Stabilization of Longitudinal Power System by Means of Superconducting Magnetic Energy Storage

By

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Abstract

A power system stabilization by means of the superconducting magnetic energy storage (SMES) has already been proposed, wherein the firing angle α of the SMES thyristor bridge is controlled, based on the angular velocity deviation $\Delta\omega$ of the generator rotor. In this paper, a simple longitudinal system is taken up as a sample system, and the optimum position of the SMES is investigated from the stabilizing point of view. Also studied is the effect of the distributed installation of the SMES from both sides of the steady-state stability by means of the eigenvalue method, and the transient stability by the simulation method.

1. Introduction

An energy storage for electric power systems using magnetic energy of a superconducting coil was proposed more than ten years ago. It has been investigated with respect to the conceptual design and the control method, since it is more efficient than the pumped storage. Also, the electric power can be rapidly controlled by means of the superconducting magnetic energy storage (SMES) through the control of the firing angle of the thyristor bridge. Therefore, it can be used for the stabilization of electric power systems, if it is properly controlled.

The authors have already proposed a method of controlling the SMES installed at the generator terminal for the power system stabilization,[1,4] wherein the SMES is controlled, based on the angular velocity deviation $\Delta\omega$ of the generator rotor. The proposed method was applied to a one-machine infinite-bus system and a multi-machine system, and its stabilizing and damping effects were verified. However, the relation between the stabilizing effect and the position of the SMES in multi-machine power systems has not been revealed, partially because the sample system used was of a complex construction including loops.

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In this paper, we take up a simple longitudinal system as a sample system, and investigate the optimum position of the SMES from the stabilizing point of view. Also studied is the effect of the distributed installation of the SMES from both sides of the steady-state stability by means of the eigenvalue method, and the transient stability by the simulation method.

2. Representation and Control Method of SMES

The conceptual scheme of the SMES is shown in Fig. 1. Its characteristics are supposed to be described by the following equations.

$$E_d = E_d' \cos\alpha - I_d X_c/2 \tag{1}$$

$$P_d = I_d E_d \tag{2}$$

$$W = I_d E_d' \tag{3}$$

$$Q_d = \sqrt{W^2 - P_d^2} \tag{4}$$

$$L\frac{dI_d}{dt} = E_d \tag{5}$$

where
- E_d, I_d : coil voltage and coil current, respectively
- E_d' : coil voltage in case of no-load and no-control
- X_c : commutating reactance
- W, P_d, Q_d : apparent power, active power and reactive power of the coil, respectively
- α : firing angle of the thyristor bridge
- L : inductance of the coil

The control of the thyristor bridge firing angle α is performed by the feedback of the angular velocity deviation $\Delta\omega$ of the generator rotor.[1] That is to say, the stabilization of the power systems and the damping of the generator swings are made

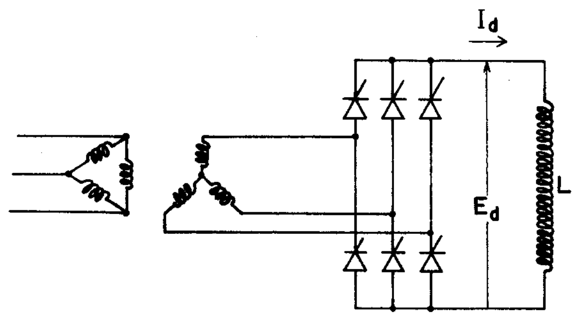


Fig. 1. Conceptual scheme of SMES.

by absorbing power when the generator accelerates, and by releasing it when the generator decelerates. The characteristics of the feedback control system for α are supposed to be a time-lag of the first-order:

$$\Delta\alpha=\frac{-K_s}{1+sT_s}\Delta\omega \qquad K_s=0.5 \qquad T_s=0.01\,\text{sec} \tag{6}$$

$$0°\leqslant\alpha_0+\Delta\alpha\leqslant 140° \quad \text{(in case of the transient calculation)}$$

