POWER SYSTEM STABILIZATION BY SUPERCONDUCTING MAGNETIC ENERGY STORAGE CONNECTED TO ROTATING EXCITER

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Abstract—This paper describes a combination of a rotating exciter and a superconducting magnetic energy storage (SMES) for an efficient power system stabilization. The SMES proposed in this paper, is connected to an exclusive exciter rotating with a turbine-rotor shaft of a generator. Since electrical power output from the SMES is converted into mechanical torque of the generator directly by the exciter, it is expected that power swings of the generator are damped out efficiently. Several numerical studies demonstrate that the proposed control system is capable of stabilizing torsional oscillations as well as electro-mechanical oscillations in power systems significantly.

I. INTRODUCTION

A long distance bulk power transmission and an interconnection between large power systems are the characteristics of recent-year power systems. With the increase of these structures, several new dynamic problems have emerged in power systems [1]. The typical examples are undamped power oscillations with low frequencies and torsional oscillations of steam turbine generators [1], [2]. Many countermeasures, therefore, have been developed so far; signal additions of a power system stabilizer (PSS) to the automatic voltage regulator (AVR), controls by a static var compensator (SVC), introductions of a DC transmission system and so on. In the circumstances a superconducting magnetic energy storage (SMES) has been expected as one of the most effective and significant stabilizers for power systems [3],[4],[5]. In this paper a new configuration of SMES to stabilize power systems more efficiently, is proposed.

A typical configuration of SMES consists of a superconducting magnet and a set of power converters, which is connected to an appropriate bus in power systems through the power converters. A proper control of the converters makes it possible to control active and reactive power simultaneously at the bus where the SMES is located [6]. Active power has an ability of damping out power oscillations by controlling the electrical torque of generators. Reactive power assists the power system stabilization by suppressing the fluctuation of the bus voltage [3]. The rapid controllability of the generator torque by the SMES produces the significant effectiveness in the power system stabilizing control. However, it should be noted that all of active power flowing into the bus from the SMES does not operate for the power system stabilization; that is, a part of the active power flows into the opposite direction against the generator, which is useless for the power system stabilization.

In this paper a SMES connected to an exciter rotating with a turbine-rotor shaft, is proposed. All synchronous generator has a conventional exciter to supply the field winding current. The exciter mentioned here is installed exclusively to supply the current of the SMES. The electrical power output from the SMES is entirely transmitted as a mechanical torque of generator directly through the exciter. Therefore, it is expected that the control system is capable of stabilizing power oscillations efficiently; i.e., energy and power capacities of the SMES necessary for the power system stabilization might be reduced.

To confirm the effectiveness of the proposed control system, several numerical investigations have been carried out by using a real scale power system model with long distance bulk power transmission. It has been demonstrated that the proposed SMES stabilizes torsional oscillations as well as electro-mechanical power swings, significantly.

Manuscript received August 24, 1992.

II. POWER SYSTEM MODEL

Figure 1 shows a model power system with a 4,480 (MVA) nuclear power plant, 500 (kV) and 50 (km) double circuit transmission lines and an infinite bus. The power plant contains four identical 1,120 (MVA) turbine generators. In numerical investigations, however, four 1,120 (MVA) generators are treated as a 4,480 (MVA) generator.

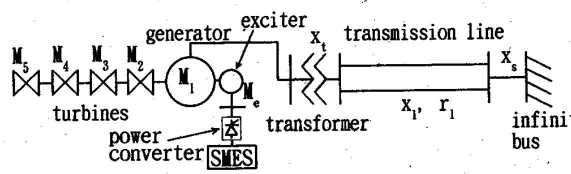

Fig 1 Model power system

Each generator has four steam turbines (a high pressure one, two middle pressure ones and a low pressure one) represented by masses M_2 through M_5, which are connected to the rotor with a mass M_1 in cascade. In addition an exciter with a mass M_e, which supplies current for a SMES, is connected to the rotor also in cascade. A mass of the conventional exciter that supplies the field winding current, is ignored.

