EXPERIMENTAL STUDY ON STABILIZATION OF MODEL POWER TRANSMISSION SYSTEM BY USING FOUR QUADRANT ACTIVE AND REACTIVE POWER CONTROL BY SMES

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Abstract

This paper presents the experimental results of stabilization of a model power transmission system by using a Superconducting Magnet Energy Storage (SMES). The SMES, which was composed of two sets of GTO (Gate Turn Off thyristor) power converters and a superconducting coil, is capable of controlling active power (P) and reactive power (Q) simultaneously in four quadrants by changing the firing angles of power converters. The model power transmission system was designed to simulate the behavior of a real scale long distance bulk power transmission system with voltage of 500 kV, capacity of 2000 MVA and length of 280 km. In this study, we have experimented power system stabilizing control by applying P-Q simultaneous control ability of SMES. From the results of experiment it was demonstrated that stabilizing effect by means of SMES is very significant.

Introduction

Much attention has been recently paid to SMES in electrical power system application,[1,2] especially power system stabilization.[3,4] Electrical power systems that have major loads and generation centers separated by long distances may experience undamped and poorly synchronized power oscillations.[5] This paper describes the experimental results of stabilization of a model power transmission system, which was designed to simulate a behavior of a real scale long distance bulk power transmission system, by means of an SMES which was composed of two sets of GTO power converters and a superconducting coil.

Typical SMES configuration contains six pulsed thyristor Graetz bridges in series and a superconducting coil, and 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 the SMES is placed.[2,3] Although the use of thyristor converters limits the range of simultaneous active and reactive power control, recent development in GTO opens up the possibility of controlling four quadrant active and reactive power.[6,7] Due to this control ability, remarkable stabilizing effects are expected if the SMES with an adequate control scheme is placed at a proper location in the power system.

In this experimental study, we have applied the four quadrant active and reactive power simultaneous control ability of SMES to the stabilization of the model power transmission system; active power is applied to damping control of power oscillation using the deviation of generator angular velocity or the deviation of line power flow as a feedback signal, and reactive power is applied to the constant voltage control using the deviation of voltage at the bus with SMES as a feedback signal.

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The stabilization effect of the use of SMES is compared with the stabilizing control by means of only reactive power which assumes the use of Static Var Compensator (SVC) and it is demonstrated that the effectiveness of SMES is remarkably significant than that of SVC. From the experimental results effective location and necessary capacities of SMES are evaluated.

Configuration of Experimental System

The configuration of a model power transmission system and an SMES is shown in Fig. 1. The power system is the most basic one machine-infinite bus system corresponding to a real scale long distance bulk power transmission system with a 2000 MVA turbine generator connected to a large power system through 500 kV and 280 km double circuit transmission line. System constants are shown in Tab. 1.

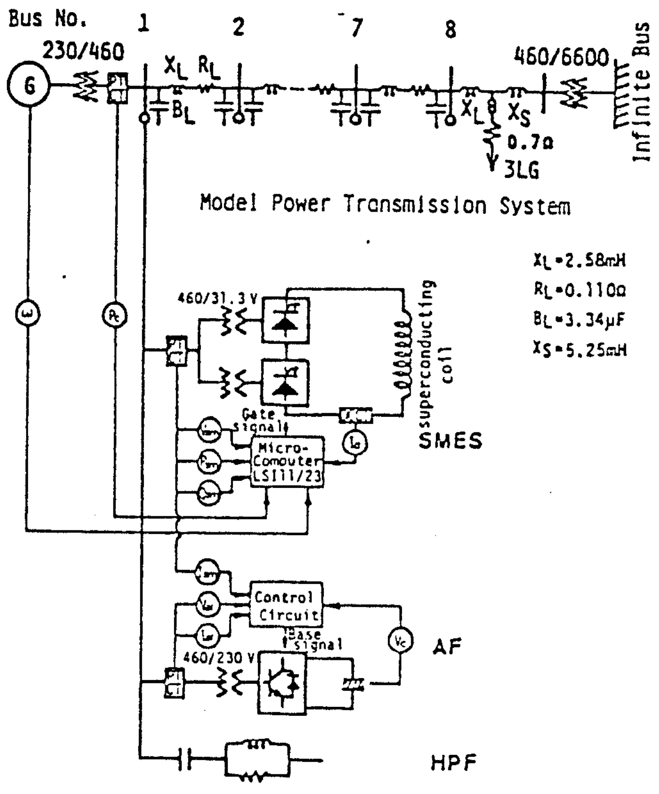

Figure 1. Configuration of a model power transmission system and an SMES.

