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APPLICATION OF SUPERCONDUCTING MAGNET ENERGY STORAGE TO IMPROVE POWER SYSTEM DYNAMIC PERFORMANCE

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Abstract - The application of Superconducting Magnet Energy Storage (SMES) to the stabilization of a power system with long distance bulk power transmission lines which has the problem of poorly damped power oscillations, is presented. Control schemes for stabilization using SMES which is capable of controlling active and reactive power simultaneously in four quadrant ranges, is proposed. The effective locations and the necessary capacities of SMES for power system stabilizing control are discussed in detail. Results of numerical analysis and experiments in an artificial power transmission system demonstrate the significant effect of the control by SMES on the improvement of power system oscillatory performance.

Keywords - Superconducting Magnet Energy Storage, Power System Stability, Eigenvalues, Power System Simulation.

INTRODUCTION

Electrical power systems that have major loads and generation centers separated by long distances may experience undamped and poorly synchronized power oscillations [1]. Currently, several stabilizing methods are suggested, such as the addition of power system stabilizer (PSS) to generator excitation control [2-4] and the control by static var compensator (SVC) [5-7]. This paper describes a control system using SMES which can be considered as one of the possible power system stabilizers [8-9].

A typical SMES configuration contains two six-pulsed thyristor Greatz bridges in series and a superconducting coil. A proper control of the firing angles of these bridges makes it possible to control active and reactive power independently, rapidly and smoothly at the bus where a SMES is placed [9-10], and this has been applied to power system stabilization [9]. The use of thyristor Greatz bridges, however, limits the range of simultaneous control of both the active and reactive power, and this may limit the effectiveness of introducing SMES for the purpose of power system stabilization. On the other hand, recent developments in Gate Turn-Off thyristor (GTO) allow us to design a converter which has the ability of power control within a circular range containing four quadrants in the active and reactive power domain [11-12]. Due to this ability, it is likely that the effectiveness of using SMES as a stabilizer in power systems will be improved significantly. Some results that have been obtained from an early experiment on a stabilizing control using the quadrant active and reactive power of SMES are described in ref[13], where the control parameters were chosen heuristically and no theoretical considerations were shown.

In this paper, the results of a numerical study based on the mathematical models of power systems are described in detail in addition to the results from a more thorough experimental study. The control scheme is basically the same as in ref[13]. That is, the active power is generated by using the deviation of generator angular velocity as a feedback signal and is applied to the power system in order to damp power oscillations. The reactive power is generated by using the deviation of voltage at the bus with SMES as a feedback signal and is used for a constant voltage control. In this paper, however, the feedback gains are determined by the eigenvalue analysis.

The effectiveness of SMES is investigated for a one machine infinite bus system which is considered as a model of a long distance bulk power transmission system. The necessary capacities of SMES and the location of SMES on the transmission line are evaluated in some details. It is demonstrated by digital simulation as well as by experiments that the effectiveness of SMES is more significant than that of SVC. It is also confirmed experimentally that the transmission capacity can be increased significantly with the proposed stabilizing control by SMES.

CONFIGURATION OF POWER SYSTEM AND SMES FOR ANALYSIS

Configuration of a power transmission system

The configuration of a model power transmission system used for analyzing the effectiveness of introducing SMES is shown in Fig.1. It is the most basic one machine-infinite bus system corresponding, on a real scale, to a long distance bulk power transmission system with a 2000 [MVA] power plant of turbine generators connected to a large power system through 500 [kV] and about 200 [km] double circuit transmission line.

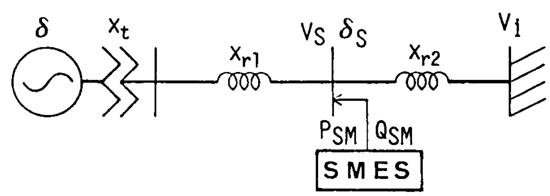

Fig.1. Long distance bulk power transmission system with SMES.

Configuration of a SMES

Figure 2 shows the fundamental configuration of a SMES considered in this paper. The main components are a superconducting coil and two sets of six pulsed GTO Greatz bridge power converters in series. The proper control of the firing angles Φ_1, Φ_2 of these

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converters makes it possible to control active and reactive power independently, rapidly and smoothly in four quadrant ranges at the bus where the SMES is placed, and this has already been achieved experimentally [11-12].