Behaviors of generators, mechanical characteristics of rotor-turbine linkage and electrical characteristics of the transmission lines are represented by the Park's model, the rotating mass-spring model and the L-R transient circuit model, respectively. Figure 2 shows the characteristic of AVR. Effect of governor is ignored. Thus mechanical input from the turbines to the generator is constant. System constants are shown in Table 1.

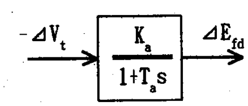

Fig 2 Block diagram of AVR.

In simulation studies a fault is assumed as a system disturbance that the infinite bus voltage drops from 1.0 (pu) to 0.8 (pu) in 4 (cycles). It corresponds to a three line grounding at a distant point, which is cleared sequentially by high speed protective relays.

III. MODELING OF CONTROL SYSTEM

The power converters of the SMES supply the exciter with active power. Therefore, output power from the SMES is converted into the generator torque by the exciter directly through a shaft linkage to the rotor. These characteristics are represented by a simplified model with a first order time lag (see Fig. 3), where ΔP_s is the deviation of the specified power output from the SMES and ΔP_m is the deviation of the really controlled power output. Here, it is assumed that ΔP_m is equivalent to the deviation of mechanical input

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Table 1 System constants.

(4,480 (MVA) base per unit)

Generator

armature winding:

x_d=1.60 x_q=1.60 r_a=0.00181

damper winding:

x_{kkd}=1.38 x_{kkq}=1.37 r_{kd}=0.007 r_{kq}=0.014

field winding:

x_{ffd}=1.44 r_{fd}=0.0006 (T_{do}'=6.37 seconds)

mutual reactance:

x_{ad}=1.35 x_{aq}=1.35

inertia (in seconds):

M_1=1.81 M_2=1.90 M_3=1.86 M_4=0.81 M_5=0.40 M_e=0.10

damping coefficient :

D_{11}=0.0 D_{22}=0.25 D_{33}=0.25 D_{44}=0.25 D_{55}=0.25 D_{ee}=0.25

D_{12}=1.2 D_{23}=0.60 D_{34}=0.60 D_{45}=0.60 D_{45}=0.60 D_{e1}=0.60

spring constant:

K_{12}=23.4 K_{23}=15.5 K_{34}=13.3 K_{45}=11.9 K_{e1}=150.0

(subscript 1:rotor, 2 - 5:turbines, e:exciter)

Transmission line (per double circuits)

x_t=0.197 x_s=0.1925 r_l=0.00463 x_l=0.14

AVR

K_a=21.7 T_a=0.01 (second)

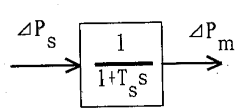

Fig 3 Characteristics of active power control by SMES.

power to the generator. The time constant T_s is set to 0.01 (s).

IV. POWER SYSTEM STABILIZING CONTROL SCHEME

In order to stabilize power system the specified value ΔP_s shown in Fig. 3 must be controlled properly. In this paper, the following control scheme has been selected based on the same idea as the SMES connected to the generator terminal bus [5].

$$\Delta P_s=-K_c\Delta\omega/(1+T_cs)+K_P(\omega_1-\omega_2) \quad (1)$$

The first term of the right side in equation (1) represents the control of power swing using the deviation of angular velocity of the rotor ($\Delta\omega$). The fist order time lag $1/(1+T_cs)$ is added as a low pass filter with a time constant T_c=0.02 (s) so that the torsional oscillation components which have high frequencies are eliminated. The second term represents the control of torsional oscillations using the difference between the angular velocities of the rotor (ω_1) and the adjacent turbine (ω_2). K_c and K_P are the control gains.

V. EVALUATION OF CONTROL EFFECT

A. Comparison of effect with a SMES located at generator terminal

In this paper the SMES connected to an exciter, is proposed. To evaluate the control effect, the SMES located at the generator terminal bus and the SMES connected to the exciter are compared with each other. To avoid confusion the former is called "the conventional SMES" and the latter, "the proposed SMES" in this paper.

