After describing the concept of stabilization by the SMES, using the simplest power system model, we show a method for analyzing a more complex model of power systems including the SMES. As for the stabilizing control methods, we propose the bang-bang control of the control angle $\alpha$ of the SMES thyristor bridge, and the control of $\alpha$ by the feedback of the angular velocity deviation $\Delta\omega$ of the generator rotor. We then apply them to a one-machine infinite-bus system to examine their effects. After that, the system's damping effects of the feedback control of the SMES on a multi-machine system are investigated, using a sample 10-machine system. Lastly, the relationship between the SMES location and the damping effect is discussed.

## 1. Introduction

Electric power systems are continuously growing in size in order to supply the increasing power demand of electric power with high quality. Accordingly, the thermal and nuclear power stations have become very large in their capacity. It is difficult for these large generators to change their output, and a constant power operation is desirable from the viewpoint of efficiency. On the other hand, the difference of power demand between day and night is increasing every year. Therefore, electric power storages are needed for peak-shaving and load-leveling. At present, only pumped-storage systems are practically used for that purpose.

Meanwhile, progress in superconductive technology has developed superconducting coils which can carry a very large current without any loss. A method for storing energy by superconducting coils after converting electric energy into magnetic energy has been proposed and investigated intensively. The Superconducting Magnetic Energy Storage (SMES) has yet many technical problems to be solved, but it has the advantage that the total efficiency exceeds 90 %, while

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that of pumped-storage is something like 70 %. Furthermore, there is the possibility of damping the power system oscillation and decreasing the frequency fluctuation by means of an appropriate control of the SMES power in case of system disturbances. This is due to the quick controllability of the SMES power by means of charging or discharging.

This paper represents the stabilizing control of an electric power system by means of the SMES. First, the concept of stabilization by the SMES is described, using the simplest power system model. Next, a method for analyzing a more complex model of power systems, including the SMES, is shown. For the system stabilization control, we propose the bang-bang control of the control angle $\alpha$ of the SMES thyristor bridge, and the control of $\alpha$ by the feedback of the angular velocity deviation $\Delta\omega$ of the generator rotor. We then apply them to a one-machine infinite-bus system to examine their effects. Furthermore, the system's damping effects of the feedback control of the SMES on a multi-machine system are investigated, using a sample 10-machine system. Finally, the relationship between the SMES location and the damping effect is discussed.

## 2. Concept of Stabilizing Power Systems by SMES[1]

The SMES can be charged with electric power or discharged by means of a thyristor bridge operated as a rectifier or an inverter, respectively. The time required to reverse the operation is very short; about 1 cycle.[2] Therefore, the SMES can dampen the power system oscillation by absorbing electric power when the generator accelerates, and releasing it when the generator decelerates. In order to suppress the generator's acceleration by consuming electric power in case of system faults, damping resistors are practically used today. We can consider that the SMES is a damping resistor which can take a plus or minus value. Fig. 1 shows the stabilizing effect of the bang-bang control of a damping resistor on

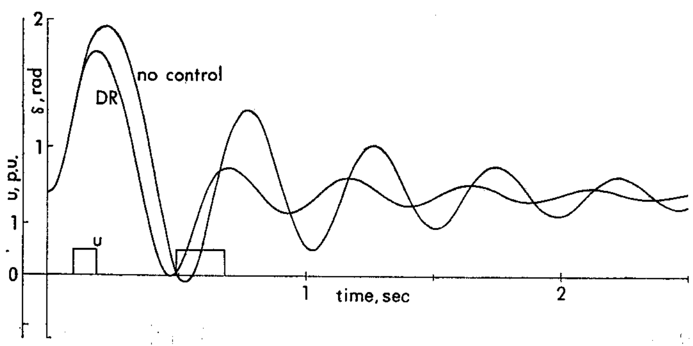



Fig. 1. Bang-bang control of damping resistor.

a one-machine infinite-bus system, where the electric power consumed at the generator terminal was assumed to be arbitrarily controllable without any time-lag. The effect of the bang-bang control of the SMES is shown in Fig. 2. The stabilizing effect of the SMES is greater than that of the damping resistor, be-