The model generator, rated at 10 kVA, 230 V and 1800 rpm, is supplied with mechanical torque by a 15 kW DC motor according to the conventional control scheme for constant generator output power, and equipped with excitation control system which has a function of conventional automatic voltage regulator.

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Table 1. Power system constants.

Transmission system (10 kVA, 460 V base)	
X_T : reactance of transformer	0.15
X_L : reactance of line	0.046 x 7
R_L : resistance of line	0.005 x 7
B_L : electrostatic susceptance of line	0.027 x 2 x 7
X_L+X_S: short circuit reactance connecting to infinite bus	0.14
Generator (10 kVA, 230 V base)	
x_d : direct axis synchronous reactance	1.35
x_d': direct axis transient reactance	0.48
x_q : quadrature axis synchronous reactance	1.31
x_q': quadrature axis transient reactance	0.55
T_{do}': direct axis open circuit transient time constant	0.21 s
M : inertia constant	8.0 s

The parameters of the generator are nearly equivalent to real ones except T_{do}', however, it appears to excitation control system that T_{do}' is about 6 (s) corresponding to a real generator constant by virtue of an additional control of voltage in the field winding circuit.

The electrical parameters (resistance, reactance and capacitance) of a real transmission line are distributed along the length of the line. These distributed parameters are modelled by connecting in series seven sections of the 460 V model line represented by lumped parameters corresponding to 40 km in length. Regarding the frequency transfer characteristic of voltage, this model line is equivalent to the real one in the range of 10 Hz through 1 kHz.

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 of the higher harmonics generated by AF.[7] The AF is composed of a condenser and a power converter using power transistors, and the HPF is a resonance circuit made of capacitors, inductors and resistors. It is possible to connect the SMES to the bus No. 1 through 8 on the transmission line. Parameters of the SMES unit are shown in Tab. 2. It should be noted that they are not necessarily optimized for the power system stabilizing control.

Table 2. Parameters of the 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).[5] For the power system stabilization, we provided following feedback control schemes for P_S and Q_S

(1) $\Delta P_S=+K_{D\omega}\Delta\omega^*$, $\Delta Q_S=+K_V\Delta V_{sm}^*$

(2) $\Delta P_S=-K_{DP}\Delta P_C^*$, $\Delta Q_S=+K_V\Delta V_{sm}^*$,

where Δ denotes the variable which represents the deviation from an operating point and superscript * denotes the variable which represents the detected value. In P_S and Q_S the positive sign represents absorption of active power and consumption of lagging reactive power, respectively.

In the control scheme (1), active power of the SMES operates for damping control of power oscillation by using the angular velocity of the generator (ω), and reactive power operates for constant voltage control by using the voltage (V_{sm}) at the bus where the SMES is located. In the control scheme (2), active power on the transmission line (P_C) flowing from the generator into the bus with SMES is selected as a local feedback signal to ΔP_S. The relation between $\Delta\omega$ and ΔP_C which is represented by the swing equation of generator

$$M\Delta\dot{\omega}=-\Delta P_C,$$

and the measurement delay due to the transducer for ΔP_C resulted in the phase difference between $\Delta\omega^*$ and ΔP_C^* about 160 degrees. Consequently, the control scheme (2) can be almost equivalent to (1) if the feedback gain K_{DP} is properly chosen.

In addition, for comparison, we provided one more control scheme (3) using only reactive power, which assumed the use of Static Var Compensator (SVC)

(3) $\Delta P_S=0$, $\Delta Q_S=+K_V\Delta V_{sm}^*$.

Experimental Results

Experimental set-up

The generator output was 8 kW with power factor of 1.0. The superconducting coil was initially charged to the current of 100 A, that is, the energy of 1.32 kJ, and at this current level the power converters were capable of controlling active and reactive power simultaneously in four quadrant circular not exceeding 8 kVA with power loss level 1.4 kW.

A three line grounding (3LG) fault through a 0.7 ohm resistor during 5 cycles was arranged as one of practical faults. In order to protect the SMES against the 3LG, when the occurrence of the fault was detected through the voltage drop at the bus with SMES, the DC circuit of SMES was electrically separated from the AC system by means of the control of power converters.[7] Power system stabilizing control started with the reconnection of the DC circuit instantly after the detection of voltage recovery.

Location of the SMES was selected at the bus No. 1, 3, 5 or 7 in the model transmission system (see Fig. 1) and, in each case, values shown in Tab. 3 were assigned for the feedback gains. The gains K_{DP} and $K_{D\omega}$ were determined so that the magnitudes of ΔP_S yielded by control schemes of (1) and (2) were to be equal to that of ΔP_C without SMES control. The gain K_V was determined to be equal to the short circuit current at the bus where the SMES was to be located.