3. System Equation and Derivation of A-Matrix

The generators are represented only by the differential equation of motion:

$$\frac{d\delta_i}{dt}=\Delta\omega_i \tag{7}$$

$$\frac{d\Delta\omega_i}{dt}=(P_{mi}-P_{ei}-D_i\Delta\omega_i)/M_i \tag{8}$$

$$i=1, 2, \ldots, n$$

The linearized differential equation $\dot{x}=Ax$ is derived from the non-linear differential equation $\dot{x}=f(x)$. The coefficient matrix A is usually calculated as follows:

$$a_{ij}=\left.\frac{\partial f_i(x)}{\partial x_j}\right|_{x=x_0} \tag{9}$$

x_0: equilibrium point

In the calculation of power systems with SMES, the SMES is represented by an equivalent admittance obtained from the SMES power and the terminal voltage.[1] Hence it is difficult, if not impossible, to calculate the partial differential of Eq. (9) analytically. In this paper, we calculated the A-matrix numerically. Giving the deviation Δx_j with a finite value ($10^{-8}\sim10^{-5}$) to x_j and calculating f_i, we have

$$a_{ij}=[f_i(x_{10}, x_{20}, \ldots, x_{j0}+\Delta x_j, \ldots, x_{n0})-f_i(x_{10}, \ldots, x_{n0})]/\Delta x_j \tag{10}$$

4. Numerical Results and Discussions

4.1 Sample Longitudinal 5-Machine System[2]

Fig. 2 shows the sample longitudinal system used for the numerical calculation. The constants of the sample system are listed in Table 1. All of the five generators and power lines are identical. The reactance of the generators x_g equals 0.8 p.u. in the steady-state stability calculation (eigenvalue calculation), and 0.3 p.u. for the transient calculation. (Both are based on the generator's own capacity.) The initial operating condition is such that all of the output of the generator is consumed by the load connected to that generator, and hence, there is no power flow on the tie

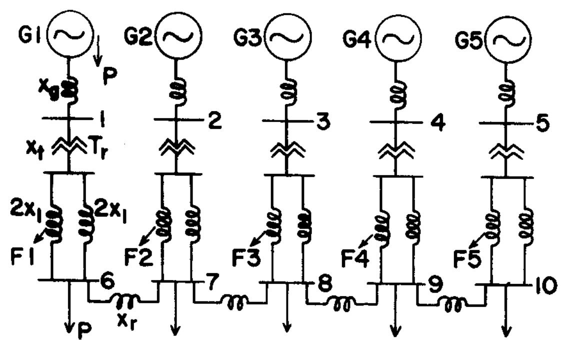


Fig. 2. Sample longitudinal 5-machine system (F1～F5: faulted point, 1～5: SMES installed bus).

Table 1. Constants of system and SMES

Generator	Capacity	5,000 MVA
	H	8 sec
	D	2 p.u.
	x_g	0.8 p.u.
Transformer	Capacity	5,000 MVA
	x_c	0.1 p.u.
Transmission line	x_l	0.06 p.u.
	x_r	0.03 p.u.
SMES	I_d	50 kA
	E_d	20 kV
	L	3 H
	X_c	0.2 p.u.

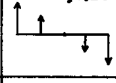
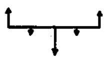
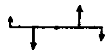
lines. The stability limit power is obtained by increasing the power of all generators and loads uniformly. In the calculation of the eigenvalues, P=5 p.u. (The base value=1,000 MVA and the steady-state power limit=6.2 p.u.) The assumed fault for the transient calculation is a three-phase short-circuit at one of the centers of the power lines, F1～F5, and it is cleared 0.1 sec after its occurrence and reclosed 0.5 sec after the clearing.

4.2 Eigenvalue Calculation

Table 2 shows the eigenvalues and eigenvectors related to the system swings for various cases. As the system is symmetrical, the effect of the SMES installed at the No. 4 or No. 5 bus on the steady-state stability is the same as the SMES at the No. 2 or No. 1 bus, respectively.

When the SMES is not installed in the system, the real part of the eigenvalues

Table 2 Eigenvalues and eigenvectors

Location of SMES	Eigenvalue (eigenvector)			
	First mode	Second mode	Third mode	Fourth mode
Without SMES	−0.125±j3.26 	−0.125±j4.78 	−0.125±j5.08 	−0.125±j5.18 
No.1, α fixed	−0.125±j3.34	−0.125±j4.84	−0.125±j5.12	−0.125±j5.20
No.1	−0.772±j3.42	−0.669±j4.64	−0.164±j4.99	−0.129±j5.16
No.2	−0.322±j3.33	−0.133±j4.80	−0.128±j5.14	−1.052±j5.06
No.3	−0.125±j3.26	−0.167±j4.98	−0.125±j5.08	−1.197±j5.04

