Improvement of Power System Transient Stability by Superconducting Fault Current Limiter

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***Abstract*—This paper presents the results of analyses of the effectiveness of a Superconducting Fault Current Limiter (SFCL) on improving power system transient stability and limiting the fault current in a two-machine-infinite bus system. In this study, the system model with two SFCLs installed at each generator terminal was used taking 3LG (three lines to ground) fault at 12 fault points into account. These analyses were performed using EMTP/ATP. It is concluded that the use of SFCL with shunt resistance value of about 1.0 pu is effective for all fault points for the improvement of power system transient stability and the limiting of fault current.**

***Index Terms*—EMTP, Fault Current Limiter, Power System Transient Stability, Shunt Resistance.**

I. Introduction

WITH the increasing demand for electric power, power systems are becoming larger and more interconnected. As a consequence, the fault currents increase, and transient stability problems become more serious. Consequently, in order to maintain the stability of power systems, replacement of substation equipment or changes in the configuration of the system will be needed, and this will ultimately lead to decreased operational flexibility and lower reliability. In recent years, Superconducting Fault Current Limiters (SFCL) as the devices of limiting of fault currents have been progressing due to the advancement of superconducting technology [1]-[3]. Their main advantages are: negligible influence on the network under normal conditions, instantaneous limiting of fault current, and automatic response without external trigger. Furthermore, they can also improve the power system transient stability if suitable shunt resistance is used as the limiting element [4]-[7]. This is because the difference between the mechanical input power and the electrical output power in the generator after a fault is decreased due to effectively absorption of the real power by the shunt resistance.

In this paper, we have studied the most effective value of the shunt resistance of SFCL on improvement of the transient stability and limitation of the fault currents during 3LG (three lines to ground) fault, taking 12 fault points into account in the two machine-infinite bus system. These simulation analyses are performed using EMTP/ATP.

II. Model System

The power system model used for the investigations of transient stability is shown in Fig. 1. It consists of two generators (G1 and G2), an infinite bus, transformers and double-circuit transmission lines. The line parameters in the figure are numerically shown in the forms $R+jX$ $(jB/2)$ per phase with one line. Two SFCLs with shunt resistance R_L are installed at Y side of both transformers, Tr.1 and Tr. 2. The SFCLs are used as an S/N (Superconducting/Normal) transforming type device. It is assumed that the resistances of superconductors rise exponentially up to 25 pu (based on each generator rating) within 1.0 ms after a quench. As the superconducting coil needs a short time in order to recover to its normal condition after a quench, two SFCL devices are connected in parallel. The first SFCLs, SFCL11 and SFCL21, are for fault, and the second ones, SFCL12 and SFCL22, are for unsuccessful reclosing. Also, two arresters, which are modeled to be ZnO type with no gap, are connected on the Y side of both transformers. When the instantaneous value of phase voltage across the arrester exceeds 1.84 pu (1.3 times of the peak value of rated phase voltage), the arrester begins to operate. The models of AVR (Automatic Voltage Regulator) and GOV (Governor) are shown in Fig. 2. Table I shows the parameters of both generators.

The time sequence of simulations is shown in Fig. 3, i.e., 1) a 3LG fault occurs at each fault point (from F1 to F12) at t=0.1 sec, and 2) the circuit breakers, CB, on the faulted line are opened at t=0.2 sec and reclosed at t=1.0 sec. It is assumed that the circuit breaker clears the line when the current through it crosses the zero level.

III. Simulation Results

A. Determination of Critical Current Value

To improve the power system transient stability effectively, the critical current value of SFCL should be determined in order to satisfy the following conditions.

(1) In steady state, SFCLs do not operate.
(2) When fault occurs, the SFCL of faulted phase operates, but SFCL of normal phase does not operate.
(3) SFCLs should not operate against the transient current after the clearing of fault.

