Power System Stabilizing Control and Current Limiting by a SMES with a Series Phase Compensator

Duangkamol Kamolyabutra, Yasunori Mitani, Kiichiro Tsuji

Abstract— **In this paper, a combined controller of a superconducting magnetic energy storage (SMES) with series phase compensator for the stabilization of a power system is proposed. By the use of a series compensator, the SMES becomes capable of absorbing the generator accelerating power during a short circuit fault. In addition, the fault current is limited by the energy absorption as well as by the leakage reactance of a series transformer. A new control scheme for damping control of the generator swing has been proposed that is suitable for a SMES with series configuration. Some numerical results demonstrate significant effectiveness for enhancement of power-system stability and fault-current limiting.**

Index Terms— **Fault current limiting, Power system stabilization, Series compensation, Superconducting magnetic energy storage(SMES).**

I. Introduction

To meet the load demands in a complex, interconnected power system and satisfy the stability and reliability criteria, either existing transmission lines must be utilized more efficiently, or new lines should be added to the system. With the ever-increasing difficulty of obtaining new transmission-line rights-of-way, the latter is often impractical. The first alternative provides an economically and technically attractive solution to the problem, particularly in view of the fact that many existing ac lines are being operated at power levels well below their thermal power-carrying capacity limits.

With the advancement of power-electronics technologies, power-system controllers become very intelligent, which has introduced a new degree of freedom into the operation of power systems. The concept is referred to as Flexible AC Transmission Systems (FACTS) [1]. This flexibility permits us to adjust certain system variables such as power flows independently of power system conditions. Among the FACTS controller, superconducting 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, maintaining a bus voltage and stabilizing power swing [2], [3], [4].

In this paper, a combined controller of a SMES with a series phase compensator for the stabilization of a power system is proposed. The apparatus injects voltage of variable magnitude and phase in series with a transmission line and it is capable of absorbing or releasing energy dynamically from a generator freely. A new scheme for this controller has also been proposed here. The apparatus also shows promise as a fault current limiter. During a short circuit fault, the output voltage from series phase compensator is insignificant compared with the voltage across the leakage reactance of a series phase compensator. Therefore, the leakage reactance reduces the short circuit current. In addition, it is controlled to absorb the accelerating energy from the generator by using a superconducting coil, which enhances the generator transient stability as well as the effect of current limiting. Under normal condition, injected voltage from phase shifter is applied to the damping control of a generator swing and voltage regulation. As a result, the proposed controller is expected to improve steady-state stability as well as transient stability. The effectiveness of the proposed controller is evaluated from the viewpoints of transient stability improvement and steady-state stability improvement based on numerical analyses.

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II. Configuration of the SMES with Series Phase Compensator

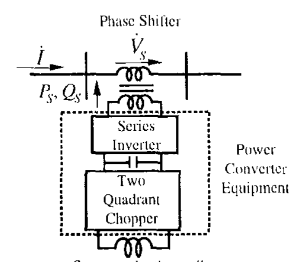


Fig. 1. Configuration of the SMES with series phase compensator

The configuration of the SMES with series phase compensator is shown in Fig. 1. It has a combined structure of thyristor controlled SMES and a thyristor controlled phase shifter. It should be noted that this configuration is the same as that of the SuperSMES [5] when parallel inverter part is removed. This controller can produce a set of alternating voltages approximately sinusoidal at the desired fundamental frequency with controllable amplitude and phase angle. Therefore, the active and reactive power from the series inverter, that is P_S and Q_S can be controlled independently with the assistance of the energy storage device. Fig. 2 shows a circuit model for power system with the SMES with series phase compensator located at generator terminal. A SMES with a series phase compensator can be modelled as a voltage source($\dot{V}_S$) connected with the leakage reactance of the phase shifter. Here, X_t is a reactance of a step up transformer, X_l is a reactance of a transmission line, X_s is a short circuit reactance, X_P is a leakage reactance of phase shifter, r_l is a resistance of a transmission line and $\dot{V}_t$ is the generator terminal voltage.

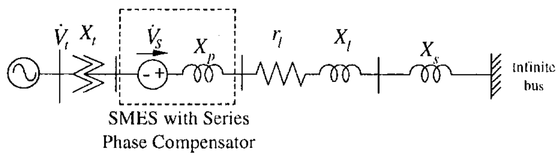


Fig. 2. Circuit model for power system with the SMES with series phase compensator located at generator terminal

III. Principles of the Operation of the SMES with Series Phase Compensator

A. Principle in Normal Condition

Under normal condition, the SMES with series phase compensator is controlled to compensate for reactance of transmission line in order to enhance the steady state stability of power system. The controller injects voltage which has phase lagging behind the line current($\dot{I}$) by 90^o, thereby emulating a capacitive reactance in series with the transmission line. This injected voltage is given by the expression

$$\dot{V}_S = jX_C\dot{I} \tag{1}$$

Here, by giving $X_C > X_P$, it is possible to compensate for reactance of transmission line.