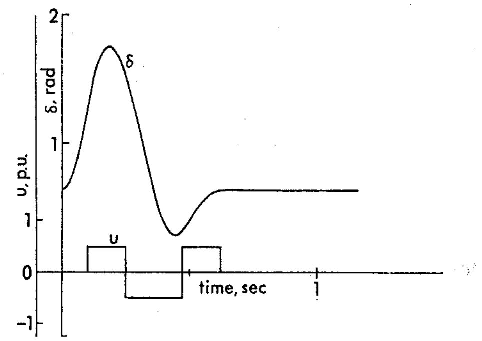
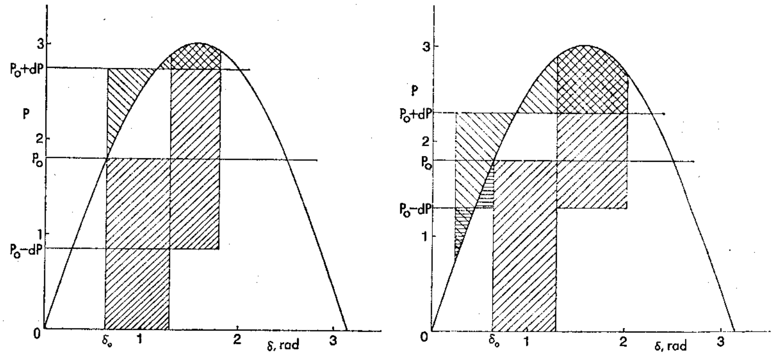
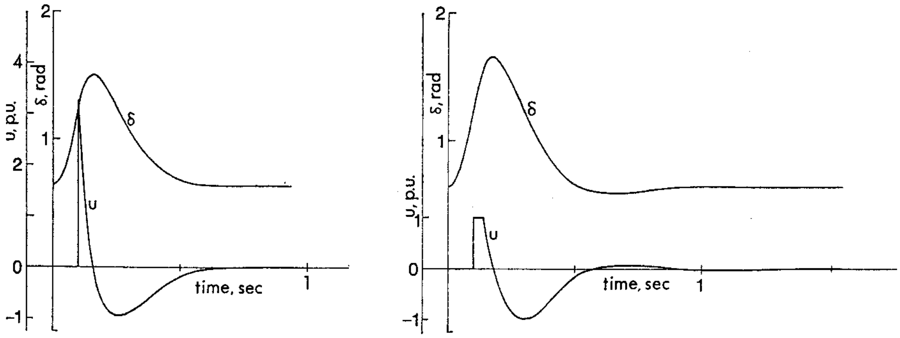



Fig. 2. Bang-bang control of SMES.




(a) two switchings (b) three switchings

Fig. 3. Equal-area criterion for bang-bang control of SMES.




(a) no-restriction (b) $|u| \leqq 1.0$ p.u.

Fig. 4. Continuous optimum control of SMES.

cause the SMES can give electrc power when the generator decelerates. As shown in Fig. 3, by using the equal-area criterion, the equilibrium can be attained after two switchings, i.e. charge-discharge, when the power of the SMES is large. However, when it is small, three switchings (charge-discharge-charge) are needed. Fig. 4 shows the result of the continuous optimum control of the SMES, which minimizes the performance index of a quadratic form.

## 3. Method of Analyzing Power Systems with SMES

As mentioned before, the electric energy is stored in the SMES after being transformed into dc from ac by means of a thyristor bridge. Therefore, during the load-flow or transient calculation of power systems with the SMES, it is advisable to represent the SMES by an equivalent admittance, just as for ac-dc interconnected power systems. The equivalent admittance is determined from the active power of the SMES, $P_d$, the reactive power $Q_d$ and the ac side terminal voltage $v_t$. In this section, we describe the $P$-$Q$ characteristics of the SMES, the derivation of the equivalent admittance of the SMES, and the procedures for a load-flow calculation and a transient calculation.

### 3.1 P-Q Characteristics of SMES and its Equivalent Representation

Fig. 5 shows the conceptual scheme of the SMES. If the loss can be neglected, the voltage of the superconducting coil $E_d$ is represented as follows.

$$E_d = E_d' \cos \alpha - I_d X_c / 2 \qquad (1)$$

where $E_d'$ : coil voltage under no-load and no-control
$I_d$ : coil current
$\alpha$ : control angle of thyristor bridge
$X_c$ : commutating reactance

Letting $L$ denote the inductance of the coil, the change of the current is governed by the following differential equation.

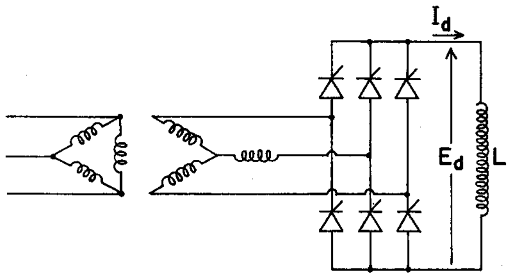



Fig. 5. Conceptual scheme of SMES.

$$L\frac{dI_d}{dt} = E_d \tag{2}$$

The stored energy $W_L$ is given by

$$W_L = L\,I_d^2/2 \tag{3}$$

Therefore, the power $P_d$ is represented as follows:

$$P_d = \frac{dW_L}{dt} = L\,I_d\frac{dI_d}{dt} = I_d\,E_d \tag{4}$$

As the no-load, no-control coil voltage $E_d'$ is proportional to the ac side terminal voltage, selecting a suitable base value leads to $E_d'=v_t$ in the per-unit representation. The per-unit value of the current $I_d$ is identical on the ac side and the dc side. Hence, the apparent power $W$ and the reactive power $Q_d$ at the ac side terminal are represented as follows:

$$\begin{aligned} W &= v_t\,I_d \\ Q_d &= \sqrt{W^2-P_d^2} \end{aligned} \tag{5}$$