Fig. 4 shows the instantaneous maximum value of current flowing into Y side of transformers, Tr.1 (Fig-a) and Tr.2 (Fig-b), for each fault point in the case of without operation of

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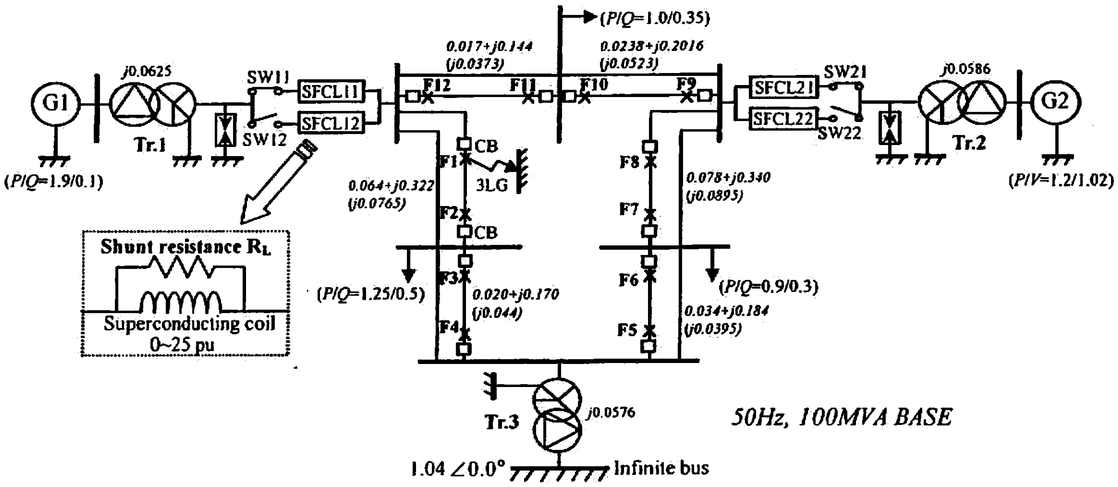


Fig. 1. Two-Generator-Infinite Bus System Model.

SFCLs. From the results, we have selected the critical current value of 3.0 pu for SFCLs not to operate after circuit breaker opening.

TABLE I
Generator Parameters of G1 and G2.

(a) G1

MVA			200
R_a (pu)	0.003	X_q'' (pu)	0.171
X_l (pu)	0.102	X_0 (pu)	0.13
X_d (pu)	1.651	T_{do}' (s)	5.9
X_q (pu)	1.59	T_{qo}' (s)	0.535
X_d' (pu)	0.232	T_{do}'' (s)	0.033
X_q' (pu)	0.38	T_{qo}'' (s)	0.078
X_d'' (pu)	0.171	H (s)	9

(b) G2

MVA			130
R_a (pu)	0.004	X_q'' (pu)	0.134
X_l (pu)	0.078	X_0 (pu)	0.13
X_d (pu)	1.22	T_{do}' (s)	8.97
X_q (pu)	1.16	T_{qo}' (s)	1.5
X_d' (pu)	0.174	T_{do}'' (s)	0.033
X_q' (pu)	0.25	T_{qo}'' (s)	0.141
X_d'' (pu)	0.134	H (s)	6

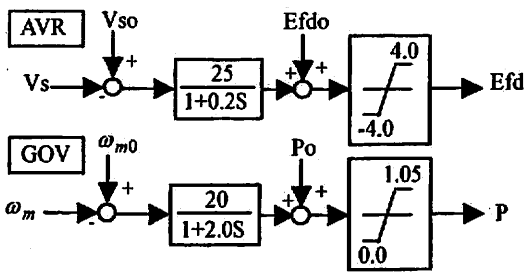


Fig. 2. AVR and Governor Models.

Fig. 3. Time Sequence of Simulation.

Table II summarizes the operating state of SFCL11 and SFCL21 for each fault point under critical current value of 3.0 pu. The symbols '1' and '0' represent "operation (on)" and "no operation (off)" of SFCLs of each phase respectively. SFCLs of all faulted phases do not always operate for each fault point as shown in Table II.