Figures 4, 5 and 6 show simulated swing curves. Initial power output from each generator is 1,000 (MW). Parameters of the controller in equation (1) are set as K_c=30.0 and K_P=150.0 for the conventional SMES and as K_c=20.0 and K_P=100.0 for the proposed SMES. These conditions have been set so that controlled swing curves are almost same with each other. Note that, however, active power output is larger in the case of the conventional SMES.

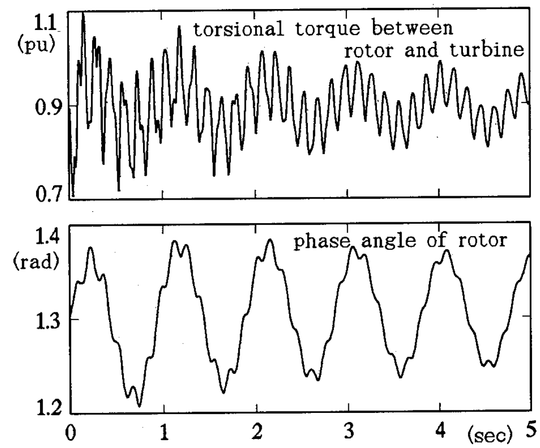

Fig 4 Simulated swing curves without SMES.

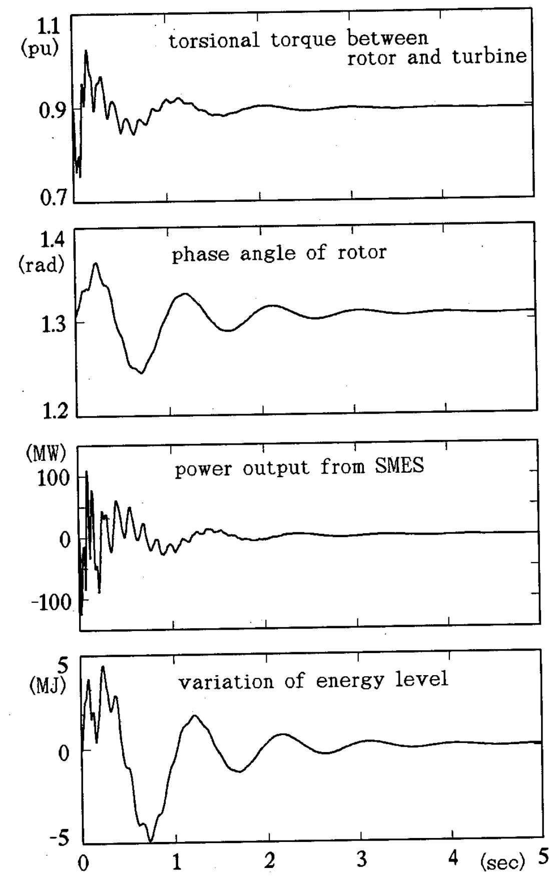

Fig 5 Simulated swing curves with the conventional SMES.

