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Power System Stabilization by Superconducting Magnetic Energy Storage with Solid-State Phase Shifter

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Abstract - **In this paper, a new configuration of power system controller with a combination of superconducting magnetic energy storage and phase shifter, is proposed to improve the stability of a long distance bulk power transmission system. A power system stabilizing control scheme is also proposed. A related simulation shows that the proposed controller is effective for enhancement of power system stability independent of the location of controller in a long distance bulk power transmission system.**

Keywords: FACTS, Phase shifter, Superconducting magnetic energy storage, Power system stabilization.

I. INTRODUCTION

Power system stability problems have attracted attention of power system engineers for several decades. Considerable progress has been made on excitation control, governor control, control by static var compensator and so on [1-4]. Modern power systems, which are growing in size and complexity, are characterized by long distance bulk power transmissions and wide area interconnections. In such power systems, undamped power swings with low frequencies are latent [5]. It has become a new serious problem since the instability often detracts from the power transmission capacity.

In the circumstances superconducting magnetic energy storage (SMES) has been expected as a new effective apparatus in power systems since a SMES is capable of leveling load demand with high efficiency, compensating for load changes and maintaining a bus voltage as well as stabilizing power swings [6-10]. However, it is a problem that each efficacy depends upon the location of the SMES in the power system because the output power from the SMES flows in accordance with line impedances viewed from the SMES location. Therefore, it is rather difficult for a SMES to serve for two different purposes at the same time.

On the other hands, much attention has been paid on the research for improving the power system behaviors by using high-speed power electronic devices. The potential of power electronics allows us to introduce a new concept of an ac power system. This concept is called FACTS (Flexible AC Transmission System) [11-14]. FACTS controllers such as thyristor-controlled series capacitors, thyristor-controlled breaking resistors, static var compensators and thyristor-controlled phase shifters, are utilized for dynamically adjusting the network configuration to enhance steady state performances as well as transient stability in power systems [15].

This paper proposes a power system stabilizer consisting of a superconducting magnetic energy storage and a thyristor-controlled phase shifter. The phase shifter, which consists of a phase shift transformer, a DC link capacitor and two sets of thyristor-controlled power converters [13, 16], is capable of controlling power flow of the transmission line arbitrary by adjusting magnitude and phase angle of the secondary voltage of the phase shift transformer. It is expected, therefore, that the combination of SMES and phase shifter can realize a power system controller with significant effectiveness less influenced by its location in power system.

First, a control scheme for power system stabilization is derived based on an equivalent model of the proposed controller which is expressed by two current sources. Numerical examples demonstrate that the proposed controller located far from a generator in a long distance bulk power transmission system is capable of stabilizing the power swing as effectively as the SMES located at the generator terminal.

II. CONFIGURATION OF THE CONTROLLER AND THE MODELING

Fig. 1 shows a one-line diagram of the proposed controller connected to a transmission line. It has a combined structure of a thyristor controlled superconducting magnetic energy storage (SMES) and a thyristor controlled phase shifter. Each power converter, which is an interface between the three-phase AC transmission system and the DC superconducting magnet, consists of several sets of GTO (Gate-turnoff) Thyristor bridge circuits [7, 13, 17]. The proposed power system stabilizer is realized by replacing the DC link capacitor of the phase shifter [13] with a superconducting magnet [18]. In this paper we

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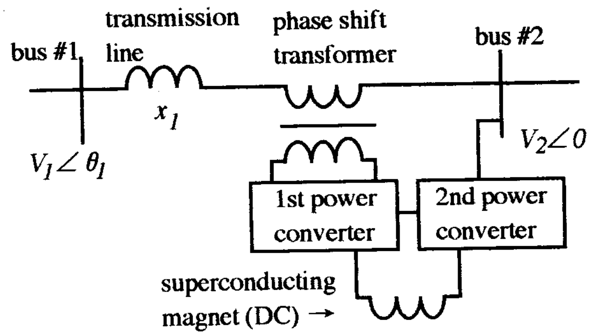

Fig. 1 One-line diagram of the SMES with phase shifter.

call it *"SMES with phase shifter"*.

