Simulation Study on Operating Characteristics of Superconducting Fault Current Limiter in One-Machine Infinite Bus Power System

Y. Shirai, *Member, IEEE*, M. Taguchi, M. Shiotsu, H. Hatta, and T. Nitta, *Member, IEEE*

***Abstract*—A simulation model of a Superconducting Fault Current Limiter (SCFCL) based on the experimental results was proposed. Simulation studies were performed in one-machine infinite bus system with parallel transmission lines, which corresponds to the experimental system. The simulation results agree well with the experimental ones. Power system operating characteristics of the SCFCL were investigated and discussed by simulation results Effects of the SCFCL to the power system are verified from the simulation results. It is shown that the SCFCL's make critical clearing time longer and improve the system stability.**

***Index Terms*—One machine infinite bus system, recovery characteristics, three-phase superconducting fault current limiter.**

I. INTRODUCTION

MANY studies have been reported on various types of superconducting fault current limiters (SCFCL's), for example [1]–[4]. They are mainly about the characteristics of SCFCL's themselves. There are a few studies on SCFCL's as a power system apparatus [5], [6]. SCFCL's are expected to improve reliability and stability of power systems. To introduce an SCFCL to power systems, the trigger current level, the limiting impedance and the recovery time are important specifications of the SCFCL. A SCFCL with adjustable trigger current level has been proposed. A model single-phase SCFCL was designed and made. Basic experiments for operating characteristics were carried out [7].

For the next step, a trial 3-phase SCFCL was designed and made for investigation on the power system characteristics by use of the model power system and basic tests were successfully carried out [8].

In this paper, a simulation model of the proposed type SCFCL for EMTP (Electro-Magnetic Transient Program) is introduced based on the experimental results. By use of the SCFCL model, power system simulation studies with SCFCL's were performed in one-machine infinite bus system with parallel transmission lines, which is corresponding to the experimental system.

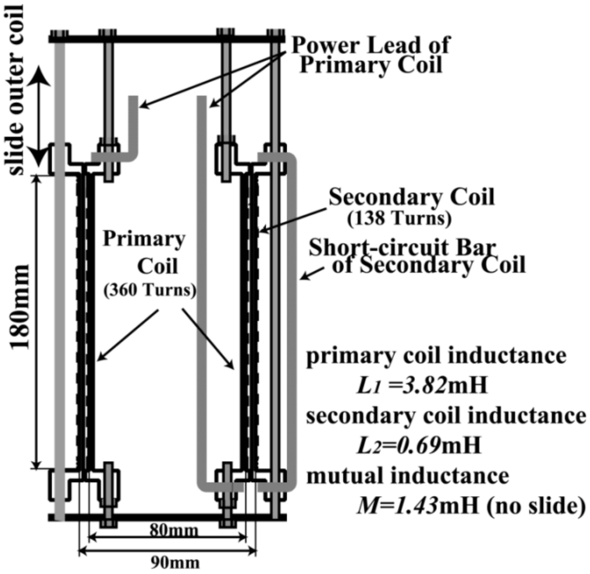

Fig. 1. Schematic configuration and specifications of proposed SCFCL. (3 SCFCL's are in a cryostat.)

II. BASIC CHARACTERISTICS OF TEST SCFCL AND ITS MODEL

A. Test SCFCL

The test SCFCL unit for three-phase operation was designed and made. It contains three SCFCL's of transformer type in one cryostat. The SCFCL consists of two superconducting coils (NbTi wire for AC use) coupled co-axially. Schematic configuration and specifications of the test SCFCL is shown in Fig. 1. The inner (primary) coil will be connected to a power line. The outer (secondary) coil is short-circuited. The secondary coil can be slided (shifted upward) with small slide distance in order to calibrate the trigger current level [9]. The trigger current levels of three SCFCL's were adjusted to be the same value 89.7 A rms. The fault current is limited by the inductance of the primary coil. Therefore, the amount of energy dissipation at the current limiting in the secondary wire is rather small. The recovery time (the required zero-current time for successful recovery from current limiting mode to waiting mode) is rather short, 450 ms at most [10], [11].