B. Principle of Fault Current Limiting

Simple power system model shown in Fig. 3 is used to explain the principle of fault current limiting of the SMES with series phase compensator.

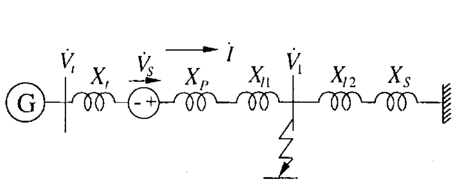


Fig. 3. Circuit model used to explain principle of current limiting

The relation between the current and the voltage under normal condition can be expressed as

$$\dot{V}_t + \dot{V}_S - \dot{V}_1 - jX\dot{I} = 0 \tag{2}$$

Where X=X_P + X_{l1} + X_t is the reactance between generator terminal and the location where a three phase short circuit fault occurs. Vector diagram of current and voltage can be expressed in Fig. 4(a) since $\dot{V}_t$ and $\dot{V}_1$ have almost same magnitude. Phase shifter injects voltage which is leading the line current by 90^o in order to compensate for reactance of transmission line. When the short circuit fault occurs and $\dot{V}_1 = 0$, the relation can be expressed as

$$\dot{V}_t + \dot{V}_S - jX\dot{I} = 0 \tag{3}$$

At this time, maintaining the injected voltage ($\dot{V}_S$) constant equal to that before the short circuit occurs, the vector diagram of the voltage and current can be expressed as shown in Fig. 4(b). It can be seen that the output voltage from the controller is insignificant compared with the voltage across leakage reactance of phase shifter. Therefore, reactance of the phase shifter is contributed to fault current limiting and short circuit fault current is limited by reactance X=X_P + X_{l1} + X_t.

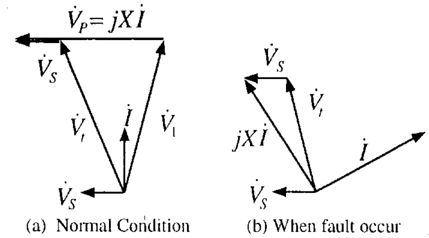


Fig. 4. Control during normal condition and control when fault occur

C. Control Scheme for Transient Stability Improvement

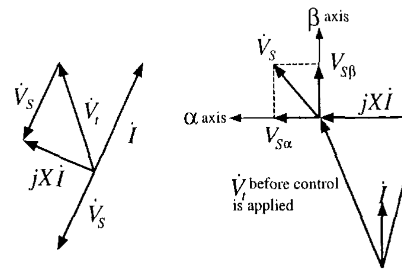
When a large disturbance occurs, the SMES with series phase compensator is controlled in order to absorb the accelerating energy from the generator by using superconducting coil. During fault, the controller is capable of absorbing the active power by injecting the output voltage which is lagging behind the line current by 180^o. This injected voltage can be expressed as

$$\dot{V}_S = -a\dot{I}/|\dot{I}| \quad (a > 0) \tag{4}$$

The vectors of the voltage and current when control scheme (4) is applied can be shown in Fig. 5(a). By comparing Fig. 5(a) with Fig. 4(b), it can be seen that the magnitude of $jX\dot{I}$ can be reduced when control scheme (4) is applied. Therefore it can be said that the effect of current limiting will be enhanced when control scheme (4) is applied.

D. Control Scheme for Steady-state Stability Improvement

Control system using line current as reference can be expressed in vector diagram as shown in Fig. 5(b). Here, α and β are the reference axes which are perpendicular and coincide with the phasor direction of the line current, respectively. From Fig. 5(b), it can be observed that injecting $V_{S\alpha}$ has an effect on a phase difference between $\dot{V}_t$ and $\dot{V}_1$ and injecting $V_{S\beta}$ has an effect on the magnitude of $\dot{V}_t$. Because decreasing or increasing a phase difference between $\dot{V}_t$ and $\dot{V}_1$ will affect the active power flow in a transmission line, therefore $V_{S\alpha}$ is used to contribute to



(a) Control during fault (b) Control system using line current as a reference

Fig. 5. Control during fault and control system using line current as a reference

the damping control of generator swing by using the angular velocity of the rotor (ω) as a feedback control signal. And $V_{S\beta}$ is used to contribute to the generator terminal voltage regulation by using the generator terminal voltage as a feedback control signal. Then a control scheme for enhancement of steady-state stability using the line current as a common reference can be expressed as

$$\hat{V}_{S\beta} = K_1 \Delta V_t, \quad \hat{V}_{S\alpha} = -K_2 \Delta\omega \tag{5}$$

Here, $\wedge$ denotes the variable is a command reference, where the dynamics of $\dot{V}_S$ control will be considered later. K_1 and K_2 are the gain of controller.