The $P$-$Q$ characteristics of the SMES are shown in Fig. 6, with $I_d$ and $\alpha$ as the parameters. The equivalent admittance of the SMES is given as follows:

$$\dot{Y}_e = G_e+j\,B_e = \frac{P_d}{v_t^2}-j\frac{Q_d}{v_t^2} \tag{6}$$

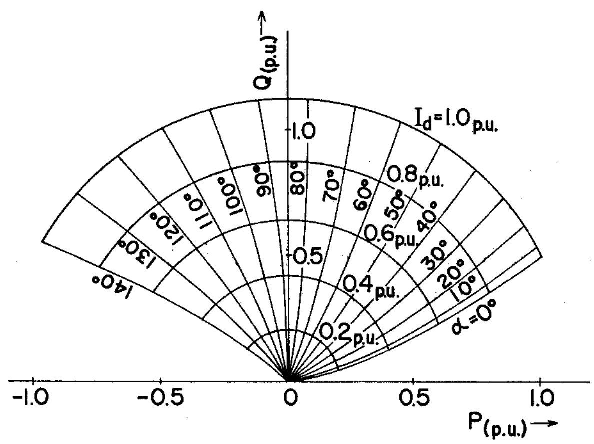



Fig. 6. $P$-$Q$ characteristics of SMES.

## 3.2 Load-Flow and Transient Calculation for Power Systems with SMES

The initial operating condition of the SMES is given by the current and the power, or by the current and the control angle $\alpha$. In the former case, $E_d$ is given by eq. (4), $Q_d$ is obtained from eq. (5), and the equivalent admittance is determined

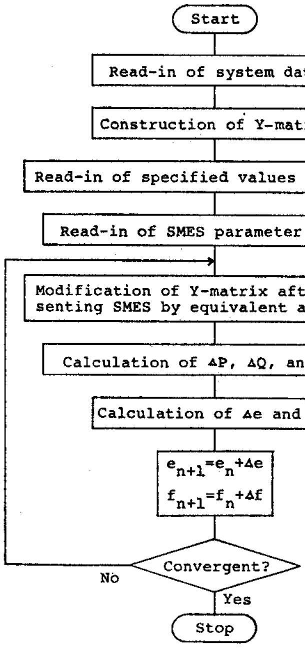



Fig. 7. Flow chart of load-flow calculation for power systems including SMES.

by eq. (6). In the latter case, $E_d$ is obtained from eq. (1), $P_d$ and $Q_d$ are calculated by using eqs. (4) and (5), and the equivalent admittance is determined by eq. (6). Fig. 7 shows the flow-chart of a load-flow calculation for power systems, including the SMES.

For transient calculations, the equivalent admittance also needs to be calculated every time the ac voltage at the SMES connected node changes. In other words, the equivalent admittance of the SMES is recalculated at every step of the transient calculation; and accordingly, the admittance matrix is modified.

## 4. Bang-Bang Control for One-Machine Infinite-Bus System

First, we investigate the stabilizing effect of the bang-bang control of the thyristor bridge control angle $\alpha$ applied to a one-machine infinite-bus system.

### 4.1 Description of the System

In the sample system shown in Fig. 8, which models the model power system in Kyoto Univ., an SMES is installed at the generator terminal. The generator is represented by a third order model as follows:

$$\dot{\delta} = \omega \tag{7}$$

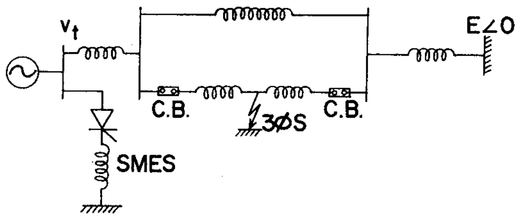



Fig. 8. Sample one-machine infinite-bus system.

$$\dot{\omega} = (P_m-(v_d\, i_d+v_q\, i_q)-D\Delta\omega)/M \tag{8}$$

$$\dot{\psi}_{fd} = -r_{fd}\, i_{fd}+r_{fd}\, v_f/x_{md} \tag{9}$$

$$i_{fd} = (\psi_{fd}+x_{md}\, i_d)/x_{fd} \tag{10}$$

The generator is equipped with an AVR, the block diagram of which is shown in Fig. 9. Its characteristics are described by the following equations:

$$\dot{v}_x = K_A(v_{\rm ref}-v_t)/T_A \tag{11}$$

$$v_x = \Delta v_f-K_A(v_{\rm ref}-v_t) \tag{12}$$

$$v_t^2 = v_d^2+v_q^2 \tag{13}$$

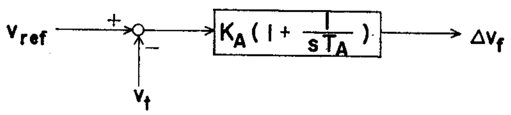



Fig. 9. Block diagram of AVR for one-machine system.

As for the coil current, from eq. (2) we get

$$\dot{I}_d = E_d/L \tag{14}$$

At the initial condition, the SMES current is assumed fixed, i.e., $E_d=0$, and $\alpha=\cos^{-1}(I_dX_c/2v_{t0})$. The bang-bang control is such that $\alpha=0°$ in the case of charging, and $\alpha=140°$ in the case of discharging, taking into account the margin angle. The effect of the control does not appear explicitly in the above differential equations, but affects the system performance through the equivalent admittance (admittance matrix) resulting from the change of the SMES power $P_d$ because of the change of $\alpha$.

As it is very difficult to obtain the bang-bang control for a multi-variable, non-linear system such as the above, not only theoretically but numerically, the control is assumed to have three switchings, i.e., charge-discharge-charge started immediately after the fault clearing. The switching times are obtained by means of an extremum seeking method.[3] That is to say, the switching times are determined in order to minimize the performance index which takes account of the control time and the distance between the equilibrium state and the final state.