In Fig. 1, V_1 and V_2 are the magnitudes of bus voltages at bus #1 and bus #2, respectively and θ_1 is the phase angle of V_1 where the voltage at bus #2 is taken as the phasor reference. Here, the bus #1 is assumed to be the point at an electrical distance with arbitrary reactance x_1 from the bus #2.

The SMES with phase shifter contains two sets of power converters, both of which are connected in common to the superconducting DC magnet; the first set of converter injects a voltage in series with the line voltage and the second one injects a current into the bus #2. Note that the power converter of the conventional SMES consists of only the second one.

Fig. 2 shows an equivalent circuit model of the SMES with phase shifter, where the voltage produced by the first power converter and the current injected by the second converter are represented by a voltage source and by a current source, respectively. x_c is a leakage reactance of the phase shift transformer and $\dot{}$ denotes that the variable is a phasor (complex number). Directly controlled values by the SMES with phase shifter are V_c and θ_c, which are controlled by the phase shifter, and the phasor quantities of $\dot{I}_s$ (or the active power P_s and reactive power Q_s), which are controlled by the second power converter [18].

Fig. 3 shows a phasor diagram of the relations between the bus voltages and the line current. It illustrates that the phase shifter injects the voltage $\dot{V}_c$ with arbitrary magnitude and phase, thereby controlling the phase angle between the voltages $\dot{V}_1$ and $\dot{V}_2$ and the line current $\dot{I}$.

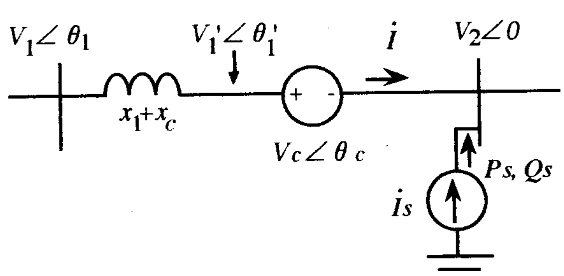

Fig. 2 Circuit model represented by a voltage source and a current source.

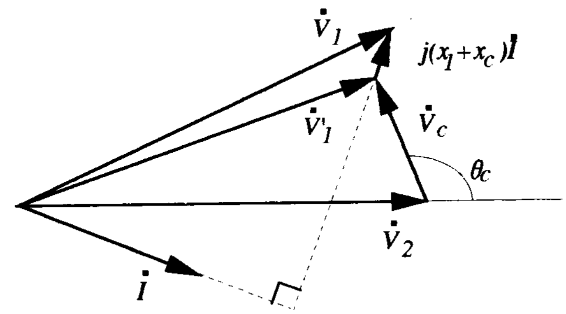

Fig. 3 Vector relationship between the bus voltages and the line current.

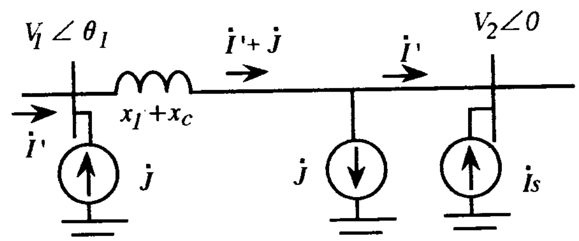

Fig. 4 Circuit model represented by current sources.

Here, the voltage source corresponding to the phase shifter is mathematically transformed into two current sources. Fig. 4 shows the model represented only by current sources.