IV. Simulation Results

System model for analysis is shown in Fig. 2, which models a 5,850 MVA nuclear power plant, 500 kV and 100 km double circuit transmission lines and an infinite bus. The power plant contains five identical 1,170 MVA turbine generators. In numerical investigation five 1,170 MVA generators are treated as a 5,850 MVA generator with an AVR. The effect of the governor is ignored. The generator model is represented by the Park's model with d-q armature winding, d-q damper winding and a field winding. The turbine-rotor system is represented by a spring-mass model with 5 masses (4 turbines and 1 rotor). System constants are shown in table I, where the notations appearing in [6] are used.

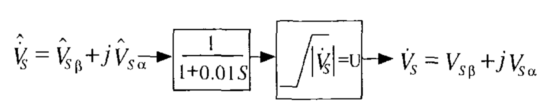


Fig. 6. Operating characteristic of the SMES with series phase compensator

The dynamic characteristic of the voltage injected from the SMES with series phase compensator are modeled in α-β coordinates as a first order time lag as shown in Fig. 6. The limiter is also modeled. When $|\dot{V}_S|$ is greater than U, the injected voltage will be limited to U. Here, U is fixed to 0.1 (pu) according to [7].

Firstly, the effect of current limiting has been examined. Fault condition is assumed to be a three phase line short

TABLE I
Power system constants.

Generator:	Park's model 5 order	1,170 MVA base
$x_d = 1.60$	$x_{ad} = 1.35$	$x_{ffd} = 1.44$
$x_{kkd} = 1.38$	$x_q = 1.60$	$x_{aq} = 1.35$
$x_{kkq} = 1.373$	$r_a = 0.00181$	$r_{kd} = 0.0062$
$r_{fd} = 0.00060$	$r_{kq} = 0.0124$	$M_1 = 1.81s$
$M_2 = 1.90s$	$M_3 = 1.86s$	$M_4 = 1.81s$
$M_5 = 0.4s$	$D_{11} = 0.0$	$D_{22} = 0.25$
$D_{33} = 0.25$	$D_{44} = 0.25$	$D_{55} = 0.25$
$D_{12} = 5.2$	$D_{23} = 5.6$	$D_{34} = 5.6$
$D_{45} = 5.6$	$K_{12} = 23.4$	$K_{23} = 15.5$
$K_{34} = 13.30$	$K_{45} = 11.90$	$\omega_0 = 120\pi$ rad/s
	AVR	
$K_A = 135$	$T_A = 0.02s$	$T_E = 1.0s$
$K_F = 0.03$	$T_F = 1.0s$	
Transmission system	5,850 MVA, 500 kV base	
$X_t = 0.14$	$X_l = 0.4490$	$r_l = 0.04625$
$X_s = 0.1930$	$X_p = 0.05$ (Phase shifter)	

circuit (3LS, which occurs at $t = 0$ s) for 3 cycle (50 ms) at the location near the generator terminal. Fig. 7 shows the fault current and output voltage from the controller (Note that only in this case, instantaneous wave forms are shown). Case1, case2 and case3 express the results when no equipment is installed, the controller is applied by maintaining injected voltage to be constant during fault, the controller is applied by absorbing accelerating energy from a generator according to equation (4) during fault, respectively. The voltage waveform express the case when the reactance compensation as shown in (1) is applied before and after fault occur and control scheme in (4) is applied during fault. a in (4) is fixed to 0.2 pu.

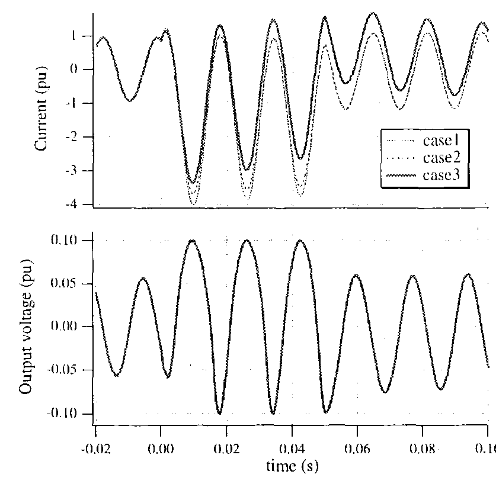
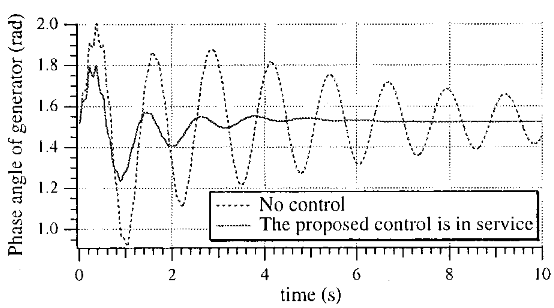