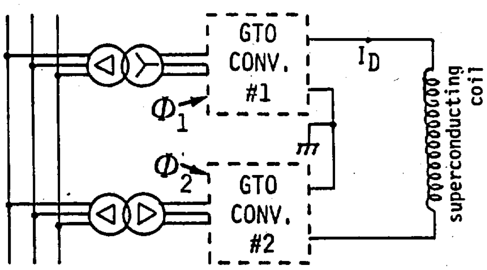


Fig.2. Fundamental configuration of a SMES.

CONTROL SCHEME OF SMES FOR POWER SYSTEM STABILIZATION

Here, the design of a control scheme of SMES for power system stabilization is presented.

Using the second-order model, only the torque relation is described by a second-order differential equation. The rests are algebraic, i.e.,

$$M\ddot{\delta}+D_M\dot{\delta}=P_m-P_e \tag{1}$$

$$P_e=V_gV_s\ \sin(\delta-\delta_s)/x_1 \tag{2}$$

$$P_{SM}=(V_sV_i\ \sin\delta_s)/x_2-[V_gV_s\ \sin(\delta-\delta_s)]/x_1 \tag{3}$$

$$Q_{SM}=(V_s{}^2-V_sV_i\ \cos\delta_s)/x_2 -[V_gV_s\ \cos(\delta-\delta_s)-V_s{}^2]/x_1. \tag{4}$$

Linearizing (1) through (4) around an operating point on the assumption that P_m and V_g are constant, we obtain

$$M\Delta\ddot{\delta}+D_M\Delta\dot{\delta}=a\Delta\delta+b_1\Delta V_s+b_2\Delta\delta s \tag{5}$$

$$\Delta P_{SM}=c_1\Delta\delta+d_1\Delta V_s+d_2\Delta\delta s \tag{6}$$

$$\Delta Q_{SM}=c_2\Delta\delta+d_3\Delta V_s+d_4\Delta\delta s \tag{7}$$

where Δ denotes the variable which represents the deviation from the operating point, and a, b_1, b_2, c_1, c_2, d_1, $\cdots$, d_4 are the elements of Jacobian.

The significance of introducing SMES is that ΔP_{SM} and ΔQ_{SM} can be varied freely. Let us assume here, for simplicity, that the active and reactive power of SMES can be changed instantaneously. This is justified, for the time constants of these power controls have already been shown as to be sufficiently small in comparison with the period of power swing [11].

Now, the reactive power of SMES is used for the constant voltage control of V_s just as a conventional operation of power system stabilization by means of SVC [5], i.e., ΔQ_{SM} is generated by

$$\Delta Q_{SM}=-K_V\Delta V_s. \tag{8}$$

Eliminating ΔV_s, $\Delta\delta_s$ and ΔQ_{SM} in (5) through (8) we obtain

$$M\Delta\ddot{\delta}+D_M\Delta\dot{\delta}+a'\Delta\delta=b'\Delta P_{SM}. \tag{9}$$

In order to increase the damping of power swing in (9), the active power of SMES is used in such a way that ΔP_{SM} is generated by

$$\Delta P_{SM}=-K_D\Delta\dot{\delta}. \tag{10}$$

NUMERICAL STUDY OF STABILIZING CONTROL BY SMES

The effectiveness of the control described by (8) and (10) is first investigated by eigenvalue analysis and digital simulation.

Mathematical models

Mathematical models for numerical analysis are represented as follows.

The generator is represented by a third-order model considering the change in flux linkage of the field winding and the torque equation.

$$T_{do}'\dot{e}_q'=e_{fd}-e_q'-(x_d-x_d')I_d \tag{11}$$

$$M\ddot{\delta}=P_m-P_e-D_M\dot{\delta} \tag{12}$$

The AVR is represented by a block diagram in Fig.3. The mechanical input Pm is regarded as constant by neglecting the effect of the governor.

