Application of Resistor Based Superconducting Fault Current Limiter to Enhancement of Power System Transient Stability

Masaki Tsuda, Yasunori Mitani, Kiichiro Tsuji, Kunihiko Kakihana

Abstract— **This paper presents an application of a superconducting fault current limiter (SFCL) to enhance the power system transient stability. Resistance as the current limiting devices is used for damping the generator accelerating power. A method to evaluate an appropriate resistance is proposed. The SFCL is combined with the superconducting magnetic energy storage (SMES) for power system stabilization. As a result the capacity of SMES is significantly reduced.**

Index Terms— **Power system stabilization, Superconducting fault current limiter (SFCL), Superconducting magnetic energy storage (SMES), Transient stability.**

I. Introduction

SYSTEM stability and protection from any disturbances are significant problems in a recent power system especially in a deregulated power system. Under the circumstances power system stabilizing apparatus such as power system stabilizer (PSS) [1], static var compensator (SVC) [2] and so on have been developed so far. Superconductivity is expected to be a powerful controller to stabilize and protect power systems. Superconducting magnetic energy storage (SMES) has been applied to the stabilization of power swings, frequency control, voltage control and power quality control [3], [4], [5]. A superconducting fault current limiter (SFCL) is expected to be an ultimate automatic protection system against short circuit faults [6], [7]. A superconducting cable and a superconducting transformer are also expected to contribute to the system efficiency and stability. Thus, superconductivity promises to provide high-performance power control apparatus in power systems. In this paper the SFCL assembled with a series damping resistor is investigated as a powerful controller for transient stability enhancement of power systems as well as current limiter. In addition, the application of SFCL combined with the SMES for power system stabilization is proposed and the effectiveness is investigated in detail.

The SFCL assembled with a high impedance devise such as a resistor or a reactor, is expected to be a strategic countermeasure to protect huge interconnected power systems from large fault currents. Here, a resistor based SFCL which is capable of quickly consuming the active power is applied to the enhancement of power system transient stability by absorbing the exceeding accelerating generator power. The resistor connected in series with a transmission line can effectively absorb energy during a short circuit since the absorbed power is determined by RI^2 in which the value of I is very large due to the short circuit. It absolutely surpasses the conventional shunt-damping resistor, which is not able to absorb enough power during the short circuit. Here, it becomes a subject of discussion how to adjust the appropriate resistance that is neither too much nor too little. In this paper a method to evaluate the proper amount of resistance calculated from the information of static generator condition is investigated.

Generally, a resistance whose voltage is supplied by a constant voltage source, consumes a specified power at two different values. Thus, the resistance to meet the generator power during short circuit has two solutions. In the sense of a practical application, it is important that the controller is robust against the changes of system parameters. As a result of investigation it is to be shown that the larger resistance is more robust and effective for limiting the fault current, although the value of resistance is very large that may be costly to manufacture, while the smaller resistance is vulnerable to the system changes.

The SFCL proposed in this paper, is an application using a by-product of the current limiter. It is to be demonstrated that the SFCL with an appropriate resistance installed near the generator is significantly effective for enhancing power system transient stability. However, it is required to keep superconductivity against few possible large disturbances. Then, the combination of resistor based SFCL with a superconducting magnetic energy storage (SMES) for power swing damping control, is proposed. The SMES is effective to damp the power swing and improve the dynamic performances of the power system. However, a large amount of capacity is required for inverter and energy storage if the SMES is also used for the transient stability enhancement. In addition the SMES is not capable of absorbing enough energy during the short circuit since the bus voltage where the SMES is installed drops significantly. As a result the SMES has to stabilize the generator swing resulting from the fault, while the SFCL is capable of directly damping the accelerating power simultaneously with the short circuit. The resistor of a SFCL absorbs the generator accelerating power and supports the bus voltage as well, which effectively assists the

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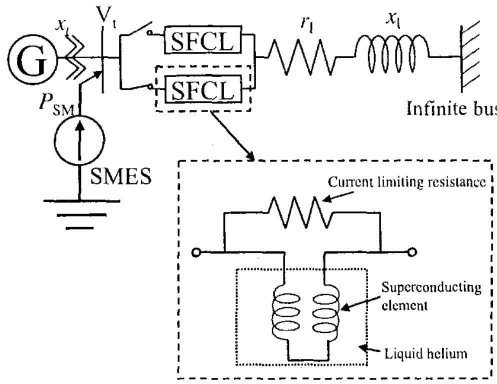

Fig. 1. Model power system with SMES and SFCL.