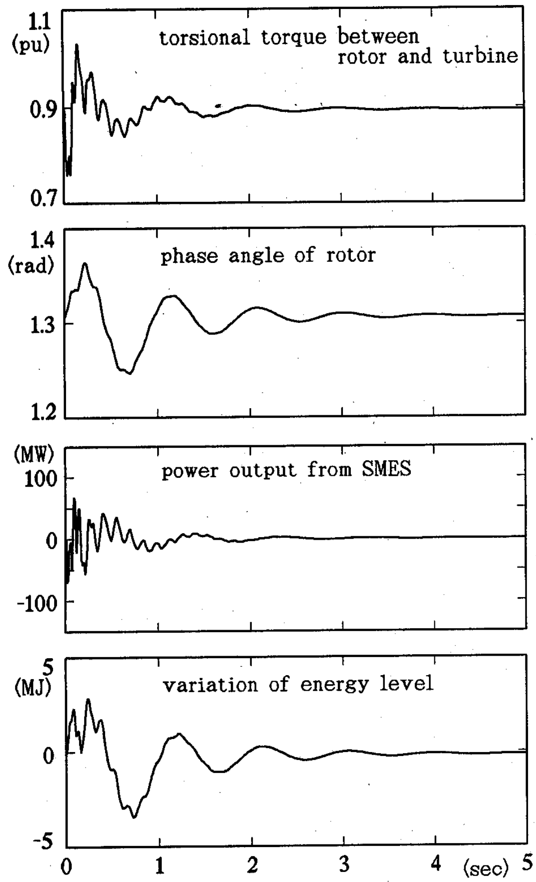

Fig 6 Simulated swing curves with the proposed SMES.

The magnitude of power output and the energy variation resulting from the power system stabilization are evaluated from the simulated curves. In the case of the conventional SMES, they are 124 (MW) and 9.4 (MJ), and in the case of the proposed SMES, 70 (MW) and 6.3 (MJ), respectively, where each value is in terms of one 1,120 (MVA) generator. These results show that the proposed SMES saves about 40(%) of power and 30(%) of energy.

B. Energy and power capacities necessary for the control

To evaluate the necessary capacities of SMES for the power system stabilization, a limit on the peak power output was set. Then the effectiveness of stabilization was calculated using the following criteria [7].

$$J_1=\int_0^5(\Delta T_{12})^2dt \tag{2}$$

$$J_2=\int_0^5(\Delta\theta_1)^2dt \tag{3}$$

where ΔT_{12} is the deviation of torsional torque between the rotor and the adjacent turbine and $\Delta\theta_1$ is the deviation of phase angle of the rotor. Figure 7 shows the variations of criteria J_1 and J_2 for different values of the limit on the peak power output.

It can be seen from Fig. 7 that effectiveness does not get worse until the limit becomes lower than around 40 (MW). Figure 8 shows the swing curves when the peak power output is limited to 40 (MW), each of which is not very much different from the corresponding curves in Fig. 6.

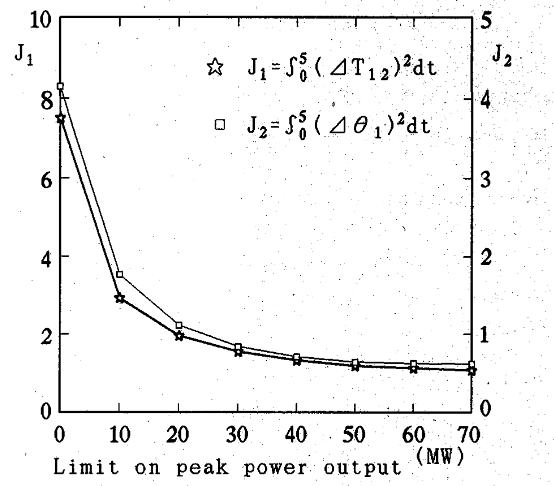

Fig 7 Variations of criteria J_1 and J_2 for different values of the limit on the peak power output.