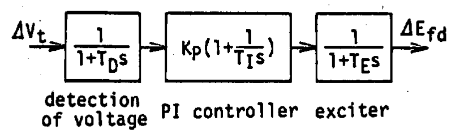


Fig.3. Block diagram of an AVR.

Transmission lines are represented by pi-figure circuits.

Operating characteristics of active and reactive power controls by a SMES are considered here, that is, the transfer characteristics of the SMES from the specified values (ΔP_S,ΔQ_S) to the actually controlled values (ΔP_{SM}, ΔQ_{SM}), are modeled as independent first order time-lags shown in Fig.4. The time constant T_a has been determined to be 0.03 [s] by experiment [11]. ΔQ_{SM} in (8) and ΔP_{SM} in (10), therefore, should be replaced by ΔQ_S and ΔP_S, respectively.

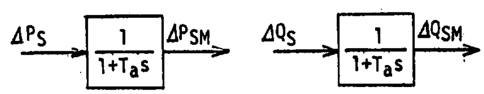


Fig.4. Operating characteristics of a SMES.

System constants are shown in Table I.

TABLE I
System constants (per unit values)

Transmission system (* : per 40 km)	
reactance of transformer	0.15
reactance of line	0.046*
resistance of line	0.005*
electrostatic suceptance of line	0.027 x 2*
short circuit reactance connecting to infinite bus	0.14
Generator	
direct axis synchronous reactance	1.35
direct axis transient reactance	0.48
quadrature axis synchronous reactance	1.31
direct axis open circuit transient time constant	6.0 s
inertia constant	8.0 s
AVR	
T_D=0.08 s Kp=40.0 T_I=2.0 s T_E=0.02 s	

Evaluation of the location of SMES

The effective location of SMES can be derived by evaluating the effectiveness of the active power and the reactive power separately.

The improvement of damping by means of the active power is more effective near the generator, which is certified through the investigation of the power system stabilizing control using Damping Resistor, and the voltage control by means of the reactive power is most effective at the center of impedance in the transmission system, which is certified through the investigation of the power system stabilizing control using SVC [5]. Considering these effects together, it can be concluded that the region between the generator terminal and the middle point of the transmission line is suitable for the location of SMES in the long distance bulk power transmission system. This has been confirmed experimentally which will be shown later in this paper.

It should be mentioned that the power system stabilizing control using SMES discussed in this paper, can be considered not only as a single function of the apparatus but also as an added value to the large scale SMES whose primary purpose is load leveling. By considering the fact that, from the economical point of view, the SMES for load leveling should be located near the demand side, the evaluation of how effective the stabilizing control is for the various location of SMES, therefore, is rather important.

Eigenvalue analysis

The eigenvalues of the system state equation derived from the linearized mathematical model, are calculated. The eigenvalues corresponding to the power swing modes for various values of K_V and K_D are shown in Fig.5, where the SMES was located at the generator terminal. The conjugate pair is omitted in Fig.5. Other eigenvalues have little significance on the discussion of stability in this paper.

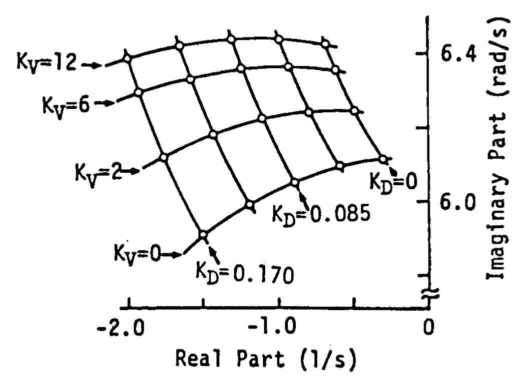


Fig.5. Variation of the eigenvalue with respect to control gains K_D and K_V.

In Fig.5, the effectiveness of the simultaneous control of active and reactive power can be compared with the reactive power control (e.g., SVC) and with the active power control (e.g., SMES with thyristor converter). The control by SVC and the active power control by SMES correspond to (8) and (10), respectively, together with the time-lags shown in Fig.4. These also correspond to the cases of K_D=0 and K_V=0, respectively, in Fig.5.