TABLE I
SYSTEM CONSTANTS

1,300 MVA 275kV base (50Hz)		
$x_d = 1.70$	$x'_d = 0.350$	$x''_d = 0.260$
$T'_{do} = 6.50[s]$	$T''_{do} = 0.0400[s]$	$x_q = 1.70$
$x''_q = 0.280$	$T''_{qo} = 0.120[s]$	$r_a = 0.00200$
$x_t = 0.100$	$x_l = 0.200$	$r_l = 0.0300$
Turbine-rotor system (spring-mass model [8])		
Inertia constants	(five masses)	$M_1 = 1.74$ [s]
$M_2 = 1.67[s]$	$M_3 = 1.72$ [s]	$M_4 = 0.311$ [s]
$M_5 = 0.186$ [s]	Spring constants	$K_{12} = 70.9$
$K_{23} = 52.0$	$K_{34} = 34.9$	$K_{45} = 19.3$

SMES to operate even during the short circuit fault. Moreover, the cooling system of the SMES can be commonly used for the SFCL. Consequently the capacity of SMES can be significantly reduced; the micro-SMES with around 10MVA and 10 MJ can be applied for the stabilization of a 1,000MVA-class generator.

Some numerical studies demonstrate the significant effectiveness of the SFCL itself and the combined apparatus with SMES.

II. Power System Model with SFCL

Fig. 1 shows a model power system with a 1,300 MVA generator, where an SFCL is located at the generator terminal. A SMES located with the SFCL will be considered in later discussions. Table I shows system constants. The generator is represented by Park's model, where the turbine-rotor torsional modes are considered by a spring-mass model [8]. The SFCL is modeled as a variable resistance such that it increases the resistance exponentially from 0 pu to 2.0 pu when it detects an fault current exceeding a predetermined threshold. Per unit values in the transmission system are represented in the capacitor base of 1,300 MVA and the voltage base of 275 kV, that is, the impedance base is 58.2 [Ω]. Another SFCL with zero resistance is switched on immediately after the fault is cleared.

III. Evaluation of Resistance in SFCL

The direct (d) and quadrature (q) components of the generator terminal voltage and generator power output are represented by

$$\begin{aligned} v_d &= -r_a i_d + x_q i_q & (1)\\ v_q &= -r_a i_q - x'_d i_d + e'_q & (2)\\ e_q &= (x_q - x'_d) i_d + e'_q & (3)\\ P &= e_q i_q = (x_q - x'_d) i_d i_q + e'_q i_q & (4) \end{aligned}$$

Here, the dynamic response of e'_q is determined by the d-axis transient open circuit time constant T'_{d0}, which usually has a large value around 5 or 10 seconds in the case of a large generator [8]. Therefore, it can be considered that e'_q is constant during the short circuit fault.

Suppose that a resistance R_D is installed in series with the transmission line when a three-line ground (3LG) fault occurs at the generator terminal, where R_D is the total resistance of the SFCL after the superconducting coil changes into the normal conductor status. Then the system condition is represented by

$$v_d = R_D i_d - x_t i_q, \quad v_q = R_D i_q + x_t i_d \qquad (5)$$

Evaluating i_d and i_q as functions of e'_q after substituting (5) into (1) and (2), and substituting them into (4) yield

$$P = \frac{(x_q - x'_d)(x_t + x_q)(R_D + r_a)(e'_q)^2}{[(R_D + r_a)^2 + (x_t + x'_d)(x_t + x_q)]^2} + \frac{(R_D + r_a)(e'_q)^2}{(R_D + r_a)^2 + (x_t + x'_d)(x_t + x_q)} \qquad (6)$$

As a numerical example, set initial operating values for P and V_t at 0.8 pu and 1.06 pu, respectively, then the initial condition of e'_q is evaluated as 1.024 pu by the power flow calculation. The solutions of (6) which is the fourth-order equation for R_D, are evaluated as

$$R_D = 1.676,\ 0.1436,\ -0.2948 \pm j1.513$$

when $P = 0.8$ and $e'_q = 1.024$.

The result implies that a large resistance, 1.676 pu and a small resistance, 0.1436 pu can consume the generator power of $P = 0.8$ pu during the short circuit, that is, the generator will not be accelerated.

IV. Evaluation of Sensitivity against System Parameter Changes

Equation (6) is derived under the condition that a short circuit fault occurs at the generator terminal. However, the change of fault location may affect the effectiveness. Besides, the value of resistance may change with the variation of resistance temperature. Thus, it is important to investigate the sensitivity of solutions against system parameter changes.