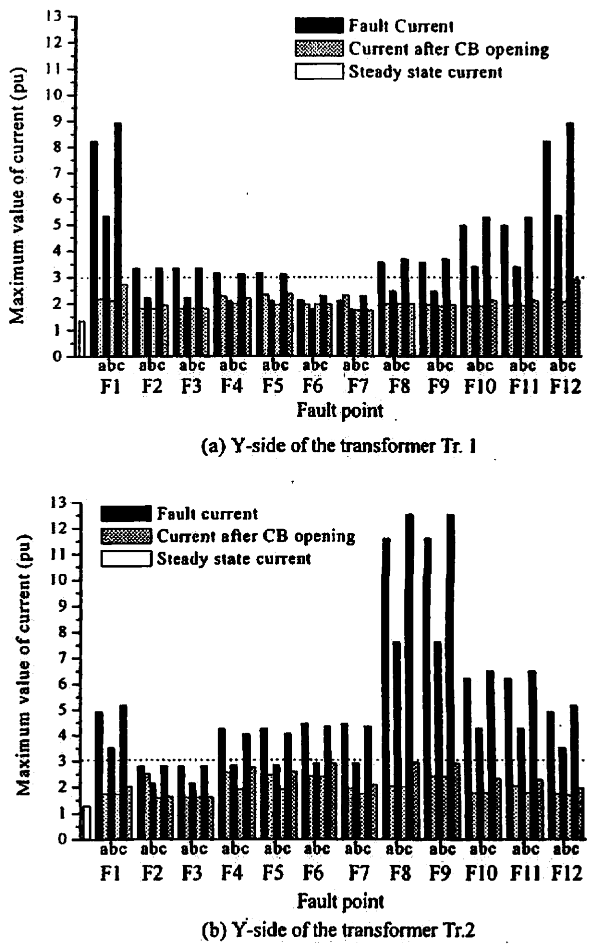


Fig. 4. Maximum Values of Currents for Each Fault Point.

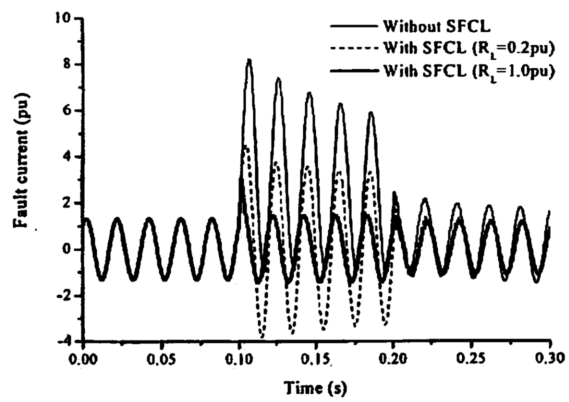
TABLE II
Operating State of SFCL11 and SFCL21 for Each Fault Point.

	Phase	F 1	F 2	F 3	F 4	F 5	F 6	F 7	F 8	F 9	F 10	F 11	F 12
SFCL11	a	1	1	1	1	1	0	0	1	1	1	1	1
	b	1	0	0	0	0	0	0	0	0	1	1	1
	c	1	1	1	1	1	0	0	1	1	1	1	1
SFCL21	a	1	0	0	1	1	1	1	1	1	1	1	1
	b	1	0	0	0	0	0	0	1	1	1	1	1
	c	1	0	0	1	1	1	1	1	1	1	1	1

