Experimental Study on Power System Stabilizing Control Scheme for the SMES with Solid-State Phase Shifter(SuperSMES)

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Abstract—**The combination of a Superconducting Magnetic Energy Storage(SMES) and High Speed Phase Shifter is considered to be a unified power system controller. The combined system has been named as SuperSMES from the viewpoint of its capability. A new control scheme of the SuperSMES for the power system stabilization with a simple control sequence composed of local signals has been proposed. This paper shows the results of a new stabilizing control scheme of the SuperSMES for power system stabilization based on experimental results with a 10 kJ superconducting magnet and a 10 kVA model power transmission system.**

I. INTRODUCTION

Power system stability problems have been attracting 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[1-2]. 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[3]. It has become a new and serious problem since the instability often detracts from the power transmission capacity.

Under these circumstances superconducing magnetic energy storage(SMES) is expected to become 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 swing[4-6].

A combination of SMES with a high-speed UPFC (Unified Power Flow Controller) has been presented and considered to be a unified power quality controller which can perform power system stabilizing control, compensation of load fluctuation, harmonic voltage and current compensation etc.[7] The combined system has been named as SuperSMES from the viewpoint of its capability. In the power system stabilization, it is expected that this combination can be a highly effective controller independent of its location. Some simulation results demonstrate that the SuperSMES with the proposed controller located far from a generator in long distance bulk power transmission system is capable of stabilizing the power swing as effectively as the SMES located at the generator terminal[8-9]. However, in order to realize this new control scheme, there is a requirement of sending signals from generator terminal to location where the SuperSMES is installed which makes realization of controller to be difficult. A control scheme using only local signals in order to realize a controller with more simple configuration has been proposed.

This paper experimentally demonstrates that the proposed apparatus with a proposed control scheme is significantly effective for the stabilization of a long distance bulk power transmission system even though it is located far from the generator.

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II. CONFIGURATION OF THE SUPERSMES

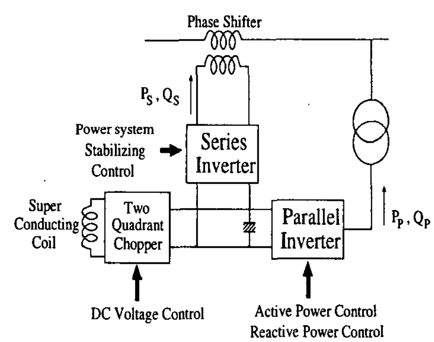


Fig. 1. Configuration of the SuperSMES

The configuration of the SuperSMES is shown in Fig.1. It has a combined structure of a thyristor controlled superconducting magnetic energy storage(SMES) and a thyristor controlled phase shifter. The active and reactive power from the series inverter, that is P_S and Q_S, and the output active and reactive power from the parallel inverter, that is P_P and Q_P, can also be controlled independently with the assistance of the energy storage device. This power can be utilized for many purposes of power quality control, such as power system stabilization, harmonic current and voltage compensation, line voltage compensation for voltage sags, swells and so on, and saving sensitive loads from short duration power outages[7]. In this paper, both the series inverter and parallel inverter are controlled to perform power system stabilizing control effectively for the case that the location is not suitable for the control by the SMES without UPFC.

III. CONFIGURATION OF THE EXPERIMENTAL SYSTEM

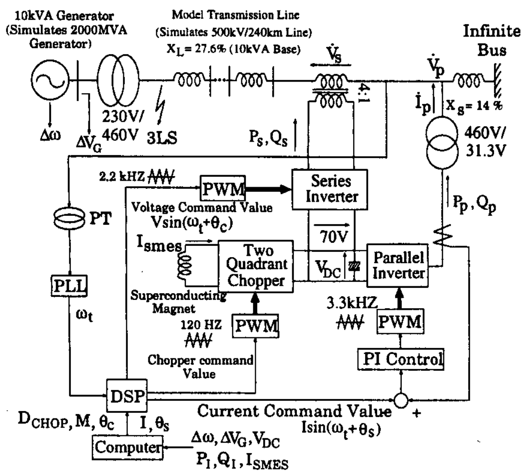


Fig. 2. Configuration of the Experimental System

The configuration of the experimental system is shown in Fig.2. Specifications of the model SuperSMES are shown in Table I and power system constants are shown in Table II. In the main circuit, three sets of single phase series inverters and one three phase parallel inverter are connected together to the common dc bus, and the primary side of transformers of single phase inverters are connected in series to the transmission line. The control circuit of the SuperSMES is composed of a PLL(Phase Locked Loop) circuit which detects the frequency and the phase angle of the line voltage, a DSP(Digital Signal Processor) and some logic circuits for PWM modulation. According to the modulation index(M) corresponding to the magnitude of $\dot{V}_S$ and voltage phase(θ) of $\dot{V}_S$ referred to $\dot{V}_P$ for the series inverters which are given from power system stabilizing controller, the DSP calculates sinusoidal reference voltage, and on-off switching signals are generated in the PWM modulation circuit. For the parallel inverter, instantaneous three phase current reference signals are calculated by DSP and ac current control is carried out in the PWM control circuit.