B. Impedance of SCFCL

The self and mutual inductances L_1, L_2 and M of primary and secondary coils are designed electro-magnetically. The nonlinear resistance R_2 of the secondary coil changes according to

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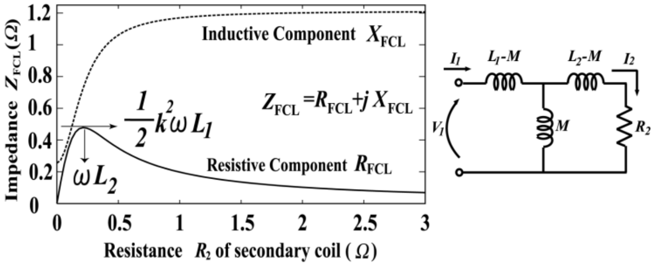

Fig. 2. Equivalent circuit and impedance of SCFCL as a function of secondary coil resistance.

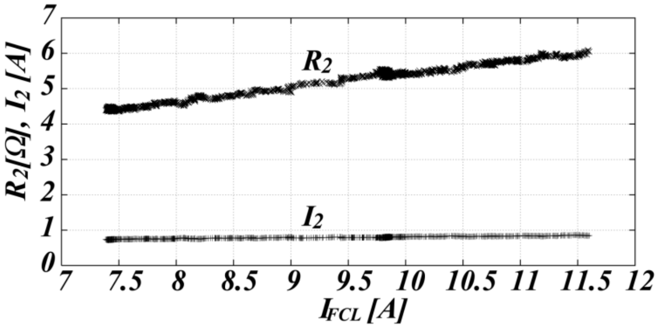

Fig. 3. Resistance and current of the secondary wire for the primary coil current.

the super/normal transition of the wire and depends on the temperature of, magnetic flux on and coil current through it. Strictly speaking, R_2 must be obtained by use of a heat equation of the superconducting secondary wire [12].

However, the impedance $Z_{FCL} = R_{FCL} + jX_{FCL}$ is given as

$$Z_{FCL} = \frac{V_1}{I_1} = \frac{\omega^2 R_2 M^2}{R_2^2 + \omega^2 L_2^2} + j\omega\left(L_1 - \frac{\omega^2 L_2 M^2}{R_2^2 + \omega^2 L_2^2}\right), \quad (1)$$

as a function of R_2 shown in Fig. 2. (k denotes the coupling coefficient.) The current limiting impedance is determined as almost the inductive component X_{FCL} and is nearly constant for wide range of $R_2 \gg \omega L_2$. Therefore, the precise design of R_2 is not necessary for the current limiting operation. When the resistance R_2 is less than ωL_2, the normal zone of the secondary wire shrinks and turns into the superconducting state because of energy unbalance on the wire. The impedance of the test SCFCL is 0.2 p.u. in the waiting mode and is 0.55∼0.60 p.u. in the current limiting mode. The impedance at the waiting mode becomes smaller for large scale as practical use.

C. Resistance of the Secondary Wire

In the current limiting mode, the ohmic loss appears only in the normal zone of the secondary wire. Therefore, we obtain the following equation

$$P = \frac{\omega^2 R_2 M^2}{R_2^2 + \omega^2 L_2^2} I_1^2 = R_2 I_2^2. \quad (2)$$

The ohmic loss of the SCFCL was measured and the relations between R_2, I_2 and the primary coil current $I_1 = I_{FCL}$ are obtained experimentally as shown in Fig. 3. The resistance R_2 is almost proportional to the primary coil current. The secondary coil current is almost constant value, which is nearly equal to the minimum propagation current I_{mpc} of the superconducting wire, independent from the primary coil current [13].