## 4.2 Numerical Results

The parameter values of the generator and AVR, and the rating of the SMES are shown in Table 1 and 2, respectively. The assumed disturbance is a three-phase short-circuit at the center of one of the two parallel transmission lines, which is cleared after 0.3 sec.

Table 1. Constants of generator and AVR for one-machine system.

| | |
|---|---|
| $x_d$ | 0.937 p.u. |
| $x_q$ | 0.761 p.u. |
| $x_d'$ | 0.315 p.u. |
| $x_l$ | 0.0865 p.u. |
| $T_{d0}'$ | 0.434 sec |
| $H$ | 5.4 sec |
| $D$ | 0.02 p.u. |
| $K_A$ | 10 |
| $T_A$ | 0.5 sec |

Table 2. Constants of SMES for one-machine system.

| | |
|---|---|
| Rated *dc* side voltage | 36 V |
| Rated *dc* side current | 96.23 A |
| Inductance of SMES | 0.5 H |
| Leakage reactance of transformer | 0.235 p.u. |

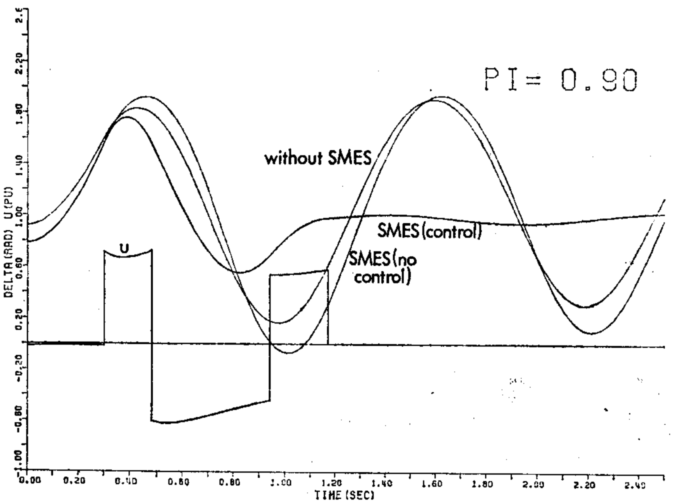



Fig. 10. Bang-bang control of control angle $\alpha$.

Fig. 10 shows the effect of the bang-bang control of the control angle $\alpha$. If the SMES is not controlled, i.e., $\alpha$ is fixed, the system oscillation is a little larger than that without the SMES. This is because the SMES discharges a small power during the fault. Fig. 11 shows the control effect when the initial current

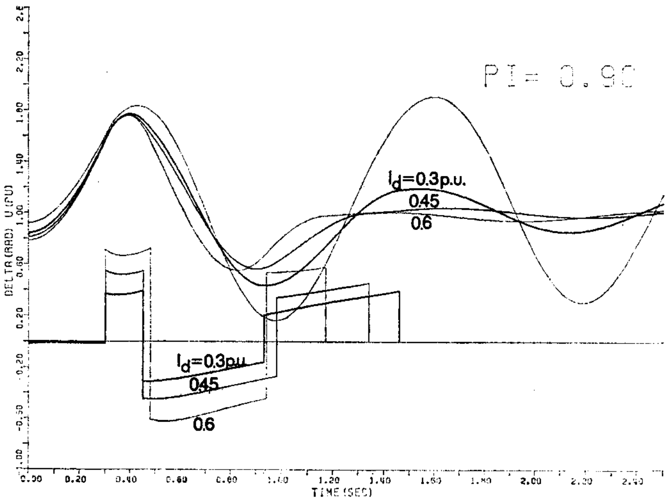



Fig. 11. Bang-bang control of control angle $\alpha$ with varied $I_d$.

of the SMES is varied. It is seen that the system can not attain equilibrium after three switchings when the initial SMES current is too small.

## 5. Feedback Control of SMES

The optimum control of the SMES described in Section 2 for a simple sample system, and the bang-bang control of the SMES control angle $\alpha$, investigated in the preceding section, were found to be very effective measures for suppressing system oscillations. It is difficult, however, to realize either control, because the former control is given only as a function of time, and in the latter case, the optimum switching line can not be obtained. As mentioned in Section 2, the stabilization and the damping of power systems by means of the SMES is performed by absorbing power when the generator accelerates and by releasing it when the generator decelerates. Therefore, it is thought appropriate to control the control angle $\alpha$ of the SMES thyristor bridge by the feedback of the angular velocity deviation $\Delta\omega$ of the generator rotor. In this section, we examine the above control strategy on a one-machine infinite-bus system, and on a 10-machine system as an example of a multi-machine power system.

### 5.1 One-Machine Infinite-Bus System

On the one-machine system used in the preceding section for the numerical example (except that L=1000H), it is assumed that the characteristics of the feedback control system of $\alpha$ by means of $\Delta\omega$ are represented by a time lag of the first-order, namely,

$$\Delta\alpha = -\frac{K_s}{1+s\,T_s}\,\Delta\omega \tag{15}$$

or

$$\Delta\dot{\alpha} = -\Delta\alpha/T_s - K_s\Delta\omega/T_s \tag{16}$$

where $0° \leq \alpha = \alpha_0 + \Delta\alpha \leq 140°$ $K_s = 0.5$ $T_s = 0.01$ sec.