The parallel inverter charges the superconducting magnet current from zero to a specified value and maintains the average current at a certain value, while the chopper is controlled to keep the dc side voltage of inverters at a specified value. The rating of line to line voltage of the model transmission line is 460V and the generator capacity is 10kVA. This model simulates 2000MVA, 500kV transmission line, and the SuperSMES is connected to a point in the system which is 240km from the generator. This is near the demand side(Infinite bus), in order to show the effectiveness of the SuperSMES for power system stabilizing control. The applied disturbance is a three phase line short circuit(3LS) for five cycles(=83.3msec) at the generator bus as shown in Fig.2.

TABLE I
Specifications of the Experimental SuperSMES

Series Inverters	
Transformers	460V/115V
Inverters (Single phase PWM Inverter)	Power Rating : 2.6 kVA, 3 sets DC Voltage : 70V Power Devices : IGBT PWM Carrier Frequency : 2.2 kHz
Parallel Inverter	
Transformer	460V/31.3V
Inverter (Three phase PWM Inverter)	Power Rating: 4.6 kVA DC Voltage 70V Power Devices: IGBT PWM Carrier Frequency : 3.3 kHz
Chopper	Power Rating: 10kW Input DC Voltage: 70V
Superconducting Magnet(NbTi)	Energy: 10kJ , Current: 140 A Inductance: 1.078H
Condensor at DC side	
Capacity	144 mF

TABLE II
Power system constants

Generator (10 kVA, 230 V base)	
M : Inertia constant	8.0s
X_d : d axis synchronous reactance	1.35
X'_d : d axis transient reactance	0.48
X_q : q axis synchronous reactance	1.31
T'_{do} : d axis open circuit transient time constant	0.8 s
Transmission system (10 kVA, 460V base)	
X_T : reactance of transformer	0.15
X_L : reactance of line	0.046
R_L : reactance of line	0.005
B_L : electrostatic susceptance of line	0.027 x 2
X_s : short circuit reactance connecting to infinite bus	0.14

IV. CONTROL SCHEMES FOR POWER SYSTEM STABILIZATION

A. Using Generator Terminal Signals

Power system stablizing control scheme for the SMES located at the generator terminal has the controlled variable as the active and reactive power released or absorbed from the SMES.[5] A control scheme of the SuperSMES located far from the generator for power system stabilization is based on the idea that a control scheme for the SuperSMES located far from the generator emulates the control scheme by the SMES at generator terminal with a control scheme $\Delta P_s = -K_D \Delta\omega$, $\Delta Q_s = -K_V \Delta V_G$.

Power system stabilizing control scheme for the SuperSMES located far from the generator with a simple control sequence by using a generator terminal voltage as a common phasor reference has been proposed in [9] which has been equivalently derived from the control scheme of SMES. In a long distance bulk power transmission system, a control scheme of the SuperSMES located far from the generator can be expressed as

$$\begin{aligned} I_{p\alpha} &= -K_2\Delta V_G \\ I_{p\beta} &= -K_1\Delta\omega \\ V_{s\alpha} &= \omega(x_1+x_s)K_1\Delta\omega \\ V_{s\beta} &= -\omega(x_1+x_s)K_2\Delta V_G \end{aligned} \qquad (1)$$

where I_P represents a current injected from parallel Inverter, V_s represents a voltage injected from UPFC, subscript β and α represent a component in phase with the phasor $\dot{V}_G$ and a component lagging behind the β axis by 90^o, respectively.

In order to realize this control scheme, there is a requirement to send signals $\Delta\omega$, ΔV_G and phase reference $\dot{V}_G$ from the generator to the location where the SuperSMES is installed which will be an obstacle to realize the controller.

B. Using Local Signals

A control scheme using only local signals in order to realize a feasible controller is introduced. Signals needed for control scheme are produced by using only signals where the SuperSMES is installed. Three approximations have been applied in order to develop a control scheme using only local signals.