represents the inherent system damping given by the damping coefficient D. Even if the SMES is installed, when α is not controlled but fixed, the damping does not change. The latter is improved by the feedback control of α based on $\Delta\omega$. When the SMES is installed at a generator which is subjected to a large swing, that mode of the oscillation is particularly suppressed. (For example, see the first mode with the SMES at the No. 1 bus or the fourth mode with the SMES at the No. 3 bus.) As the steady-state stability of such a longitudinal power system is mainly governed by the first mode, in which the generators at both ends swing to the opposite direction,[2] it is advantageous from the viewpoint of the system damping to install the SMES at the end of the system. On the other hand, the steady-state power limit was not affected by the SMES, and was equal to 6.2 p.u. Therefore, it is concluded that the SMES with α controlled by $\Delta\omega$ increases the damping torque, but does not contribute to the synchronizing torque.

Next, in order to investigate the stabilizing effects of a distributed installation of SMES, we assume two SMESs installed, each having a half of the rated current as before. The eigenvalues for these cases are listed in Table 3. The following conclusions are drawn from this table.

Table 3. Eigenvalues (distributed installation of SMES)

Location of SMES	Eigenvalue				Stability measure T
	First mode	Second mode	Third mode	Fourth mode	
Without SMES	−0.125±j3.26	−0.125±j4.78	−0.125±j5.08	−0.125±j5.18	55.4
No. 1 and 2	−0.695±j3.17	−0.213±j4.77	−0.134±j5.13	−0.477±j5.32	48.0
No. 1 and 3	−0.412±j3.28	−0.329±j4.84	−0.160±j5.06	−0.568±j5.28	37.6
No. 1 and 4	−0.335±j3.33	−0.285±j4.81	−0.623±j5.22	−0.214±j5.12	42.8
No. 1 and 5	−0.337±j3.34	−0.729±j4.81	−0.235±j5.12	−0.142±j5.14	50.3
No. 2 and 3	−0.232±j3.28	−0.548±j4.77	−0.164±j5.03	−0.497±j5.40	35.7
No. 2 and 4	−0.225±j3.30	−0.156±j4.82	−0.454±j5.02	−0.587±j5.36	41.1

(i) When the SMESs are installed at the generators which swing greatly, that mode of the oscillation is particularly suppressed. (The same is true for the case of a lumped installation of SMES).

(ii) The damping is improved more when the two SMES-installed generators swing to the same direction rather than to the opposite direction. For example, when the second mode and the fourth mode are compared for the case of an SMES installed at both the No. 1 and No. 3 buses, the latter has a greater damping than the former. The damping is especially increased when the SMESs are installed at two generators which are next to each other and swing as a group (for example, the No. 1 and No. 2 generators in the first mode). In the third mode with the SMESs installed at the No. 1 and No. 2 buses, the No. 1 and No. 2 generators swing to the opposite direction with a comparable magnitude. Therefore, the oscillation between the No. 4 and No. 5 generators is not much dampened and the damping of the total system is scarcely improved, although the damping between the No. 1 and the No. 2 may be improved.

In Table 3 is also shown the value of T, the index of the steady-state stability based on the Lyapunov function.[8] This index can be said to be a kind of time constant according to which the system approaches equilibrium. (See Appendix.) The smaller the value of T, the better the steady-state stability. So far as this index is concerned, the installation positions No. 2 and No. 3 are the best. However, the result is questionable because the index takes all the oscillation modes into account with the identical weight.

4.3 Transient Power Limits

All of the generator output powers and the load powers are increased simul-

Table 4. Transient power limits for various assumed faults (p.u.)