When the control by SVC is applied (K_D=0), the eigenvalue is shifted to the upper direction in the complex plane, which means that the synchronizing power is reinforced as the gain K_V becomes larger while the improvement of damping is small. When the active power control is applied (K_V=0), the eigenvalue is shifted to the left, which means that the damping of power swing is improved as the gain K_D becomes larger, on the other hand, the synchronizing power becomes small. Comparing these results each other, the synchronizing power as well as the damping can be reinforced at the same time by choosing K_V and K_D properly when the active and reactive power control is applied. Therefore, there is a definite advantage of implementing the simultaneous control of active and reactive power.

Digital simulation

The results of digital simulation are shown in Fig.6. The fault was assumed to be a 3 line short circuit where the fault circuit was cut off after 3 cycles (50 [ms]). The SMES was located at the generator terminal. When the simultaneous control of active and reactive power is applied, both voltage and power swing are damped out quickly.

From these results, it can be said that the necessary capacity of the AC/DC converter in the SMES is about 400 [MVA] and that the energy used for power stabilization is about 120 [MJ]. These values correspond to the amplitude and the half cycle integral of the deviation in power swing, respectively.

Effect of increasing stably transmitted power

Figure 7 shows the variation of the real part of the eigenvalue for different power outputs of generator, where the gains K_D and K_V are set to 0.13 [pu/(rad/s)] and 3.4 [pu/pu], respectively. The stabilizing effect by the active and reactive power control by SMES is very significant that the power system is stable up to 1.4 [pu].

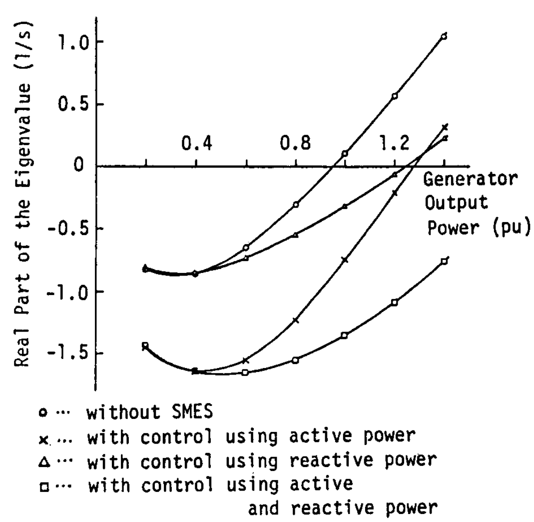
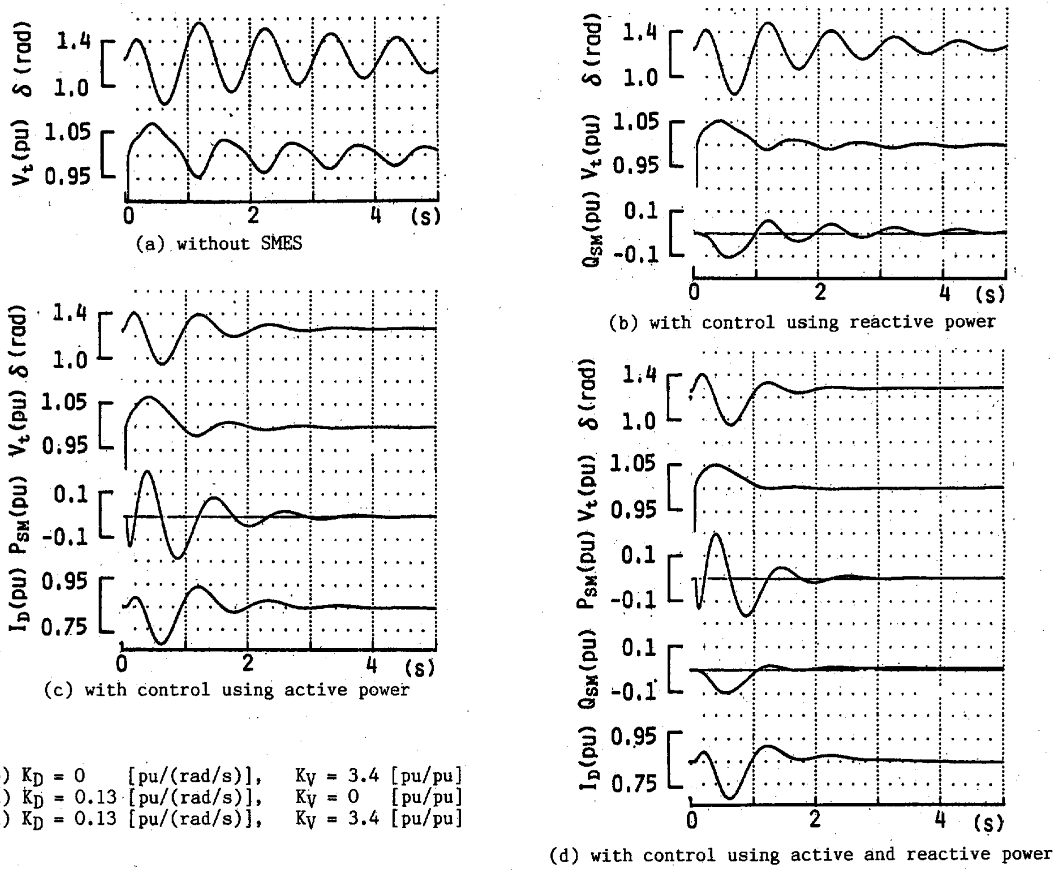