1. The deviation of angular velocity of generator($\Delta\omega$) is approximated by using the deviation of transmission power flow(ΔP_e) measured at the SuperSMES bus as

$$\widetilde{\Delta\omega} = \frac{-1}{M}\frac{s}{s+\omega_R}\frac{\Delta P_e}{s+a},$$

   where M is Inertia constant, a and ω_R are constants which are set to 0.67 and 0.1, respectively.

2. The phasor $\dot{V}_G$ as the phase reference is substituted by the phasor $\dot{V}_P e^{j\theta}$, where the angle θ is constant defined by the phase difference between $\dot{V}_G$ and $\dot{V}_P$ at the initial operating point.

3. The deviation of the Generator terminal voltage (ΔV_G) is substituted by the deviation of voltage at the SuperSMES bus(ΔV_P)

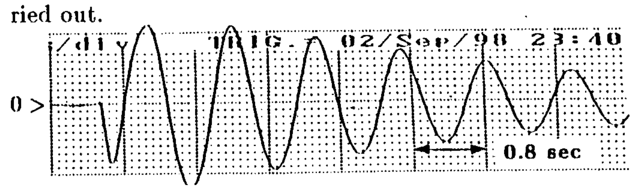
As a result of these approximations, a control scheme using only local signals can be expressed as

$$\begin{aligned} I_{p\tilde{\alpha}} &= -K_2\Delta V_P \\ I_{p\tilde{\beta}} &= -K_1\widetilde{\Delta\omega} \\ V_{s\tilde{\alpha}} &= \omega(x_1+x_s)K_1\widetilde{\Delta\omega} \\ V_{s\tilde{\beta}} &= -\omega(x_1+x_s)K_2\Delta V_P \end{aligned} \qquad (2)$$

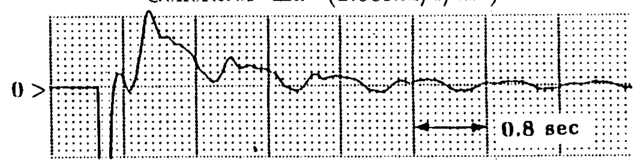
Here, subscripts $\tilde{\beta}$ and $\tilde{\alpha}$ represent a component in phase with the phasor $\dot{V}_G$ and a component lagging behind the $\tilde{\beta}$ axis by 90^o, respectively.

V. EXPERIMENTAL RESULTS

Experiments of power system stabilizing control after the five cycle three phase line short circuit(3LS)were carried out.

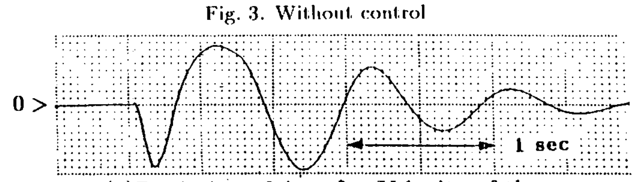


(a)Deviation of Angular Velocity of the Generator $\Delta\omega$ (2.68rad/s/div)

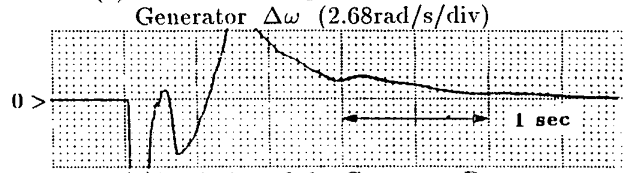


(b)Deviation of the Generator Bus Voltage ΔV_G (80v/div)

Fig. 3. Without control

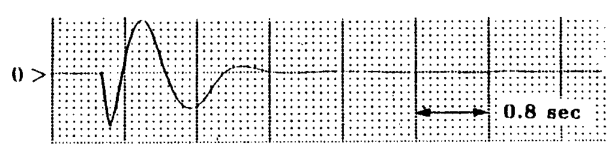


(a)Deviation of Angular Velocity of the Generator $\Delta\omega$ (2.68rad/s/div)

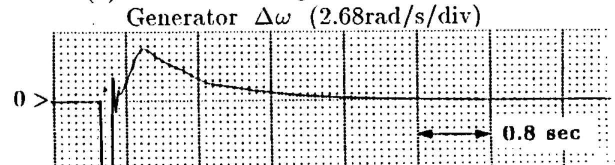


(b)Deviation of the Generator Bus Voltage ΔV_G (80v/div)

Fig. 4. With control of the SMES with Control Scheme 1)

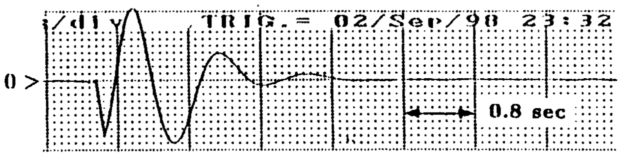


(a)Deviation of Angular Velocity of the Generator $\Delta\omega$ (2.68rad/s/div)