The numerical results are shown in Figs. 12–14. Fig. 12 shows a case where the initial SMES power equals zero, i.e., the power is stored under a fixed current ($\alpha_0 = 87.0°$). In Fig. 13, the SMES is initially being charged with power ($\alpha_0 = 0°$), and in Fig. 14, the SMES is initially discharging ($\alpha_0 = 140°$). The generator output power is 0.9 p.u. in either case. Therefore, the power flow on the transmission line is varied, being the largest in the case of discharging. As is shown in Fig. 12, when the initial value of $P_d$ is 0, $\alpha$ equals about 90° and the SMES has

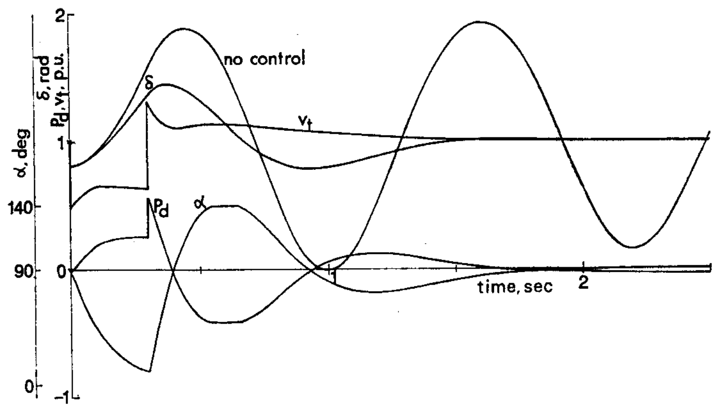



Fig. 12. Feed-back control of $\alpha$ ($\alpha = 87.0°$).

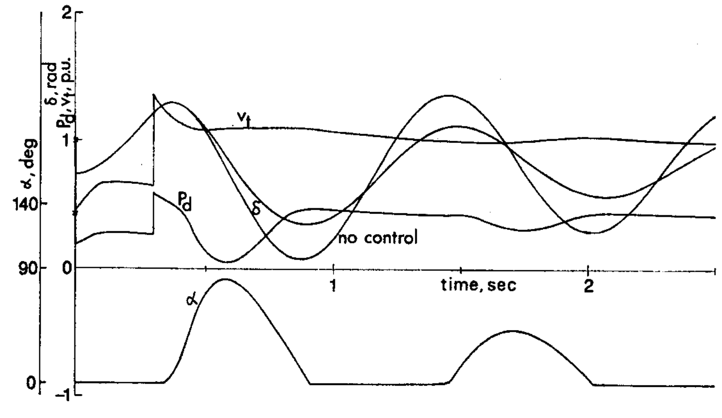



Fig. 13. Feed-back control of $\alpha$ ($\alpha = 0°$).

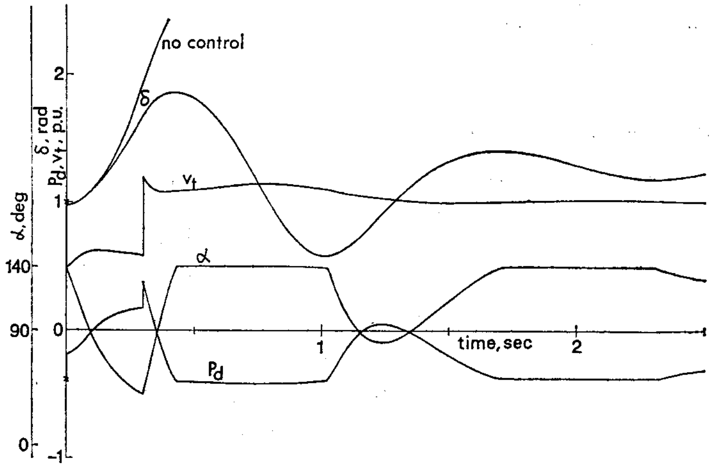



Fig. 14. Feed-back control of $\alpha$ ($\alpha=140°$).

a sufficient damping effect within the admissible range of $\alpha$; $0° \leq \alpha \leq 140°$.

In Fig. 13, on the other hand, the damping is not so much improved as in Fig. 12, as the amount of power absorption at the first stage of the transient is limited by the restriction $\alpha=0°$. When the SMES is initially discharging, the generator goes out of step in case of no-control, owing to the heavy power flow on the transmission line. It can be stabilized, as shown in Fig. 14, by means of the feedback control of the SMES.

As was seen in Figs. 12–14, the proposed control method can be considered to be effective, because it gives greater damping under the discharging of the SMES, which is a more severe case than the charging from the viewpoint of stability.

### 5.2 10-Machine System

Next, we examine the effect of the feedback control of the SMES control angle $\alpha$ by $\Delta\omega$ in a 10-machine system[4], shown in Fig. 15. The generators are represented by a fourth order model, and are equipped with an AVR and a governor, the block diagrams of which are shown in Figs. 16 and 17, respectively. Since the No. 1 generator represents the adjacent power system, it is chosen as the reference generator. The ratings of the SMES are listed in Table 3, which is assumed to be a 3000 MWh class.[5] The control system of the control angle $\alpha$ is the same as for the one-machine system. The SMES is initially operated under a constant current, i.e., the initial SMES power is zero. The disturbance assumed is a 0.19 sec three-phase short-circuit at the point A or F in Fig. 15.