Fig.7. Variation of the real part of the eigenvalue for different generator outputs.



(b) $K_D = 0$ [pu/(rad/s)], $K_V = 3.4$ [pu/pu]
(c) $K_D = 0.13$ [pu/(rad/s)], $K_V = 0$ [pu/pu]
(d) $K_D = 0.13$ [pu/(rad/s)], $K_V = 3.4$ [pu/pu]

Fig.6. Simulated waveform.

EXPERIMENTAL STUDY

Configuration of experimental system

The configuration of an artificial power transmission system and an experimental SMES is shown in Fig.8 [13].

The generator, rated at 10 [kVA], 230 [V] and 1800 [rpm], is supplied with mechanical torque by a 15 [kW] DC motor which has a slow response control scheme for constant generator output power. It is equipped with excitation control system which has the function of automatic voltage regulator expressed by the block diagram in Fig.3. Distributed parameters of real transmission line are modeled by connecting pi-figure sections of 460 [V] line in series, each of which is represented by lumped parameters corresponding to 40 [km] in length. The parameters of the system expressed in 10 kVA base are the same in Table I.

The SMES is composed of a superconducting coil and two sets of six pulsed GTO Greatz bridge power converters in series with an active filter (AF) for harmonics and a high pass filter (HPF) for compensation for the higher harmonics generated by AF. The AF is composed of a condenser and a power converter using power transistors, and the HPF is a resonance circuit which is made of capacitors, inductors and resistors. The parameters of the SMES unit are shown in Table II. It should be noted that these parameters are not necessarily optimized for the power system stabilizing control.

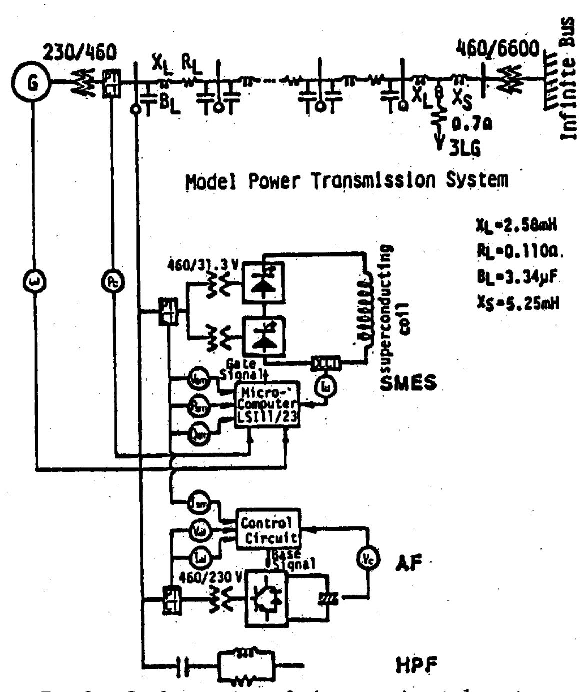


Fig.8. Configuration of the experimental system.