Location of SMES	Fault F1	F2	F3	F4	F5	Minimum value
Without SMES	5.0	5.4	5.6	5.4	5.0	5.0
No. 1	5.9	5.5	5.7	5.6	5.1	5.1
No. 2	5.0	6.4	5.7	5.6	5.1	5.0
No. 3	5.1	5.5	6.5	5.5	5.1	5.1
No. 1 and 2	5.5	6.0	5.7	5.6	5.1	5.1
No. 1 and 3	5.5	5.5	6.2	5.5	5.1	5.1
No. 1 and 4	5.6	5.5	5.7	6.0	5.1	5.1
No. 1 and 5	5.6	5.6	5.7	5.6	5.6	5.6
No. 2 and 3	5.0	6.0	6.2	5.5	5.1	5.0
No. 2 and 4	5.1	6.0	5.7	6.0	5.1	5.1

taneously and the transient power limits are computed for each of the faults F1～F5. They are listed in Table 4 along with the minimum value among them. From the case without a SMES, it is seen that a fault at the end of the system is severe from the viewpoint of the transient stability. When one SMES is installed on the system, the power limit for the fault near the SMES-installed generator is particularly increased, (0.9～1.0 p.u.). In the case of a distributed installation of the SMES, the power limit for the two faults is increased by 0.5～0.6 p.u., (half of the above). The maximum of the minimum power limits is attained with the SMESs installed at the No. 1 and No. 5 buses, i.e., at both ends.

4.4 Transient Calculations

Some examples of the transient calculations are shown in Figs. 3～6. The initial output power of the generators is 5 p.u. and the fault is assumed at F1. The phase angle δ of the generator rotor is measured with the No. 3 generator as the

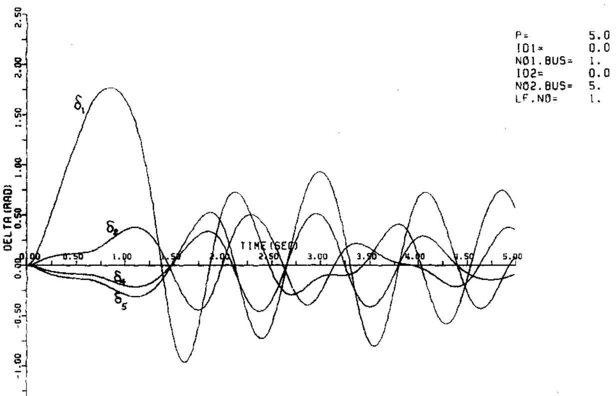


Fig. 3. Swing curves without SMES.

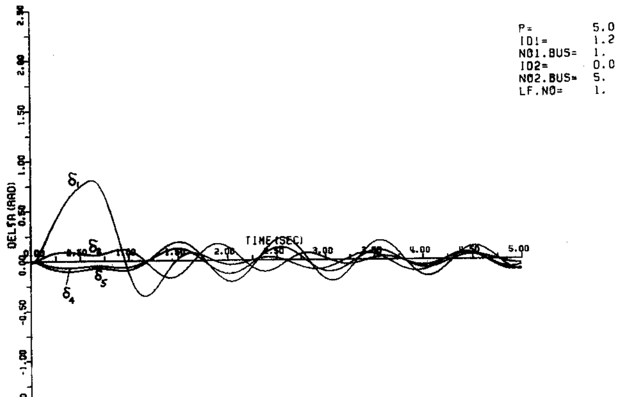


Fig. 4. Swing curves with SMES at No. 1 bus.

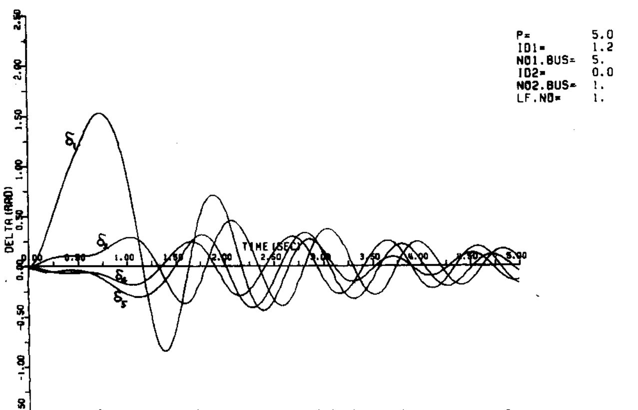
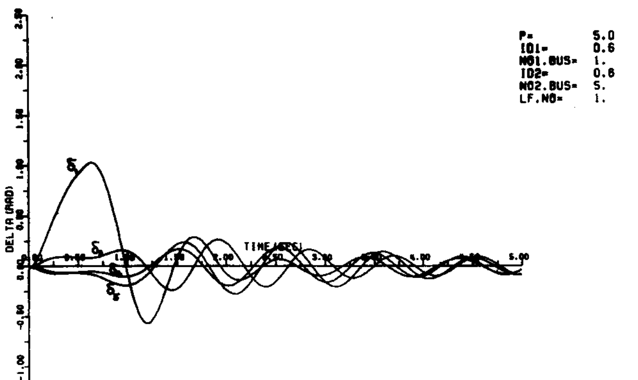
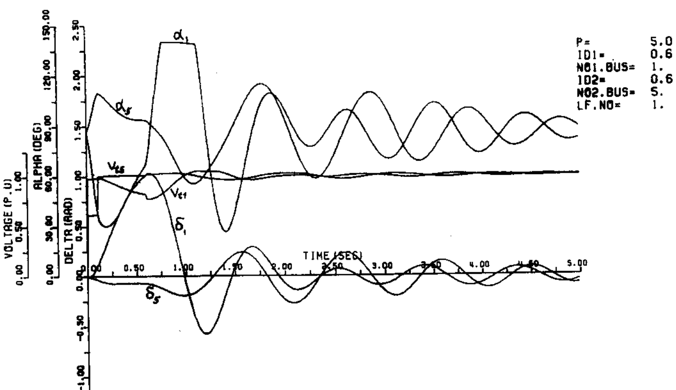