Fig. 18 (a) and (b) shows the system oscillation without the SMES. The fault at A is an example where the No. 2 generator swings a lot, and the fault at F

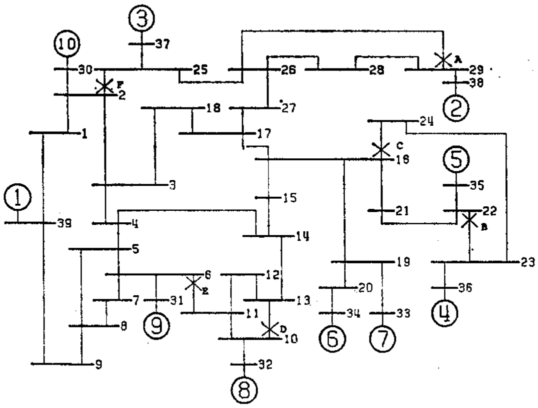


Fig. 15. Sample 10-machine system.

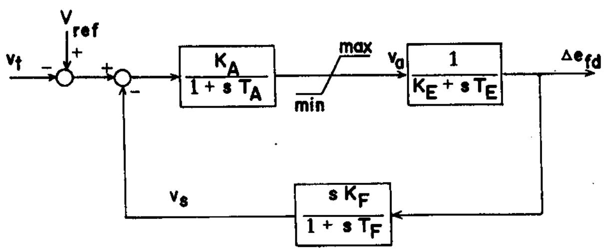



Fig. 16. Block diagram of AVR for 10-machine system.

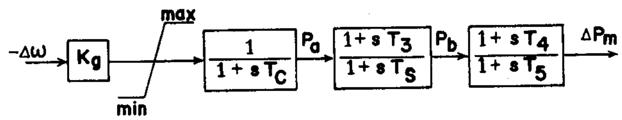
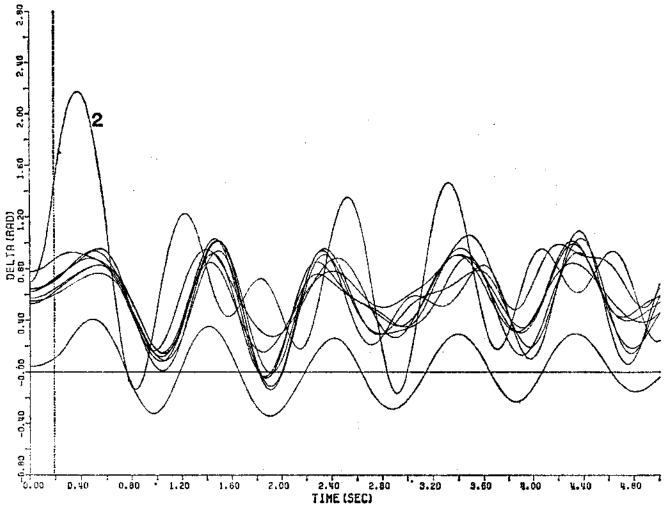


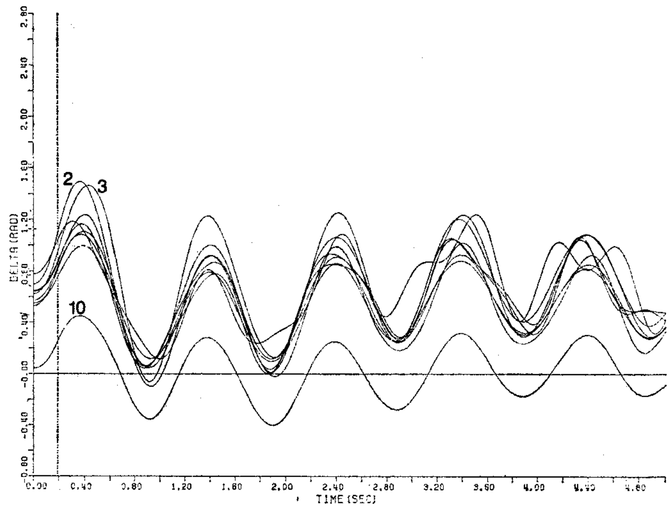

Fig. 17. Block diagram of governor for 10-machine system.