TABLE II
Parameters of a SMES unit

Superconducting coil	
inductance	0.264 H
winding inner diameter	310 mm
winding outer diameter	494 mm
winding length	256 mm
material	NbTi/Cu/CuNi
GTO power converters	
ratio of transformer	460/31.3 V
connection of transformer	Delta-Delta & Star-Delta
no load maximum voltage	42.3 V x 2
Active filter	
ratio of transformer	460/230 V
capacitance of condenser	4400 μF
High pass filter	
capacitance	30 μF
inductance	0.25 mH
resistance	1.0 Ω
resonant frequency	1.8 kHz

Control scheme of SMES for power system stabilization

The SMES is capable of controlling active and reactive power simultaneously so as to follow the specified active power (P_S) and reactive power (Q_S) [11-12]. For the power system stabilization scheme represented by (8) and (10), the following feedback control for P_S and Q_S is provided.

$$\Delta P_S=-K_D\Delta\dot{\delta}, \quad \Delta Q_S=-K_V\Delta V_s \tag{13}$$

In addition, the following reactive power control represented by (14) and the active power control represented by (15) are provided for the purpose of making comparison.

$$\Delta P_S= 0 \quad , \quad \Delta Q_S=-K_V\Delta V_s \tag{14}$$

$$\Delta P_S=-K_D\Delta\dot{\delta}, \quad \Delta Q_S= 0 \tag{15}$$

Experimental set-up

The superconducting coil is initially charged to the current of 100 [A], that is, the energy of 1.32 [kJ]. At this current level the power converters are capable of controlling active and reactive power in a four quadrant circular not exceeding 8 [kVA] with power loss level of 1.2 [kW].

Experimental results

Figure 9 shows the experimental results, where the SMES is located at the generator terminal.

When the reactive power control is applied, the fluctuation of voltage is suppressed although the damping of power oscillation is hardly improved. The damping is improved when the active power control is used. In contrast with these, the fluctuation of voltage is suppressed and the damping is improved as well when the simultaneous control of active and reactive power is applied.

From these experimental results, the necessary capacity of the power converter is estimated as approximately 2 [kVA] by neglecting the power loss. The energy used for stabilizing control (the difference between the maximum and the minimum stored energy levels) is about 500 [J]. These values correspond to 400 [MVA] and 100 [MJ], respectively, in terms of a 2000 [MVA] real power system. These values are in good agreement with the results of numerical analysis.

Evaluation of SMES location

In order to evaluate the effective location of SMES quantatively, damping component exp(-σt) is roughly calculated, based on the power oscillation mode with a frequency of about 1 Hz which is dominant in the waveform of δ. Table III shows the increment of σ (1/s) from the case without control. It can be concluded from Table III that the effective location is at the generator bus.

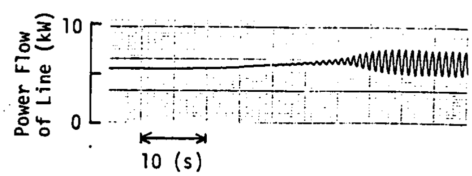
TABLE III
Experimental evaluation of SMES location

location of SMES (equivalent distance from the generator) \ control scheme	by only reactive power	by active & reactive power
0 km	0.5	2.1
80 km	0.6	1.8
160 km	0.5	1.6
240 km	0.4	0.8

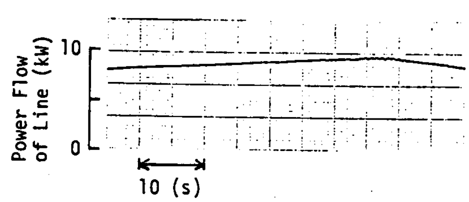
Effect of increasing stably transmitted power

Figure 10 shows the behavior of power oscillation with respect to the gradual increase in generator power output. Here, only for this case, the torque angle between the generator and the infinite bus is enlarged by dropping the generator terminal voltage to 220 [V] in order to simulate the heavy power flow condition.

Without control, the power system is able to transmit power up to only 6.4 [kW]. When the active and reactive power control by SMES is applied, the power system becomes stable up to 9.3 [kW] which is the power limit of this experimental apparatus.