Fig. 7. Fault current and output voltage from phase shifter (Instantaneous waveforms)

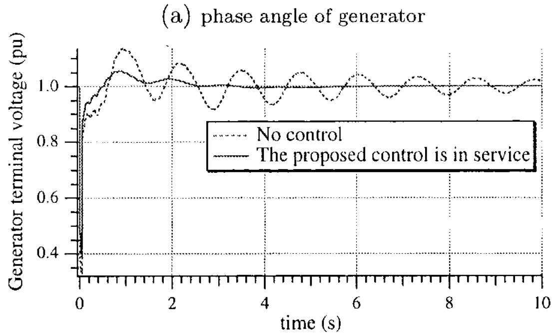
It can be seen from Fig. 7 that the effect of current limiting is improved when the controller is installed and when control scheme in (4) is applied in order to absorb the accelerating energy from a generator, the effect of current limiting is much more improved. By comparing the fault current and output voltage wave forms, it can be observed that the injected voltage is lagging behind the fault current by 180^o during fault which means that the apparatus is controlled in such a way to absorb the accelerating energy of the generator during fault. And it can be observed that before and after fault occurrence, the fault current and the injected voltage has a phase difference by 90^o which means that the apparatus is controlled in such a way to compensate for reactance of transmission line.

Fig. 8 shows control effect when the proposed control scheme is applied. It is shown that the transient stability has been significantly improved when the proposed controller is applied. And it can be seen that the swing of generator is effectively stabilized and the fluctuation of the generator terminal voltage is suppressed when the proposed control is in service. Figs. 9 and 10 show the output power from SMES and the deviation of energy in superconducting magnet when $K_1 = 1.0$ and $K_2 = 12$ is applied. In Fig. 9 the reactive power has a DC bias due to the compensation for reactance in the transmission line.

It is observed from Fig. 10 that energy about 180 MJ from the superconducting magnet is used to contribute to damping the first swing of the generator. After the fault is cleared, the energy from the superconducting magnet still keep changing since it is used to contribute to the generator terminal voltage regulation according to (5). It should be noted from the simulation that the capacities of energy storage and power converter equipment should be at least about 300 MJ and 300 MVA.



(a) phase angle of generator



(b) generator terminal voltage

Fig. 8. Control effect by the proposed control scheme when the proposed control with $K_1 = 1$ and $K_2 = 12$ is applied

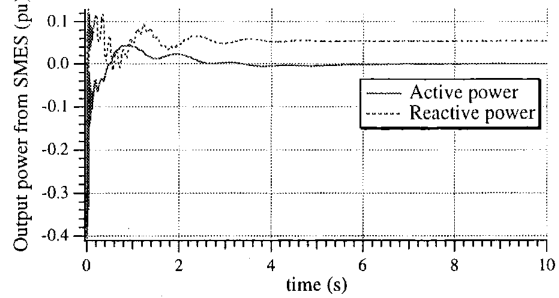


Fig. 9. Output power from SMES when $K_1 = 1.0$ and $K_2 = 12$ is applied

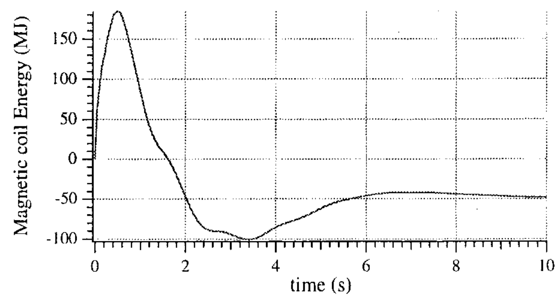


Fig. 10. Deviation of energy in superconducting magnet

V. Conclusion

A combined controller of the SMES with series phase compensator and its control scheme for power system stabilization is proposed. In this paper, a new control concept for the SMES with series phase compensator to contribute to new application referred as fault current limiting has been proposed. This paper numerically confirmed the effectiveness of this controller for power system stabilization and fault current limiting.

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