Table 3. Constants of SMES for 10-machine system.

| | |
|---|---|
| Rated *dc* side voltage | 3 KV |
| Rated *dc* side current | 33.3 kA |
| Storage capacity | 3000 MWh |
| Inductance of SEMS | 2160 H |
| Leakage reactance of transformer | 0.2 p.u. |



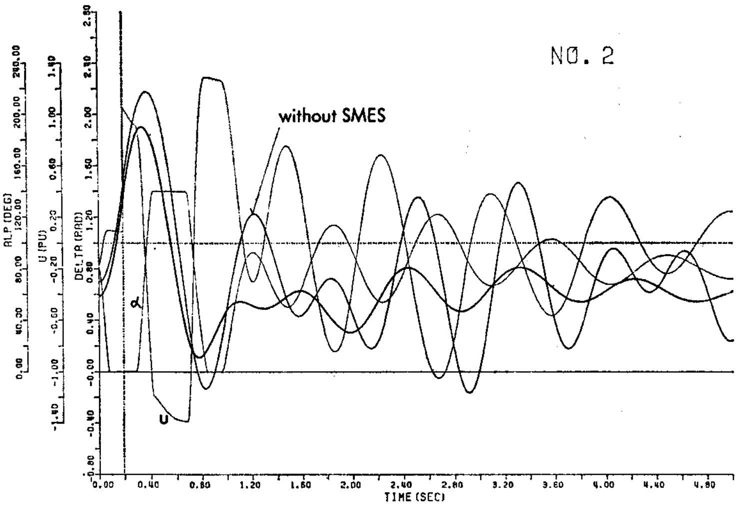

(a) fault at point *A*



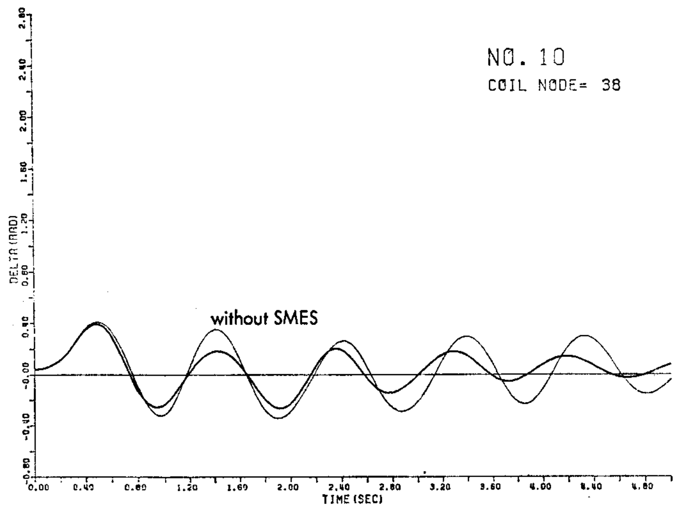

(b) fault at point *F*

Fig. 18. System swing without SMES.

is a case where all of the generators swing almost uniformly. Fig. 19 shows the swings of the No. 2 and No. 10 generators in case of a fault at A with the SMES installed at the terminal of the No. 2 generator. The No. 10 generator is an example of a generator located far from the faulted point. The oscillation of No. 2 is suppressed by the controlled SMES, and accordingly, the damping of No. 10 was improved. Fig. 20 shows the results in a case where the SMES is installed



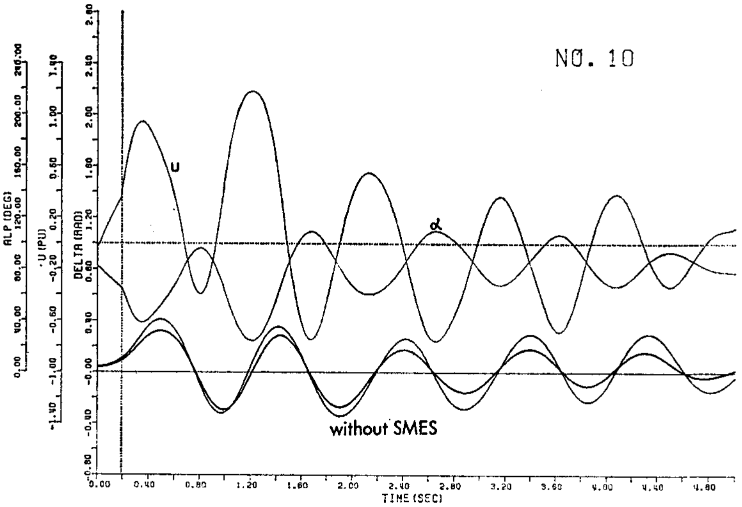

(a) swing of generator No. 2



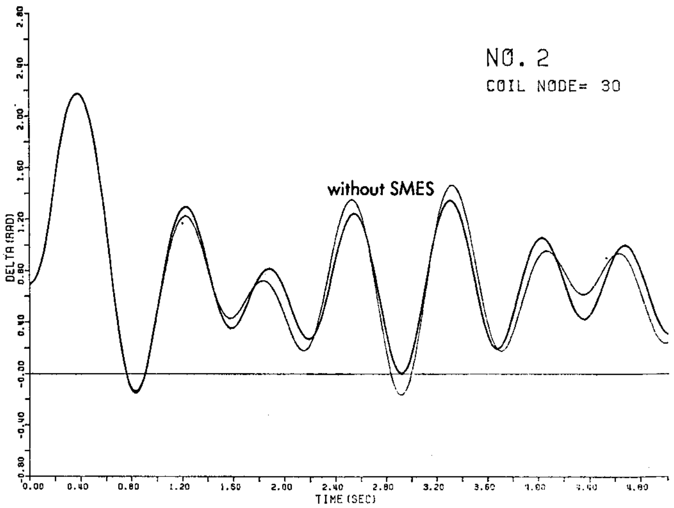

(b) swing of generator No. 10

**Fig. 19. System swing with fault at point *A* and SMES at generator No. 2.**

at the No. 10 generator terminal, the faulted point being the same as Fig. 19. In this case, the oscillation of No. 2 is only slightly dampened. In Fig. 21, the swings of the generators Nos. 2, 3, and 10 are shown with a fault at point F and with the SMES at the No. 2 generator. It is seen from this figure that, when the whole system swings almost uniformly as for the fault at F, the SMES has an appreciable damping effect, even if it is installed electrically far from the faulted point.