Fig. 2 shows the variation of P when the reactance x_t in (6) is changed between 0 pu and 0.5 pu, while the resistance R_D is fixed at 1.676 pu and 0.1436 pu, respectively. Note that $P = 0.8$ pu when $x_t = 0.1$ for both resistance cases. Fig. 3 shows rearranged results that the variation of P is plotted for different values of resistance. These results

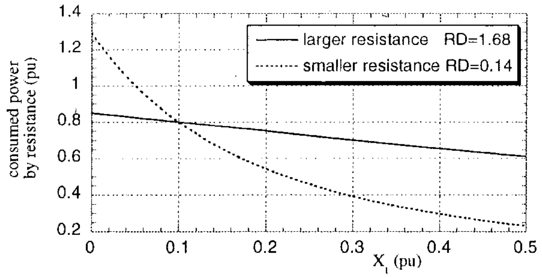

Fig. 2. Variation of consumed power by resistance for different amounts of reactance.

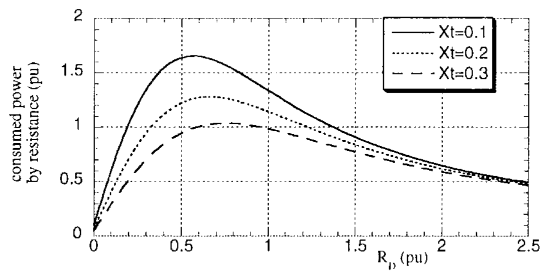

Fig. 3. Variation of consumed power by resistance for different values of resistance.

show that in the case of the smaller resistance, P is highly vulnerable to the change of power system parameter.

In this context the larger resistance should be suitable for power system stabilization. However, it may cost highly because a large amount of resistance is required for the superconducting coil after the transition to normal conductivity as well as for the current limiting resistor and because the shared heat dealt with by the superconducting coil is large.

Here, the effect of SFCL on the transient stability is evaluated by digital simulation. Figs. 4 and 5 show results of generator phase angle behaviors for different locations of a 3LG fault with a clearing time of 6 cycles. These results demonstrate the robustness of the larger resistance case.

V. Control with SMES

It has been found that in the case of smaller resistance, the enhancement of transient stability is highly affected by the change of system parameters. Also in the case of larger resistance an apparatus which adjusts the control mismatch

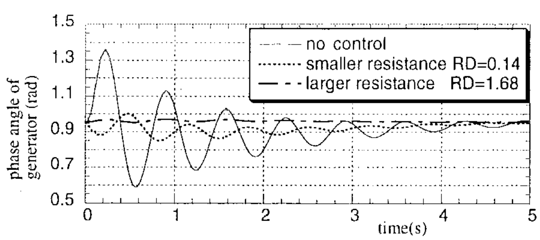

Fig. 4. Phase angle behavior of generator when a 3LG fault occurs near the generator.

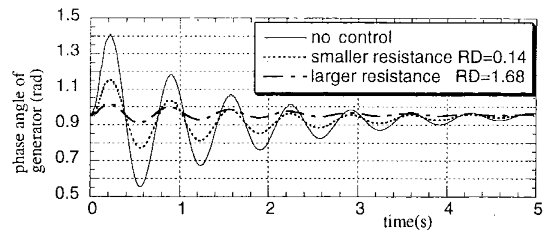

Fig. 5. Phase angle behavior of generator when a 3LG fault occurs at the point apart from the generator by 0.2 pu reactance.

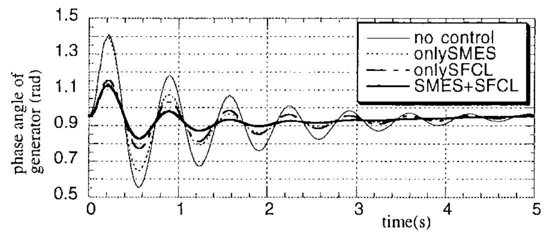

Fig. 6. Phase angle of generator when a 3-LG fault occurs at the point apart from the generator by 0.2 pu reactance. (The resistance of SFCL is 0.14pu).

due to the system changes, is advantageous. Here, the use of SMES together with the SFCL is proposed as a universal power system stabilizer. The SMES compensates for the amount of consumed active power by the SFCL resistor to suppress the generator acceleration during a short circuit. On the other hand, the SMES can not operate during the short circuit because the bus voltage drops significantly, while the installation of SFCL suppresses the voltage drop. Thus, the SFCL and the SMES work as supplementary apparatus for each other.