The relation between the bus voltages and the line current in Fig. 2 is derived from Fig. 3 as

$$V_1 \exp(j\theta_1) = V_2 + V_c \exp(j\theta_c) + j(x_1+x_c)\dot{I}\,, \tag{1}$$

therefore,

$$\dot{I} = \frac{V_1 \exp(j\theta_1) - V_2}{j(x_1+x_c)} - \frac{V_c \exp(j\theta_c)}{j(x_1+x_c)}\,. \tag{2}$$

Similarly, the relation in Fig. 4 is represented by

$$V_1 \exp(j\theta_1) = V_2 + j(x_1+x_c)\,(\dot{I}'+\dot{J}), \tag{3}$$

therefore,

$$\dot{I}' = \frac{V_1 \exp(j\theta_1) - V_2}{j(x_1+x_c)} - \dot{J}\,. \tag{4}$$

By comparing (2) with (4) it is clear that the circuit in Fig. 4 is mathematically equivalent to the circuit in Fig. 2, if

$$\dot{J} = \frac{V_c \exp(j\theta_c)}{j(x_1+x_c)}\,. \tag{5}$$

The summation of two current sources $\dot{J}$ and $\dot{I}_s$ connecting in common to the bus #2 yields Fig. 5, where

$$\dot{J}' = \dot{I}_s - \dot{J}\,. \tag{6}$$

The current sources $\dot{J}$ and $\dot{I}_s$ are not constrained by each other if the stored energy of the superconducting magnet is sufficiently large. Then, Fig. 5 means that the SMES with phase shifter is equivalently represented by two independent

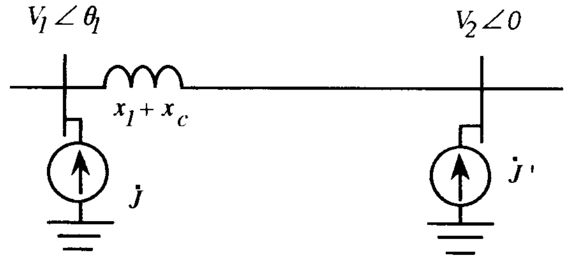

Fig. 5 Circuit model represented by two independent current sources.

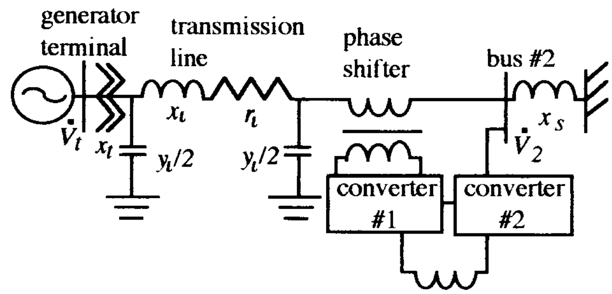

Fig. 6 SMES with phase shifter installed in a long distance bulk power transmission system.

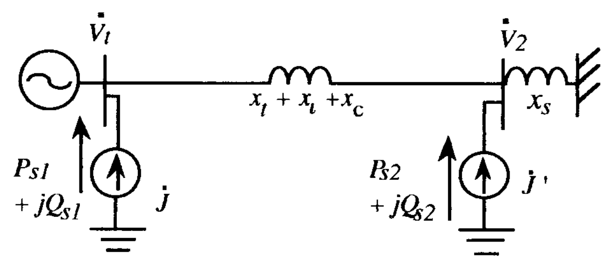

Fig. 7 Apporoximated equivalent circuit.

current sources facing each other across a reactance. It looks as if two sets of SMES are located apart from each other.

Here, the active and reactive power outputs from the current sources $\dot{J}$ and $\dot{J}'$ are represented by using V_c, θ_c, P_s and Q_s which are the directly controlled variables by the SMES with phase shifter. First, active power P_{s1} and reactive power Q_{s1} from the current source $\dot{J}$ are represented by

$$P_{s1}+jQ_{s1}=V_1\exp(j\theta_1)\,\bar{\dot{J}}, \tag{7}$$

where $^{-}$ denotes complex conjugate. Substituting (5) into (7) yields

$$P_{s1}+jQ_{s1}=V_1\exp(j\theta_1)\frac{V_c\exp(-j\theta_c)}{-j\,(x_1+x_c)}. \tag{8}$$