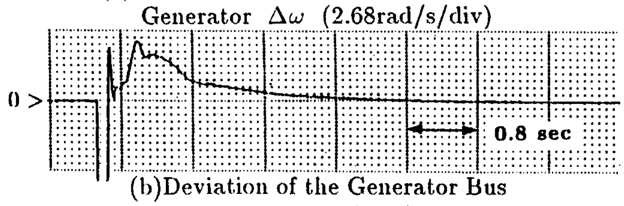


(b)Deviation of the Generator Bus Voltage ΔV_G (80v/div)

Fig. 5. With Control of the SuperSMES with Control Scheme 1)

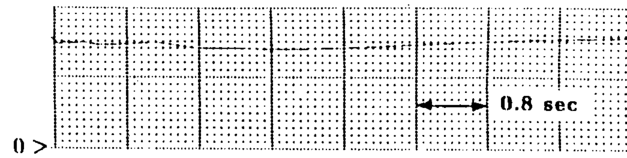


(a)Deviation of Angular Velocity of the Generator $\Delta\omega$ (2.68rad/s/div)

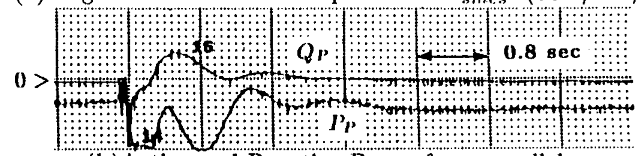


(b)Deviation of the Generator Bus Voltage ΔV_G (80v/div)

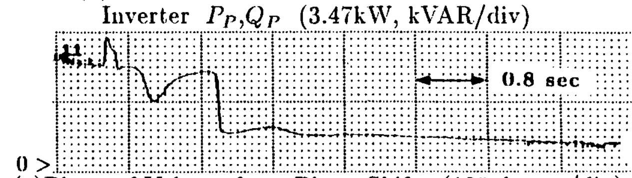
Fig. 6. With Control of the SuperSMES with Control Scheme 2)



(a)Magnet Current of the SuperSMES I_{smes} (50A/div)



(b)Active and Reactive Power from parallel Inverter P_P,Q_P (3.47kW, kVAR/div)



(c)Phase of Voltage from Phase Shifter(180 degree/div)

Fig. 7. With Control of the SuperSMES with Control Scheme 2)

Fig.3 shows experimental waveforms when the SuperSMES is out of service. Fig.4 shows waveforms when the SMES without the operation of UPFC is applied with the control scheme 1) for comparison. Fig.5 shows waveforms when the SuperSMES with the control scheme 1) is applied. In Fig.6, the control scheme 2) is applied. The SMES without phase shifter is not very effective for power system stabilization when it is located far from the generator. On the contrary, the SuperSMES with the controller using generator terminal signals is capable of damping the oscillation of phase angle as well as suppressing the generator bus voltage fluctuation effectively. The control scheme for the SuperSMES, which is composed of the locally acquired signals, is as effective as the control scheme 1).

Fig.7 shows the magnet current of the SuperSMES, the active and reactive power suppied by the parallel inverter for the power system and the phase of voltage $\dot{V}_S$ referred to $\dot{V}_P$.

The energy which was released from the Superconducting magnet can be evaluated from the magnet current by the relation

$$E = \frac{1}{2}LI_{max}^2 - \frac{1}{2}LI_{min}^2 \quad ,$$

where I_{max} and I_{min} are the maximum and minimum currents.

The result is about 750J which is almost the same as the result when the SMES is located at the generator terminal and is used for power system stabilization[5].

In Fig.7(b) the active power has a DC bias due to the loss compensation for the SuperSMES model. The power deviation evaluated by the value around the steady state is about 2 kVA, which is also same as the case of SMES at generator terminal.

It is observed from Fig.7(C) that the phase of voltage $\dot{V}_S$ referred to $\dot{V}_P$ can vary in a range of 0^o to 360^o, which implies that the active and reactive power from series inverter can be controlled simultaneously in a four quadrants circular.

VI. CONCLUSION

Power system stabilization is one of promising applications of SMES in power systems. This paper experimentally confirmed the effectiveness of SMES combined with Phase Shifter(SuperSMES) for the power system stabilization. The SuperSMES is significantly effective although it is located far from the generator. As a result it is expected that the SuperSMES is utilized for load leveling, system frequency control, power quality control and so on at the same time with power system stabilization.

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