A control scheme using the deviation of generator angular velocity $\Delta\omega$ is adopted as follows [3].

$$\Delta P_{SMI} = -K\Delta\omega \qquad (7)$$

where P_{SMI} is the control reference for the active power and K is a proportional gain. Reactive power control by the SMES is ignored for the sake of brevity. The dynamics of SMES control from the control reference to the real active power output is represented by the first order time lag with a time constant of 10 ms. Figs. 6 and 7 show simulation results; Fig. 6 shows the case when the resistance of the SFCL is small and Fig. 7 shows the larger resistance case. The results show that the SMES damps out the generator swing quickly after the SFCL suppresses the generator acceleration significantly.

Here, the capacity of the power converter and the energy capacity, which are used for the control have been evaluated. The results are summarized in Tables II and III, where the MVA capacity is defined by the maximum power output from the SMES and the MJ capacity is defined by the difference between the maximum and the minimum energy levels. In case 1 the fault occurs at the generator terminal and in case 2 the fault location is apart from the generator by a 0.2 pu reactance.

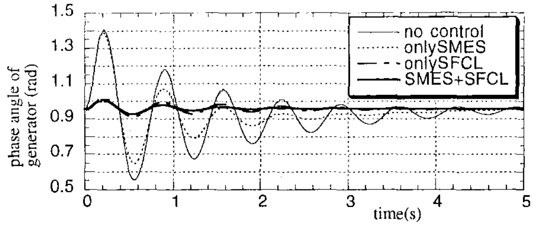

Fig. 7. Phase angle of generator when a 3-LG fault occurs at the point apart from the generator by 0.2 pu reactance. (The resistance of SFCL is 1.68pu).

TABLE II
EVALUATED MVA CAPACITY OF SMES WITH RESPECT TO THE RESISTANCE OF SFCL.

	no SFCL	$R_D = 0.14$	$R_D = 1.68$
case1	198.9MVA	57.3MVA	8.32MVA
case2	224.9MVA	104.0MVA	35.23MVA

TABLE III
EVALUATED MJ CAPACITY OF SMES WITH RESPECT TO THE RESISTANCE OF SFCL

	no SFCL	$R_D = 0.14$	$R_D = 1.68$
case1	54.9MJ	11.2MJ	0.859MJ
case2	60.2MJ	32.4MJ	8.76MJ

The results show that the capacities of SMES are significantly reduced when the SMES is installed with the SFCL. Especially, when the larger resistor is used for SFCL, the capacities are around 1/10 of the case by the SMES without SFCL.

In Figs. 6 and 7 there may be little difference between the control results by the SFCL and the SFCL with SMES. It is because the power system has sufficient damping. The SMES should be effective when the small-signal stability margin of the power system is small. Generally, the power system stability becomes worse as the power flow becomes heavy, which implies that the available transmission capacity of the line is diminished by the system stability. Thus, the SMES is effective for enhancing the power transmission capacity.

Fig. 8 shows a simulation result when the response of the automatic voltage regulator (AVR) is very fast (a ten-times gain has been set) and the distance of transmission is triple, that is, the power system is near the stability boundary and has a sustained power oscillation after a small disturbance. In Fig. 8 the generator loses the synchronization after a six-cycle 3LG fault.

The SMES with SFCL is applied to the power system, where the output power from the SMES is limited at 0.023 pu (30MVA). The resistor of SFCL is the larger one and the short circuit fault occurs apart from the generator. When a SFCL is applied to the system, the synchronization of the generator is recovered. However, the power system has a

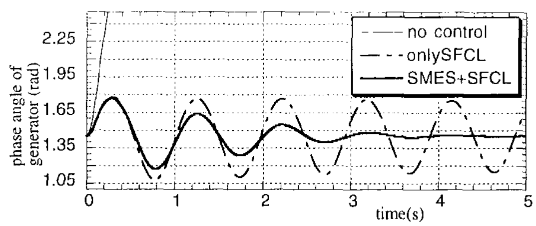

Fig. 8. Generator phase angle curve when the damping of power swing is weak.

sustained oscillation. The SMES with SFCL is very much effective for damping the power swing as well as for the transient stability enhancement. In this case the capacities of SMES are 30MVA and 3.52 MJ, which implies that a small SMES like a micro-SMES is available [9].

VI. Conclusions

In this paper, an SFCL is applied as a powerful controller for the transient stability enhancement, where a method to evaluate a couple of necessary values of resistors is proposed. It is found that the larger resistance is more robust against the system parameter changes. The SFCL is applied as a subsidiary device to the SMES for power system stabilization. By the use of SFCL the capacity of SMES necessary for the power system stabilization is significantly reduced. The proposed SMES with SFCL is a powerful controller to augment the transmission capacity of power system by enhancing the transient stability as well as by increasing the system damping.

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