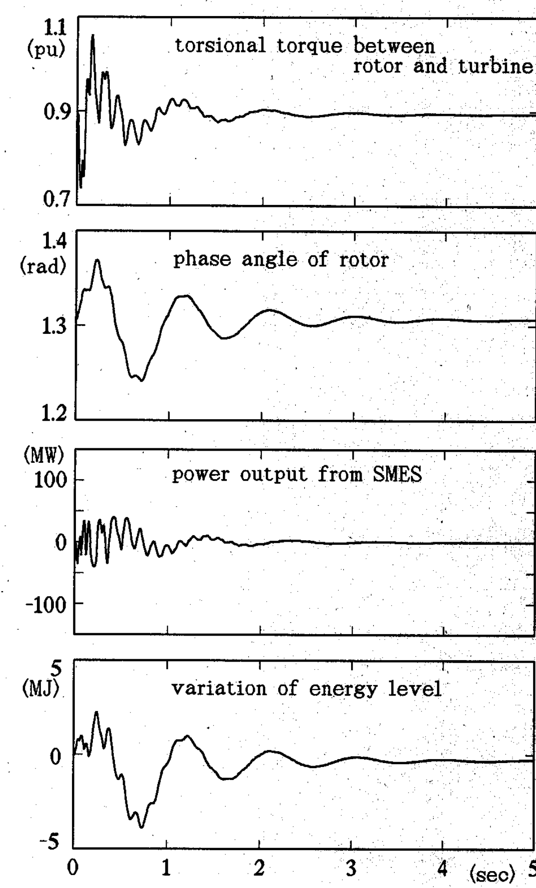

Fig 8 Swing curves when the peak power output is limited to 40 MW.

These results mean that an exciter that can generate electrical and mechanical power of more than 40 (MW) is necessary for the realization of the proposed control system. A conventional exciter used for the high speed AVR of a 1,000 (MVA) class generator has a capacity of about 10 (MVA). The exciter used for the proposed SMES should be several times larger.

C. Effect of increasing transmission power

In a power system with long distance transmission lines, power swings after any disturbances tend to be unstable when the power flow is heavy. The model power system is almost unstable without the SMES when 4,000 (MW) is transmitted (see Fig. 4). Here, the maximum power that can be transmitted stably when the proposed SMES is applied, has been evaluated by increasing the number of 1,120 (MVA) generators. Figure 9 shows the swing curves when ten generators are installed and 10,000 (MW) power is transmitted. The power system becomes almost unstable at this power flow. Stable transmission power has increased to about twice by applying the proposed SMES. In this case the peak power output of SMES has been limited to 40 (MW). The variation of energy evaluated from the simulated curves is about 16 (MJ). It is because the period of power swing is much longer that the variation of energy is larger than that in Fig. 8.

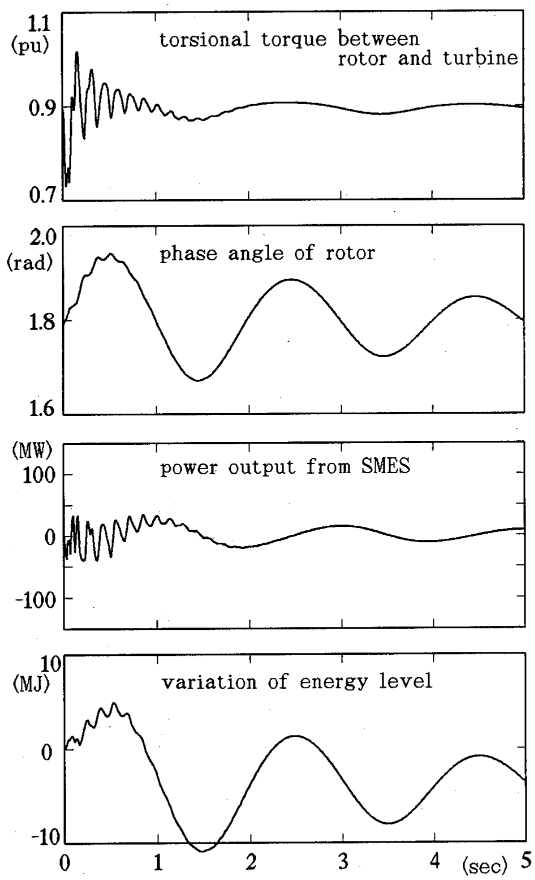

Fig 9 Swing curves with the proposed SMES when 10,000 MW is transmitted.

VI. CONCLUSION

A power system stabilizing control system using a superconducting magnetic energy storage (SMES) which is connected to a generator through an exciter, is proposed. This system is capable of stabilizing torsional oscillations as well as electro-mechanical power swings more efficiently than the SMES connected to the generator terminal bus. Necessary capacity of the exciter for a 1,120 (MVA) generator is about 50 (MVA) and the amount of energy variation in the SMES is about 15 (MJ). Transmission capacity of the model power system has been increased significantly by the proposed SMES.

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