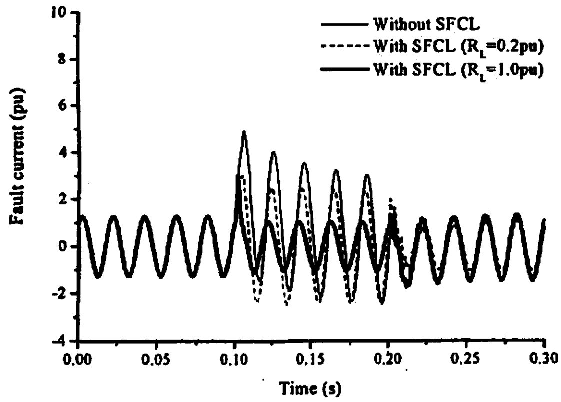
0: off, 1: on

B. Limitation of Fault Current

Figs. 5 (a) and (b) show the current waveforms (phase 'a') flowing into the Y-side of the transformers, Tr.1 (Fig-a) and Tr.2 (Fig-b), during 3LG fault at point F1 respectively. The dotted line, bold line and thin line in the figures show the results of 3 cases: with the use of an SFCL with shunt resistance R_L=0.2 pu, R_L=1.0 pu, and without SFCL, respectively. In the cases of "without SFCL" and "R_L=0.2 pu", the fault currents rise up significantly and DC component in the currents decreases slowly. On the other hand, in the case of "R_L=1.0 pu", the fault currents are limited to less than 3.0 pu



(a) Y-side of the transformer Tr. 1



(b) Y-side of the transformer Tr. 2

Fig. 5. Fault Current Waveforms for Each Shunt Resistance Values (Fault Point F1).

(critical current value) and the DC component decreases rapidly. Fig. 6 shows the maximum value of fault current for each shunt resistance value where R_L=0.0 means "without SFCL". From this figure, it can be seen that the effect of limiting fault current is maximum when the shunt resistance value is more than 0.4 pu in the case of fault point F1. Fig. 7 shows such effective values of shunt resistance on limitation of fault current for each fault point. The asterisk depicted in the figure means non-existence of effective shunt resistance, that is, the maximum values of currents flowing into SFCLs corresponding to the asterisk case become always less than 3.0 pu. From this figure, it is concluded that SFCLs with shunt resistance value of more than 0.5 pu are effective on the limitation of fault current for all fault points.

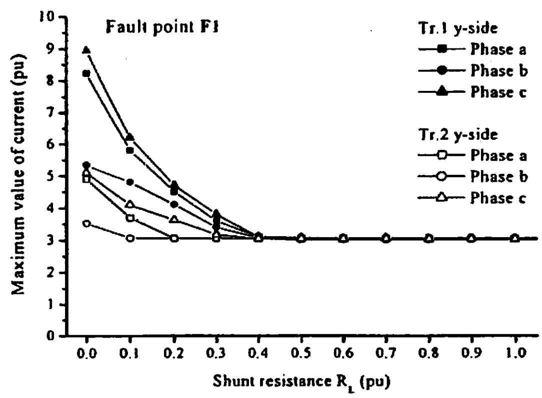


Fig. 6. Shunt Resistance Values vs. Maximum Value of Currents (Fault Point F1).

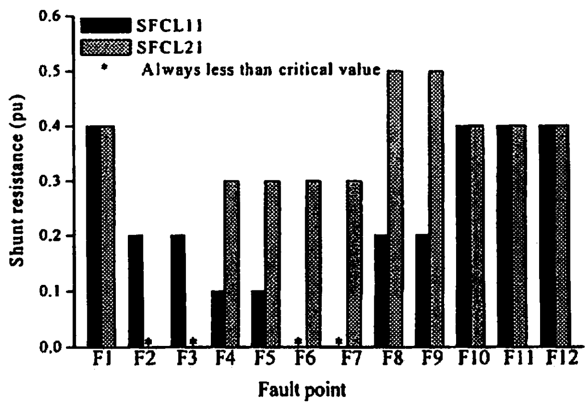


Fig. 7. Effective Values of Shunt Resistance for Each Fault Point.