As a result,

$$P_{s1}=V_1V_c\sin(\theta_c-\theta_1)\,/\,(x_1+x_c) \tag{9}$$

$$Q_{s1}=V_1V_c\cos(\theta_c-\theta_1)\,/\,(x_1+x_c). \tag{10}$$

Similarly, active power P_{s2} and reactive power Q_{s2} from the current source $\dot{J}'$ are represented by

$$P_{s2}=-V_2V_c\sin(\theta_c-\theta_2)\,/\,(x_1+x_c)+P_s \tag{11}$$

$$Q_{s2}=-V_2V_c\cos(\theta_c-\theta_2)\,/\,(x_1+x_c)+Q_s, \tag{12}$$

Hypothetical active and reactive power outputs P_{s1} and Q_{s1} at the bus #1 and P_{s2} and Q_{s2} at the bus #2 are respectively controlled by V_c, θ_c, P_s and Q_s according to (9) through (12).

III. DESIGN OF POWER SYSTEM STABILIZING CONTROL SCHEME

Here, it is assumed that a SMES, which is used for load leveling, load frequency control or so on, has been already located far from the generator in a long distance bulk power transmission system. In the circumstances it is difficult for the SMES to stabilize the power swing of the generator. Here, power system stabilization by the SMES with phase shifter (see Fig. 6), is undertaken.

For simplicity, let the resistance and the susceptance of the transmission line be ignored for the design of control scheme. Then, by assigning the total reactance of the line and the transformer to the reactance x_l in Fig. 1, an approximated equivalent circuit for the single machine against an infinite bus system is represented by Fig. 7.

In Fig. 7 an equivalent power system model with a SMES at the generator terminal and a SMES far from the generator has been obtained. The significant effectiveness for enhancement of power system stability by a SMES located at the generator terminal has been already confirmed in the literature [9, 17]. Here, we can apply the same control scheme to the SMES with phase shifter, that is, active and reactive power of the hypothetical current source $\dot{J}$ are utilized for the damping control of the electro-mechanical oscillation as follows;

$$P_{s1}=-K_D\Delta\omega \tag{13}$$

$$Q_{s1}=-K_V\Delta V_t, \tag{14}$$

where $\Delta\omega$ is the deviation of angular velocity of the generator and ΔV_t is the deviation of the generator terminal voltage.

In addition, there is another active and reactive power injection (P_{s2} and Q_{s2}) coming from the hypothetical current source $\dot{J}'$. They are utilized for the original purpose, that is, load leveling, load frequency control, etc..

Actual control variables of the SMES with phase shifter can be easily calculated from (9) through (14) in which V_1, θ_1 and (x_1+x_c) are replaced with V_t, θ_t, and x ($x=x_t+x_l+x_c$), respectively, as follows;

$$V_c=\frac{x\sqrt{(K_D\Delta\omega)^2+(K_V\Delta V_t)^2}}{V_t} \tag{15}$$

$$\theta_c-\theta_t=\tan^{-1}\left(\frac{-K_D\Delta\omega}{-K_V\Delta V_t}\right) \tag{16}$$

$$P_s=V_2V_c\sin(\theta_c-\theta_2)\,/\,x+P_{s2} \tag{17}$$

$$Q_s=V_2V_c\cos(\theta_c-\theta_2)\,/\,x+Q_{s2}. \tag{18}$$

(16) represents that the phase angle θ_c is controlled by taking the generator terminal voltage as the reference.

IV. SIMULATION STUDY

Simulation study has been carried out by using a model power system shown in Fig. 6, which models a 4,000 MVA nuclear power plant, 500 kV and 100 km double circuit transmission lines and an infinite bus. The power plant contains four identical 1,000 MVA turbine generators. In numerical investigation four 1,000 MVA generators are treated as a 4,000 MVA generator with an AVR and a governor each of which is simply represented by first-order time lag. System constants are shown in Table I.