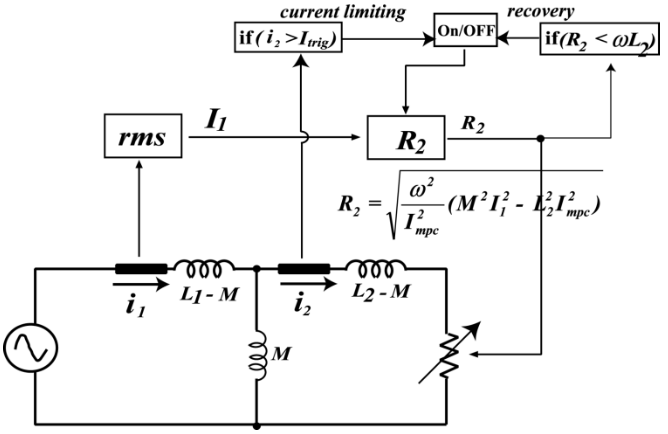

Fig. 4. Outline of the simulation model of the transformer type SCFCL.

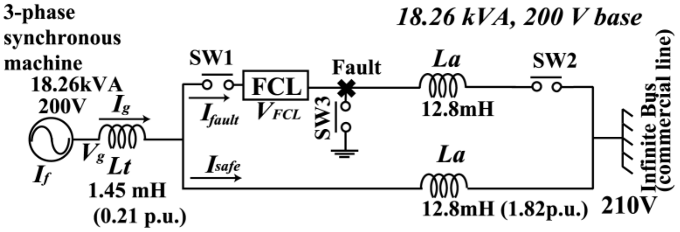

Fig. 5. Simulation target: Experimental one machine infinite bus system with parallel transmission lines including 3-phase SCFCL.

If the secondary current in the current limiting mode is minimum propagation current, we can obtain the resistance

$$R_2 = \sqrt{\frac{\omega^2}{I_{mpc}^2}(M^2 I_1^2 - L_2^2 I_{mpc}^2)}, \quad (3)$$

as a function of the primary coil current.

D. Simulation Model of SCFCL

Under the above discussions, the simulation model of the SCFCL is introduced as shown in Fig. 4. The SCFCL turns into the current limiting mode when the secondary coil current i_2 exceed the super/normal transition current I_{trig} (=255 A for the trial SCFCL which corresponds to 89.7 Arms of primary coil current). The calculation of the resistance R_2 begins according to (3). The SCFCL recovers to the waiting mode when the resistance R_2 becomes less than ωL_2 in this model. In order to simulate the recovery time, the temperature of the normal zone of the secondary wire should be considered [12]. However, in this paper, we do not discuss the recovery characteristics in detail and remain the factor for the future problem.

III. CURRENT LIMITING OPERATION IN ONE MACHINE INFINITE BUS SYSTEM

A. Model Power System

Fig. 5 shows an experimental one-machine infinite bus system including 3-phase SCFCL, which is a target system of

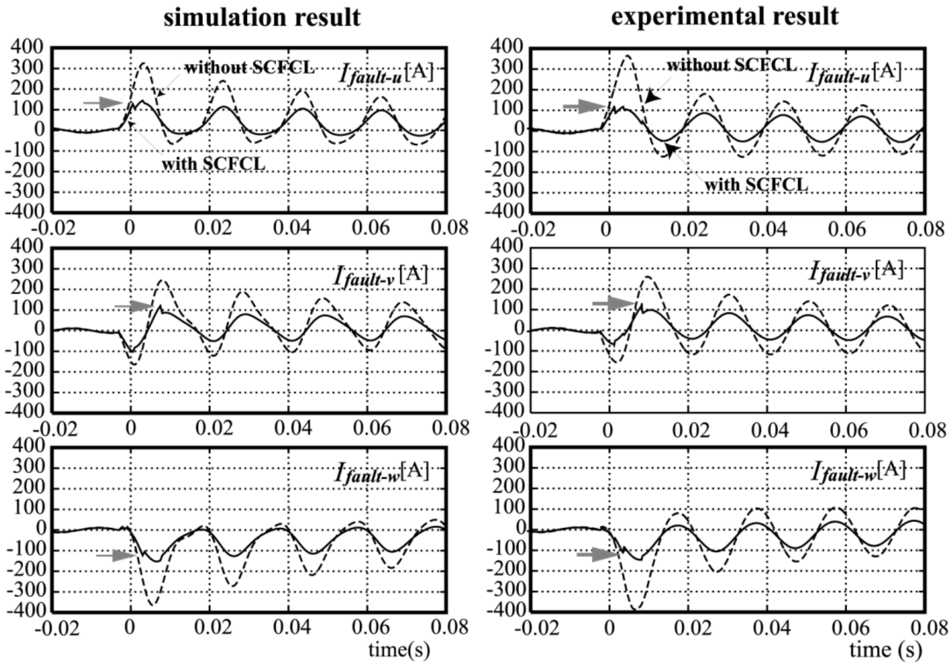

Fig. 6. Simulation result of the fault line current with and without SCFCL and corresponding experimental results.