Table 3. Feedback gains.

location of SMES / gain	No.1	No.3	No.5	No.7
K_{DP} (kW/kW)	1.5	1.5	1.5	1.5
$K_{D\omega}$ (kW/ rad/s)	1.3	1.3	1.3	1.3
K_V (kVar/V)	0.62	0.73	0.91	1.29

Experimental results

With changing the location of SMES, above-mentioned, three kinds of control schemes were carried out.

Figures 2, 3, 4 and 5 shows the experimental results of each stabilizing control when the SMES was located at the bus No. 1. The reason, why just after the fault duration, the magnitude of power oscillation with each SMES control is a bit larger than that without SMES, is an impact due to the power loss component of the SMES was added to the power system as a result of the disconnection and reconnection of the DC circuit of SMES which were the sequence of protection against the 3LG as mentioned in the previous section.

Now, in order to evaluate the stabilizing effect quantitatively, damping component exp($-\sigma t$) was roughly calculated, based on the power oscillation mode with a frequency of about 1 Hz which was dominant in the waveform of $\Delta\omega^*$. Table 4 shows the increment of σ (1/s) over that without SMES control, which was caused by each stabilizing control.

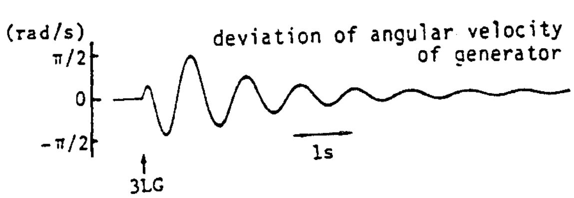

Figure 2. Experimental result without SMES control.

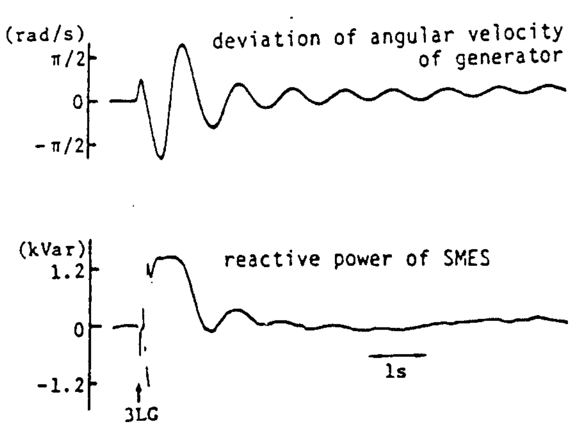

Figure 3. Experimental result with control scheme (3).

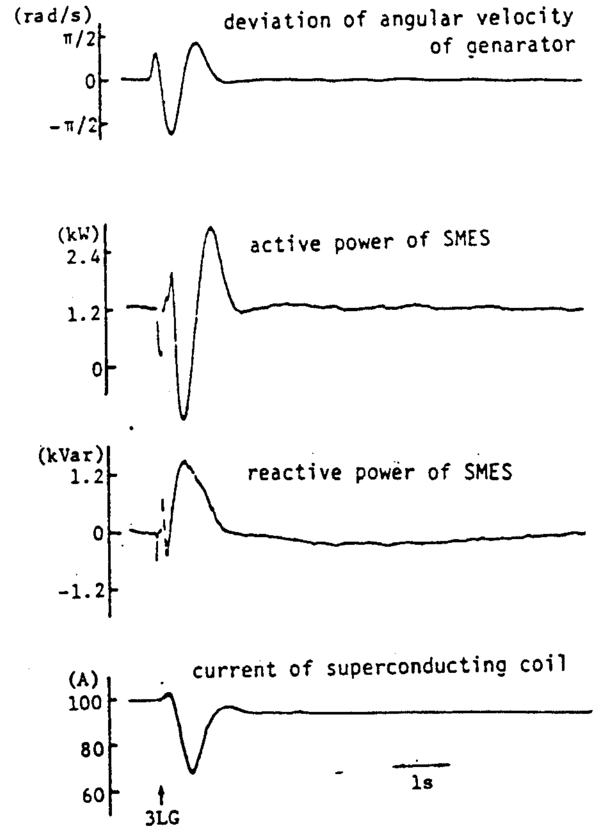

Figure 4. Experimental result with control scheme (1).