(a) without SMES



(b) with control using active and reactive power
(K_D = 0.13 [pu/(rad/s)], K_V = 3.4 [pu/pu])

Fig.10. Behavior of power oscillation with respect to the gradual increase in generator power output.

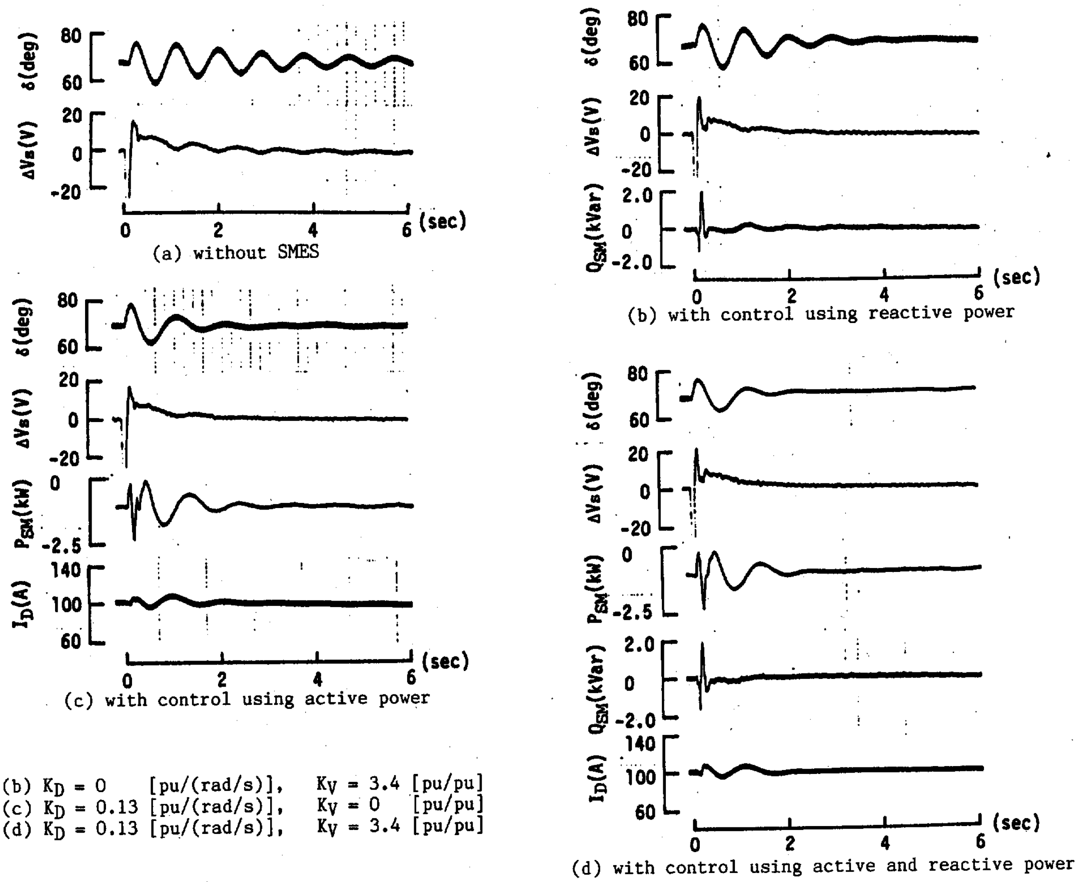


Fig.9. Experimental results.

CONCLUSION

(1) Control system using superconducting magnet energy storage (SMES) has been presented as one of the powerful stabilizers for undamped power oscillation which tends to occur in a long distance bulk power transmission system.

(2) Stabilizing control scheme, using simultaneous control of active and reactive power of SMES in four quadrant ranges, has been constructed.

(3) Effective location of SMES in a long distance bulk power transmission system has been examined, and the region near the generator terminal is recommended as suitable.

(4) Stabilizing effect of SMES has been demonstrated numerically by digital simulation, as well as experimentally by using the SMES system and the artificial power transmission system installed at the Laboratory for Applied Superconductivity, Osaka University. Also the ability of increasing transmission capacity has been confirmed.