TABLE I
SPECIFICATION OF SYNCHRONOUS GENERATOR

item	value	
rated voltage	200	V
frequency	50	Hz
poles	4	
rated capacity	18.26	kVA
field current	19.2	A
synchronous reactance	1.227	p.u.
q-axis synchronous reactance	1.200	p.u.
d-axis transient reactance	0.394	p.u.
q-axis transient reactance	1.200	p.u.
d-axis sub-transient reactance	0.128	p.u.
q-axis sub-transient reactance	0.450	p.u.
d-axis open circuit time constant	0.210	s
d-axis sub-transient open circuit time constant	0.031	s
armature resistance	0.034	p.u.

the simulation. A 3-phase synchronous generator is connected to the infinite bus (210 V commercial power line) through parallel artificial transmission lines. The upper line (fault line) has SW3 in parallel for simulated fault and has the three-phase SCFCL and circuit breakers (SW1 and SW2) in series. The line impedance is rather large compared with that of real system so as to obtain operating conditions near a stability limit. The specification of the test generator is listed in Table I. The field current is supplied by a constant voltage source.

The switch SW3 is closed to simulate several types of faults. The fault currents flow through the SCFCL. The SCFCL immediately start to limit the fault current. After a certain time (clearing time), the switches SW1 and SW2 are open to remove the fault line and the system move to the single-transmission line operation. All switches are magnetically controlled and operated at the same time in three phases.

The generator current $\boldsymbol{I}_g$, the voltage $\boldsymbol{V}_g$, the field current $\boldsymbol{I}_f$, the fault line current $\boldsymbol{I}_{fault}$, the normal line current $\boldsymbol{I}_{safe}$, the voltage $\boldsymbol{V}_{FCL}$ across the FCL and the FCL current $\boldsymbol{I}_{FCL}$ are measured in the experiments. The experiments were successfully carried out and the results were already reported [5]. In the following sections, the simulation results were compared with those of the corresponding experiments.

B. Fault Line Current and Limiting Operation

The operating conditions for the simulation are as follows. The output power 0.28 p.u., the fault type is 3LS (3-phase Line Short) and the clearing time is set to be 300 ms.

The fault line currents of each phase with and without SCFCL obtained by the simulation are shown in Fig. 6. The fault current with SCFCL (:solid line) is successfully limited compared with that without SCFCL (:dotted line). At first, the u-phase SCFCL begins to limit the current, then the w-phase one turns to the limiting mode and at last, the v-phase one works. This sequence depends on the phase of the current at the fault. It can be seen that the current waveform is affected by the other SCFCL operations. The corresponding experimental result is also shown in Fig. 6. The simulation results agree well with those of the experiments.

C. Generator Terminal Voltage

Fig. 7-left shows the simulation results of the terminal phase-voltage of the generator at the fault with and without SCFCL. Fig. 7-right shows the experimental results. The terminal voltages step down to almost 0.1 p.u. during the fault without SCFCL, however, the SCFCL keeps up them up to 0.5