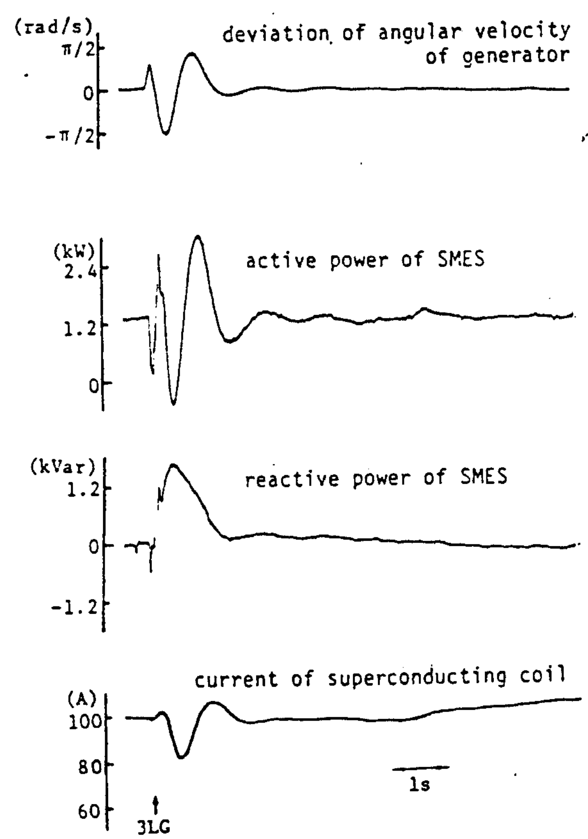

Figure 5. Experimental result with control scheme (2).

Table 4. Increment of damping coefficient σ over that without SMES control.

location of SMES \ control scheme	(1)	(2)	(3)
No.1	2.1	1.7	0.5
No.3	1.8	1.5	0.6
No.5	1.6	1.3	0.5
No.7	0.8	0.7	0.4

Next experiment was evaluation of the stabilizing effect related with the location of a load. Stabilizing control by means of the control scheme (2) was carried out with respect to various locations of the SMES and an 8 kW resistor load. Table 5 shows the increment of σ (1/s) over that without SMES control, which was caused by stabilizing control.

Table 5. Increment of damping coefficient σ over that without SMES control in the case with a load on the transmission line.

location of SMES \ location of load	No.1	No.3	No.5	No.7
No.1	1.6	1.8	1.8	1.6
No.3	1.5	1.4	1.5	1.4

Discussion

Evaluation of stabilizing control scheme

As shown in Figs. 2, 3, 4, 5 and Tab. 4, when the control scheme (3) assuming an operation of SVC is applied, a synchronous power is reinforced in power oscillation by the effect of voltage control, which can be recognized from the result that the frequency of power oscillation becomes a bit higher, and at the same time, a damping of power oscillations is slightly improved. In contrast with this, when the control scheme (1) using the four quadrant active and reactive power control ability of the SMES is applied, the damping is significantly improved as well as the synchronous power is reinforced. The control scheme (2) realized by local feedback signals is almost equivalent to the control scheme (1).

Evaluation of SMES location

It can be concluded from Tab. 4 that the stabilizing control is more effective when the SMES is located on the transmission line near the generator and, from Tab. 5, that the stabilizing effect is not so much influenced by location of the load.

Evaluation of the necessary capacities of SMES

It is found from Figs. 4 and 5 that the model power transmission system is effectively stabilized by properly controlling active power of SMES which is comparable to the magnitude of power oscillation after the fault and then the magnitude of reactive power of SMES used for voltage control is comparable to the magnitude of controlled active power.

In this experiment the necessary capacity of the power converters is about 2.0 kVA and the energy used for the stabilizing control is about 650 J, where the necessary capacity of the power converters is estimated based on the deviation from the initial operating point and the energy used for the stabilizing control is the difference between the maximum and the minimum stored energy level. These values correspond to 400 MVA and 130 MJ, respectively, in terms of a real 2000 MVA power system.

Conclusion

The experimental study on the stabilization of a model power transmission system was performed by using four quadrant active and reactive power control ability of Superconducting Magnet Energy Storage (SMES). The results showed that the stabilizing control by means of SMES using local feedback signals is very effective to damp out power oscillation quickly and that the effectiveness of SMES is remarkably significant than that of SVC.

Effective location of SMES in a power transmission system has been examined. From the experimental result, it was concluded that the stabilizing control is more effective when the SMES is located near the generator and that the effectiveness is not so much influenced by location of a load.

The necessary capacities of SMES (capacity of the power converters and the energy used for the stabilizing control) are almost same ratings as the power fluctuation without SMES control. It will be possible to stabilize a power transmission system of several thousand MVA class by means of an SMES of several hundred MVA and several hundred MJ.

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