C. Improvement of Transient Stability

For evaluation of transient stability in multi-machine system, we have used the total kinetic energy, W_{total}, the summation of kinetic energy of each generator. By using W_{total}, we can evaluate the transient stability of overall power system, taking each generator power rating into account. Fig. 8 shows the total kinetic energy of G1 and G2 with respect to each shunt resistance in the case of fault at point F1. In the cases of "with SFCL", the swings of total kinetic energy are restrained effectively more than that of "without SFCL". Furthermore,

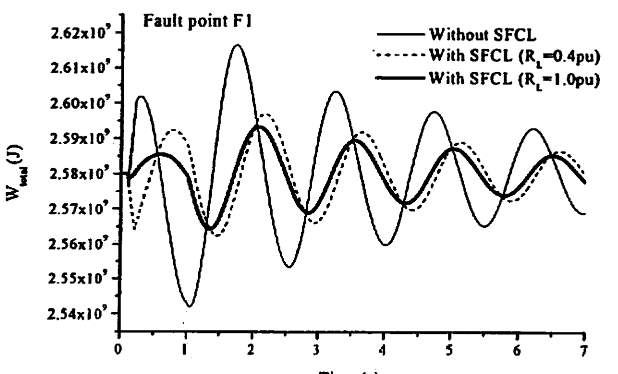


Fig. 8. Waveforms of Total Kinetic Energy W_{total} (Fault Point F1).

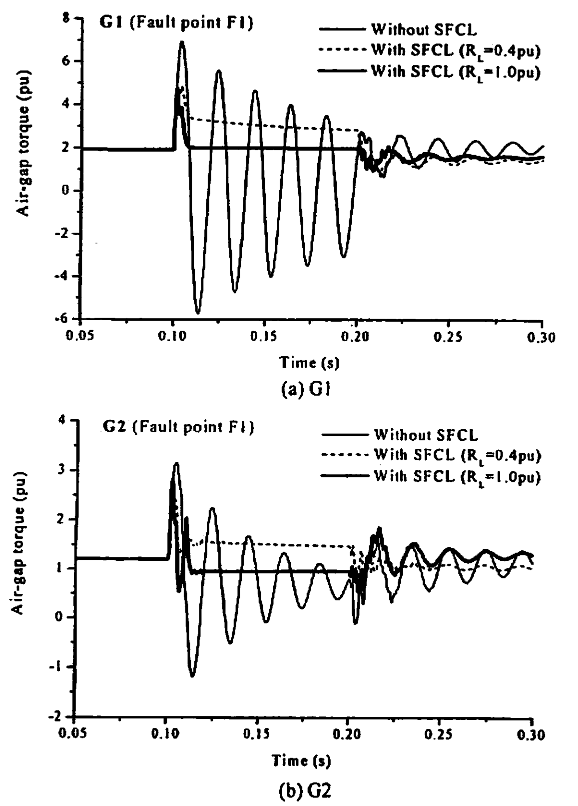


Fig. 10. Air-gap Torque Waveforms in Each Generator (Fault Point F1).

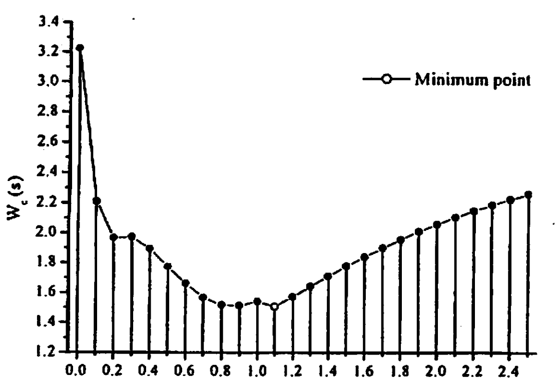


Fig. 11. Mean Values of Wc's for All Fault Points.