Fig. 5. Swing curves with SMES at No. 5 bus.



(a) Swing curves.



(b) Variations of firing angles α
and terminal voltages v_t.

Fig. 6. System transients with SMES at No. 1 and No. 5 buses.

reference. Since 5 p.u. is the transient power limit for the fault F1 without the SMES, the oscillations are poorly damped without SMES as shown in Fig. 3. The amplitude of the first swing becomes less and the damping is improved in Fig. 4, compared with Fig. 3, as the SMES is installed near the faulted point. On the other hand, in Fig. 5, the SMES is far from the fault and the damping effect is not so large as in Fig. 4. If two SMESs of half capacity are installed at the both ends, the damping gets better regardless of the faulted point (Fig. 6).

5. Conclusion

The relation between the position of the SMES and the stabilizing effect was investigated on a simple longitudinal 5-machine system from the viewpoint of the system damping and the transient power limit. From the results of the eigenvalue calculations and the simulation of the transients, it was made clear that installing a SMES at both ends of the system is most effective for suppressing the system oscillation and increasing the transient power limit. However, the advantage of the power system stabilization by means of a SMES is found rather in the steady-state stability than in the transient stability. Hence, it is hoped that a control method will be developed for improving the steady-state stability.

Acknowledgements

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References

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Appendix Index of Stability of Linear Systems Based on the Lyapunov Function

The equilibrium state $x=0$ of a continuous-time, free, linear, stationary dynamic system

$$\dot{x}=Ax \tag{A1}$$

is asymptotically stable if, and only if given any symmetric positive-definite matrix Q there exists a symmetric, positive-definite matrix P which is the unique solution of the set of $n(n+1)/2$ linear equations

$$A'P+PA=-Q \tag{A2}$$

Then

$$V=x'Px \tag{A3}$$

is a Lyapunov function for the system, because V is positive-definite and

$$\begin{aligned}\dot{V}&=\dot{x}'Px+x'P\dot{x}\\&=x'(A'P+PA)x\\&=-x'Qx\end{aligned} \tag{A4}$$

is negative-definite. V can be considered a measure of the distance of the system state from the equilibrium point, and the index of the rapidity of the transient response is defined as follows:

$$T=\max_x\left[\frac{-V(x)}{\dot{V}(x)}\right]=\max_x\left[\frac{x'Px}{x'Qx}\right]=\max_x[x'Px;\ x'Qx=1] \tag{A5}$$

In order to calculate the value of T, consider the following function with λ as the Lagrange multiplier:

$$F(x)=x'Px-\lambda x'Qx=x'(P-\lambda Q)x \tag{A6}$$

Maximizing $F(x)$ with respect to x implies that the maximum occurs at a value x^* of x such that

$$(P-\lambda Q)x=0 \tag{A7}$$

Therefore

$$x^{*\prime}Px^*=\lambda x^{*\prime}Qx^*=\lambda>0 \tag{A8}$$

which is a maximum if λ is the maximum. On the other hand λ is an eigenvalue of $Q^{-1}P$ because $(P-\lambda Q)x^*=0$. Therefore

$$T=\max[\text{eigenvalues of } Q^{-1}P] \tag{A9}$$