(5) The peak ratio of AC/DC converter and the energy used for stabilizing control are almost the same ratings as the fluctuation of power swing without SMES control.

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APPENDIX

NOMENCLATURES

M	inertia constant of generator
D_M	damping factor of generator
P_m	mechanical input of generator
P_e	generator output
δ	torque angle based on the infinite bus
x_d'	d-axis transient reactance
V_t	generator terminal voltage
V_i	voltage of the infinite bus
P_{SM}	active power of SMES
Q_{SM}	reactive power of SMES
P_S	specified value for the control of P_{SM}
Q_S	specified value for the control of Q_{SM}
V_s	voltage of the bus with SMES
δ_s	phase of V_s
I_D	DC current of the superconducting coil
s	Laplace operator
$\cdot$	time differential
x_t	reactance of transformer
x_{r1}	reactance of the line between generator and SMES
x_{r2}	reactance of the line between SMES and the infinite bus

****** applied to the second-order model ******

V_g	voltage behind x_d'
x_1	$= x_d' + x_t + x_{r1}$
x_2	$= x_{r2}$

****** applied to the third-order model ******

T_{do}'	d-axis open circuit transient time constant of generator
e_q'	$= V_q + x_d' I_d$
V_q	projection on the q-axis of V_t
I_d	projection on the d-axis of armature current
x_d	d-axis synchronous reactance
e_{fd}	voltage of field winding circuit

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Yoshishige Murakami was born in Taiwan, Japan in 1932. He received the B.S. and the M.S. degrees, and Dr. of Engineering degree from Osaka University, Osaka, Japan in 1955, 1962 and 1967, respectively.

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Dr. Murakami is a member of the Institute of Electrical Engineers of Japan.

Discussion

Peter Donalek (Harza Engineering Co., Chicago, IL): The authors are to be congratulated on an interesting and informative paper. The description of voltage and power control aspects of SMES should be of use to electric utility engineers.

My question is with regard to the parameters used in the transmission line model. The ratio of series reactance to series resistance is on the order of 9.2. This seems high when compared to similar values for transmission lines. How would the results of the SMES experiments change if the X/R ratio were on the order of 5.0 to 6.5?

There are other ways to provide system damping for system stability. See: IEEE paper F76 626-2, "A Description of Discrete Supplementary Controls For Stability", Trans. PAS Jan/Feb 78 pages 149-165. Among these is the shunt resistor brake. As a point of reference it would be interesting to know what size of resistor brake would be required to obtain the same effect as the SMES.

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Y. Mitani, K. Tsuji and Y. Murakami : The authors would like to express their appreciation to Mr. Peter Donalek for his valuable discussion.

Concerning the first question; the parameters shown in Table I are the measured ones in the artificial power transmission system. For the design of the artificial system, emphasis was laid on the value of reactance rather than resistance, which is because the value of reactance corresponds to the electrical distance in AC power systems. It is the reactance which dominates the power system stability, and therefore, the power system stabilizing control by SMES would give the same effective results even if the X/R ratio were on the order of 5.0 to 6.5.

Concerning the second question; the effect on the power system stabilizing control by using the active power of SMES is essentially the same as that of the shunt resistor brake. Therefore, it is very interesting to compare these effects as pointed out by the discusser. With regard to this, the authors would like to give the following comments:

1) The shunt resistor brake is only able to consume the accelerative power and is not able to supply the power.

2) When the power system voltage drops, power consumption by the shunt resistor brake decreases proportionally to the square of the system voltage. However, in the case of the SMES, the active power is not only consumed but also supplied exactly as specified since the system voltage is maintained by the reactive power control. Therefore, it can be said that the effectiveness of the power system stabilization by SMES is always more significant than that by the resistor brake of the same size.

Taking these points into consideration, it can be concluded that the resistor brake would require at least twice the capacity of SMES in order to obtain the same effect as the SMES.

3) Discrete control like the resistor brake is effective on the improvement of the transient stability. However, it is almost impossible to control the instability of power system dynamic performance; that is, the effect of increasing stably transmitted power as shown in Fig.10 cannot realistically be achieved using the resistor brake.

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