Since the phase shift transformer is connected in series with the transmission line, it is desired that the leakage impedance of the transformer is large in order to protect the phase shifter from the short circuit currents, whereas it should be small from the viewpoint of power system stability. In this study, the value of the leakage impedance was set to 0.15 pu,

TABLE I
SYSTEM CONSTANTS.

Generator (Park's 5-th order model, 1,000 MVA base)	
d-axis synchronous reactance	x_d=1.79 pu
d-axis transient reactance	x_d'=0.355 pu
d-axis subtransient reactance	x_d''=0.275 pu
q-axis synchronous reactance	x_q=1.66 pu
q-axis transient reactance	x_q'=0.570 pu
q-axis subtransient reactance	x_q''=0.275 pu
leakage reactance	x_{leak}=0.215 pu
armature resistance	r_a=0.00480 pu
field winding circuit time constant	T_{do}'=7.90 s
d-axis subtransient time constant	T_{do}''=0.0320 s
q-axis transient time constant	T_{qo}'=0.410 s
q-axis subtransient time constant	T_{qo}''=0.0550 s
inertia constant	M=2H=7.53 s
damping coefficient	D=2.00 s
Transmission system (π type circuit, 4,000 MVA base)	
reactance of transformer	x_t=0.150 pu
reactance of line	x_l=0.252 pu
resistance of line	r_l=0.00842 pu
susceptance of line	y_l=0.0611 pu
short circuit reactance	x_s=0.133 pu
SMES with phase shifter	
leakage reactance of phase shifter	x_c=0.150 pu
control gains	K_D=50.0 pu/pu
	K_V=1.00 pu/pu
AVR (first-order time lag model)	
gain	K_a=60.0 pu/pu
time constant	T_a=0.10 s
Governor (first-order time lag model)	
gain	K_g=10.0 pu/pu
time constant	T_g=2.0 s

which is as large as the case of the step-up transformer used for generator.

Here, to evaluate only the effectiveness of the power system stabilization, P_{s2} *and* Q_{s2} in (17) and (18) were set to zeros. Assumed system disturbance is a three phase short circuit at the transmission line near the generator terminal. The fault duration time is 0.01 s. In order to comparatively investigate the effectiveness of the SMES with phase shifter, the cases that the conventional SMES (that is, the SMES without phase shifter) is located far from the generator and that the conventional SMES is located near the generator, are considered. Control scheme of the active power P_s and reactive power Q_s of the conventional SMES is

$$P_s = -K_D \Delta \omega \quad (19)$$

$$Q_s = -K_V \Delta V_s , \quad (20)$$

where $\Delta\omega$ is the deviation of generator angular velocity and ΔV_s is the deviation of the voltage at the SMES location.

Figs. 8, 9, 10 and 11 show the simulation results. The maximum output of V_c is limited to 0.03 pu (15 kV) in the case of the SMES with phase shifter since it becomes pulsive right after the fault without the limit.

The power flow is very heavy that the power system without control is unstable. The conventional SMES located far from the generator does not sufficiently stabilize the power swing. In contrast, the conventional SMES located at the generator terminal stabilizes the power swing effectively. The effectiveness of the SMES with phase shifter is almost the same as that of the SMES located at the generator terminal, although the SMES with phase shifter has a large leakage reactance in series with the transmission line. It can be concluded that the addition of the phase shifter to the SMES located far from the generator is significantly effective on the power system stabilization.