the swing of "R_L=1.0 pu" is restrained more than that of "R_L=0.4 pu". To evaluate the transient stability for each shunt resistance value in all fault points, we have used the stability index, W_c, given by

$$W_c\ (\text{sec}) = \int_0^T \left|\frac{d}{dt}W_{total}\right| dt \ \ / \text{ system base power} \qquad (1)$$

where T is the simulation time selected to 7.0 (s) in this work. It can be said that the transient stability is improved effectively as long as W_c becomes a small value. Fig. 9 shows the W_c versus shunt resistance value characteristic for all fault points. We can determine the most effective shunt resistance value for each fault point from the observation of the responses. For example, the most effective value of shunt resistance is 1.0 pu in the case of fault point F1 (Fig. 9 (a)). Fig. 10 shows the air-gap torque waveforms of both generators for each shunt resistance value in the case of fault point F1. The air-gap torque oscillations of both generators can be restrained by the SFCLs as shown in the Figs. 10 (a) and (b) respectively. In the case of "R_L=1.0 pu", the air-gap torques after SFCLs operate are nearly equal to the initial value. It means that the difference between the mechanical input power and the electrical output power during a fault is reduced due to effectively absorption of the real power by the shunt resistance. Consequently, the transient stability is improved effectively by SFCLs with shunt resistance of 1.0 pu.

In general, it is impossible to predict the fault point in a practical power system. However, the effective shunt resistance value for any fault point may be evaluated from the response of the mean value of W_c's for all fault points, which is shown in Fig. 11. From this figure, we can see that the most effective shunt resistance value for the SFCL is 1.1 pu.

In the cases of fault point F6 and F7 shown in Figs. 9 (f) and (g), W_c changes discontinuously when SFCLs with shunt resistance value of 1.1 pu are used. This is because the SFCL11 of phases 'a' and 'c' begin to operate when the fault occurs in the case of shunt resistance value of 1.1 pu. In other words, the maximum values of currents of phases 'a' and 'c' flowing into SFCL11 exceed the critical current value of 3.0 pu in the case of shunt resistance value of 1.1 pu. Fig. 12 shows the maximum values of current of each phase flowing into Y side of the transformer Tr. 1 in the case of fault point