(a) swing of generator No. 10




(b) swing of generator No. 2

Fig. 20. System swing with fault at point $A$ and SMES at generator No. 10.

## 6. Conclusion

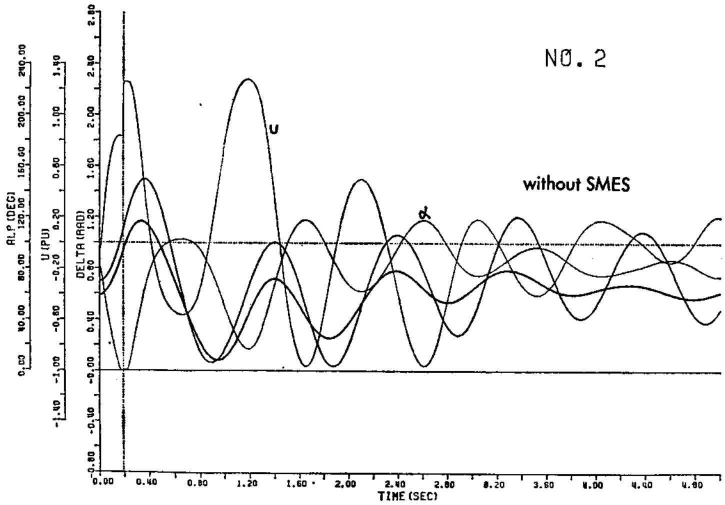
From the results of examining the effects of the bang-bang control of the SMES control angle $\alpha$ and the feedback control of $\alpha$ through $\Delta\omega$ on a sample one-machine system, it was found that the feedback control is easy to realize and has a sufficient damping effect. Furthermore, transient calculations were performed on a 10-machine system as an example of a multi-machine power system.

From the results, we can draw the following conclusions.

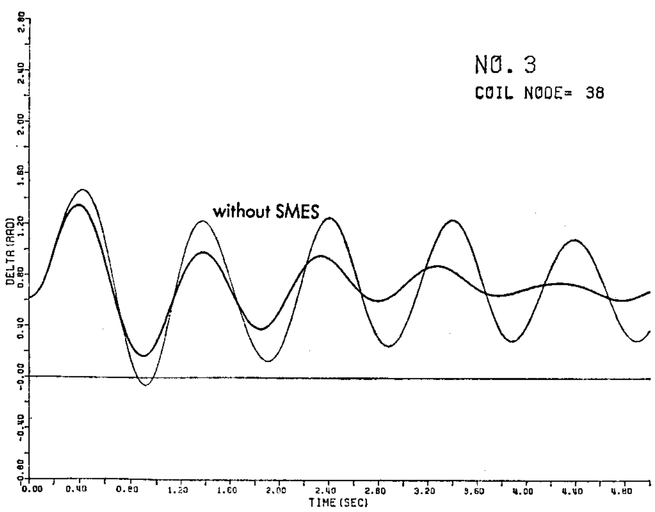
(a) The damping effect is large when the SMES is installed near a generator which is subjected to a large disturbance.

(b) When the whole system swings uniformly, the damping effect does not depend much on the installation position of the SMES.

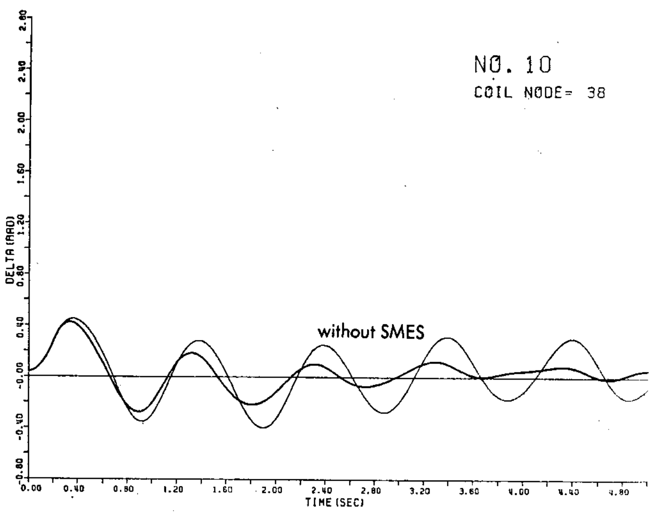
The location of the SMES in the power system should be decided, taking not only the stability but also the transmission loss and geographical constraints into




(a) swing of generator No. 2




(b) swing of generator No. 3




(c) swing of generator No. 10

Fig. 21. System swing with fault at point *F* and SMES at generator No. 2.

account. Even if we confine the discussion to the stability, there are not a few problems still to be solved, for example, which is more advantageous, one large SMES or some smaller SMES's; what is the interaction of the SMES with other stabilizing measures etc. problems.

## Acknowledgements

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