It is very interesting that the active power from the converter #2 of the SMES with phase shifter in Fig. 11 has almost the same waveform as the active power from the SMES located at the generator terminal in Fig. 10. It can be said that the active power from the converter #2 is effectively directed toward the generator by the phase shifter for stabilizing the generator power swing. It is calculated from the simulation

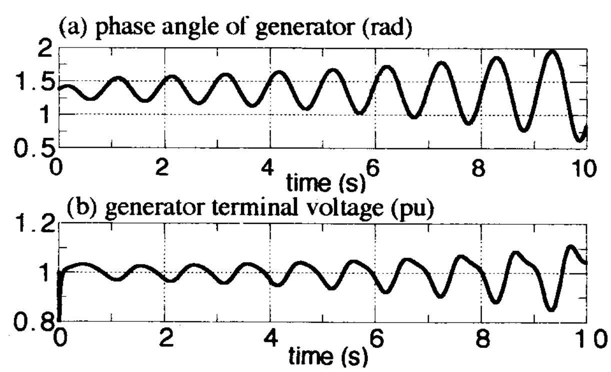

Fig. 8 Dynamic responses for the system without control.

results in this case that the necessary capacity of the phase shifter is about 120 MVA while the exchanged energy in the superconducting magnet is about 70 MJ and the maximum power passing through the converter #2 is about 200 MVA.

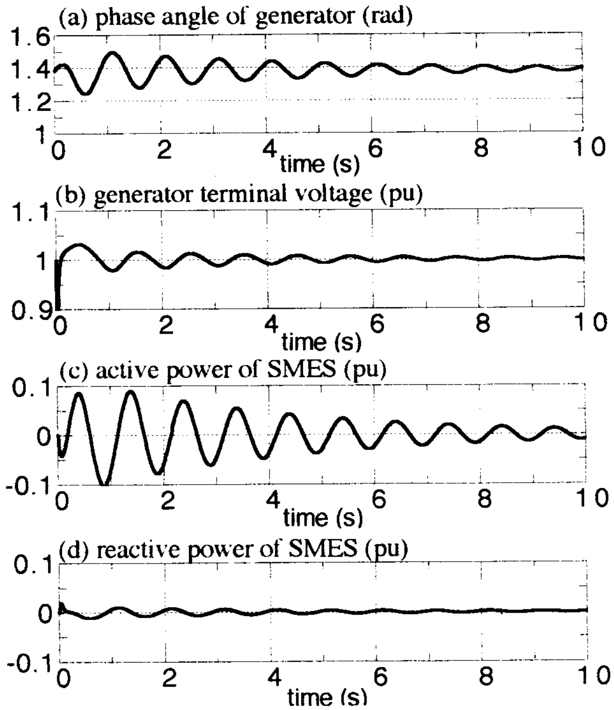

Fig. 9 Dynamic responses for the system controlled by the SMES located far from the generator.

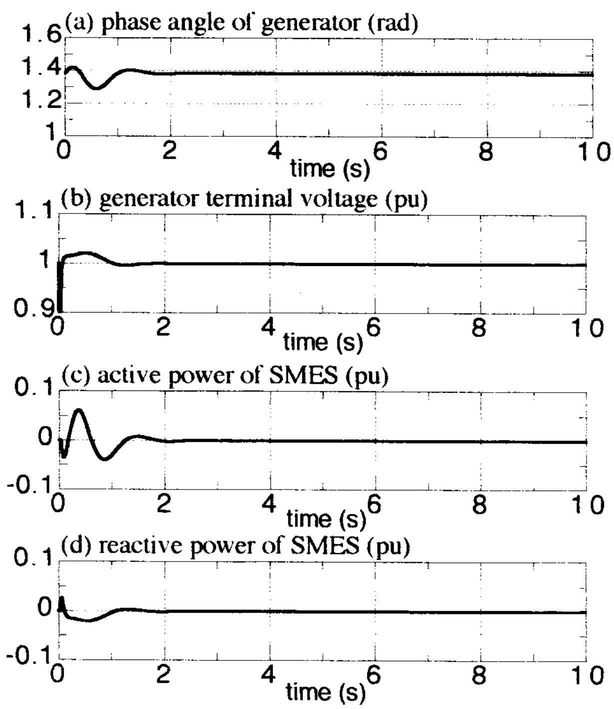

Fig. 10 Dynamic responses for the system controlled by the SMES located at the generator terminal.