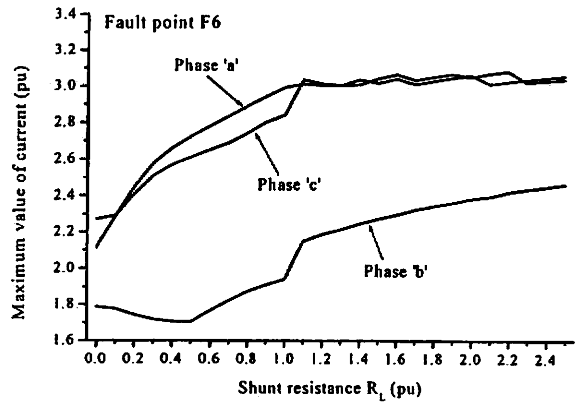
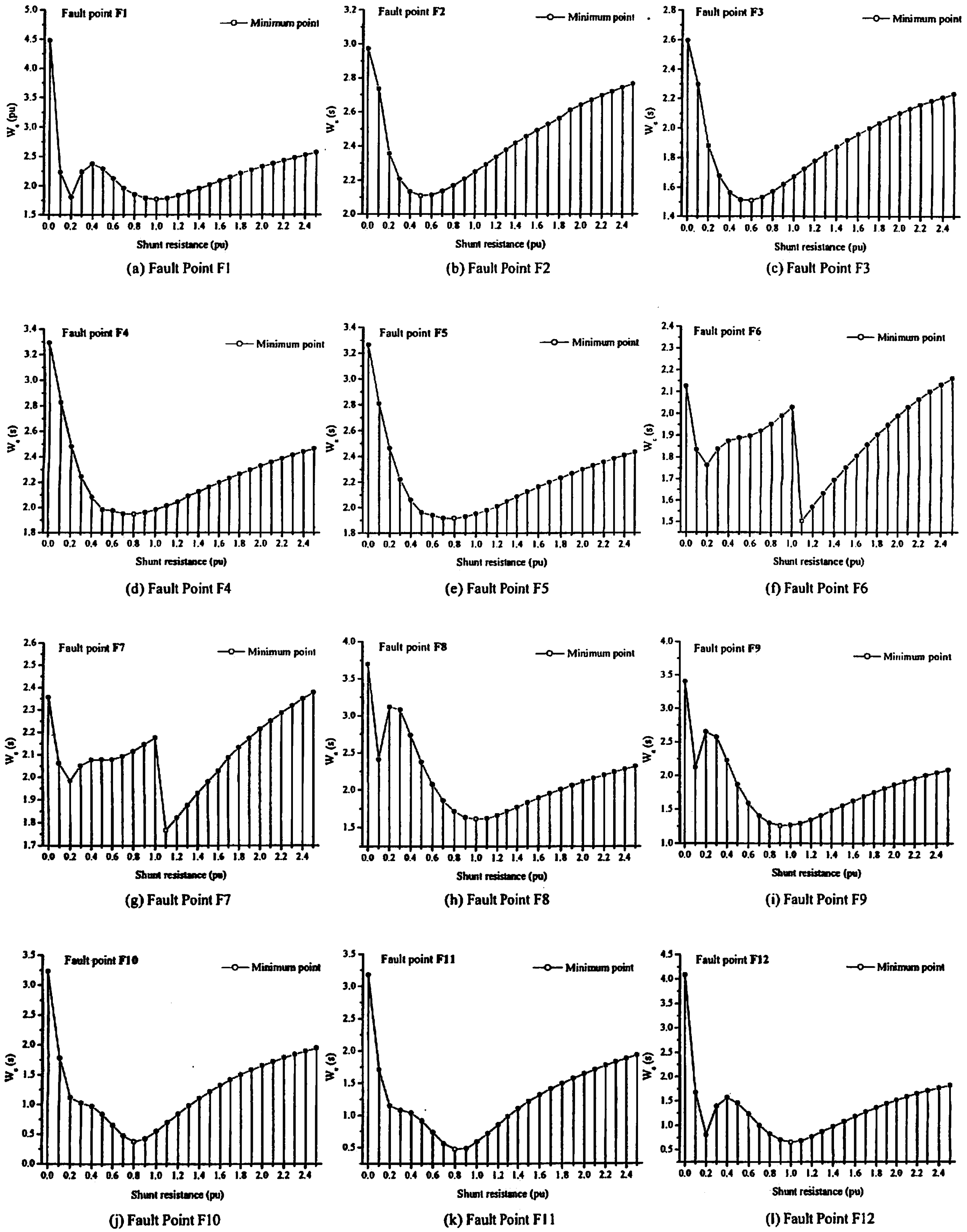


Fig. 12. Maximum Values of Currents Flowing Into the Transformer Tr. 1 for Each Shunt Resistance Values (Fault Point F6)



(a) Fault Point F1 (b) Fault Point F2 (c) Fault Point F3

(d) Fault Point F4 (e) Fault Point F5 (f) Fault Point F6

(g) Fault Point F7 (h) Fault Point F8 (i) Fault Point F9

(j) Fault Point F10 (k) Fault Point F11 (l) Fault Point F12

Fig. 9. *Wc* vs. Shunt Resistance Values for Each Fault Point.

F6. The maximum values of currents flowing into SFCL11 rise up with the increasing of shunt resistance value. As a consequence, the maximum values of currents of phases 'a' and 'c' reach 3.0 pu in the case of shunt resistance value of 1.1 pu.

IV. Conclusions

The effects of a superconducting fault current limiter (SFCL) on the dynamic behavior of synchronous generators during 3LG (three lines to ground) fault in the two-machine-infinite bus system are analyzed by simulation studies using EMTP/ATP. The following results have been obtained.

(1) The fault currents can be limited by SFCLs with shunt resistance value larger than 0.5 pu.
(2) The power system transient stability can be improved effectively by SFCLs with shunt resistance value of 1.1 pu.

V. Acknowledgment

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VI. References

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