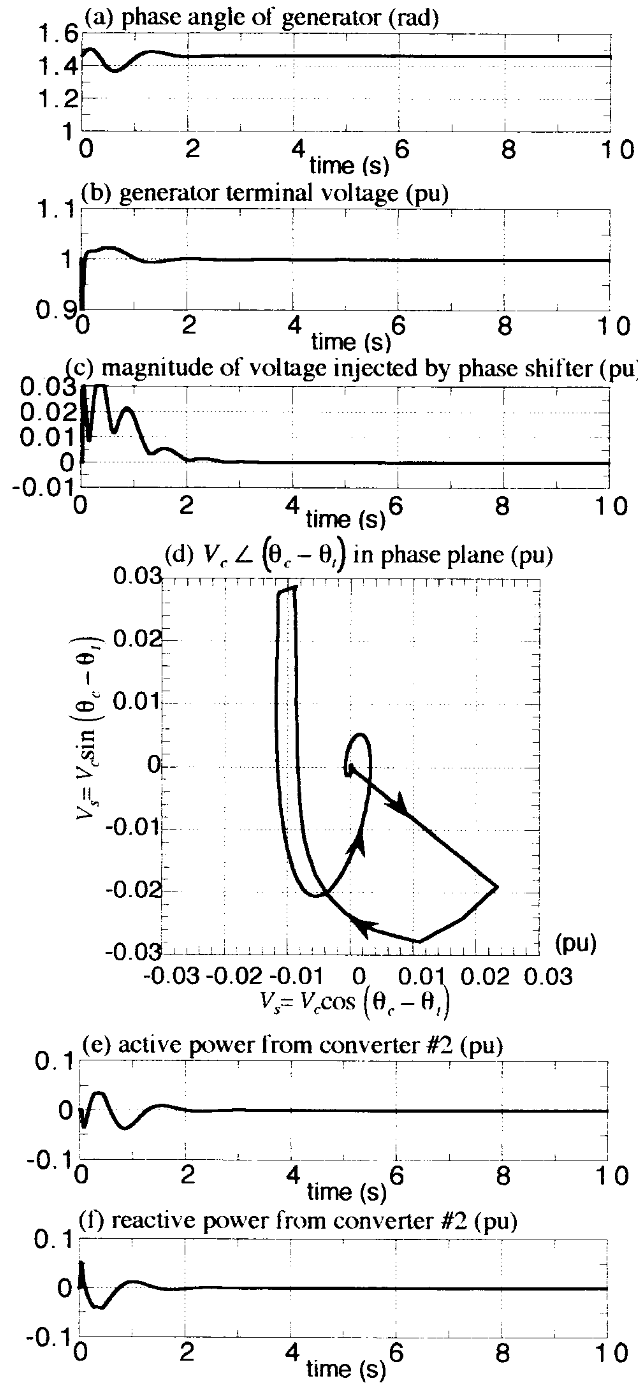

Fig. 11 Dynamic responses for the system controlled by the SMES with phase shifter.

V. CONCLUSIONS

A new stabilizing controller for power systems, which is composed of a superconducting magnetic energy storage and a solid-state phase shifter (SMES with phase shifter), has been proposed. The main results are summarized below.

(1) The SMES with phase shifter has been modeled as two independent current sources which look like two sets of SMES

located apart from each other.

(2) A power system stabilizing control scheme has been introduced based on the two current source model, in which a current source near the generator has been used for the power system stabilization.

(3) It has been numerically confirmed that the SMES with phase shifter is significantly effective for the stabilization of a long distance bulk power transmission system even though it is located far from the generator.

(4) Although the leakage reactance of the phase shifter might make the power system stability worse, the effect on enhancement of the power system stability by the SMES with phase shifter is larger by far.

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