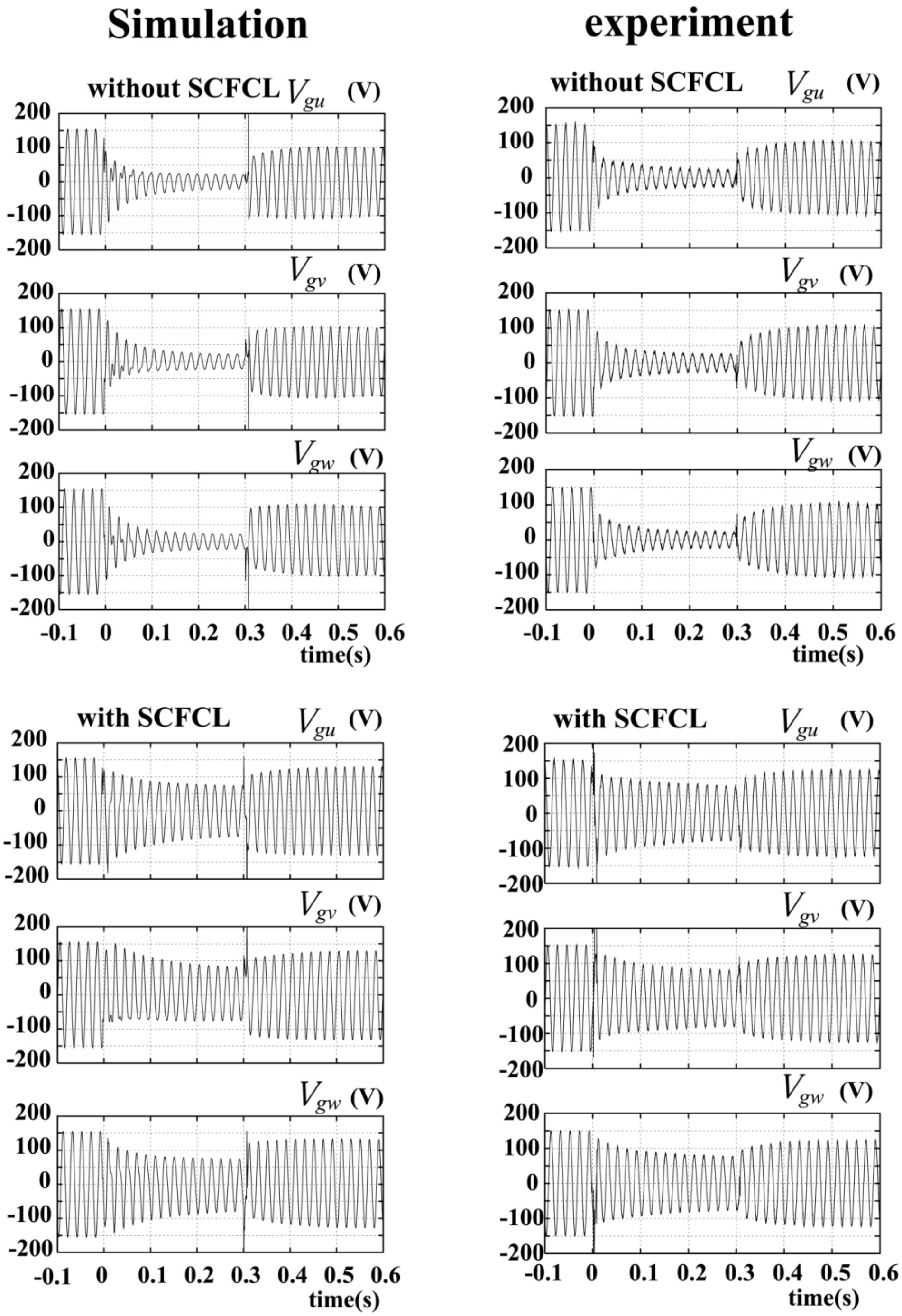

Fig. 7. Simulation and experimental results of generator terminal voltages at the fault with and without SCFCL.

p.u. The simulation results express well the voltage change and the SCFCL performance.

D. Generator Output Power

Simulation result of the generator output at the fault and after the fault line removal (single line operation) is shown in Fig. 8. The simulation results shows that the generator steps out, that is, loses the synchronism after the fault line removal without SCFCL. On the other hand, during the fault, the SCFCL keeps the terminal voltage and the generator continues to generate the power of over 2 kW. Then after the fault line removal, the generator can keep the synchronism. Experimental result is also shown in the same figure.

E. Rotating Speed and Rotor Angle

Fig. 9 shows the simulation result of the deviation of angular velocity of the generator rotor at the fault with and without SCFCL. The acceleration of the rotor during the fault suppressed by the SCFCL compared with that without SCFCL. Then, after clearing the fault line, the oscillation of the generator rotor is damped.

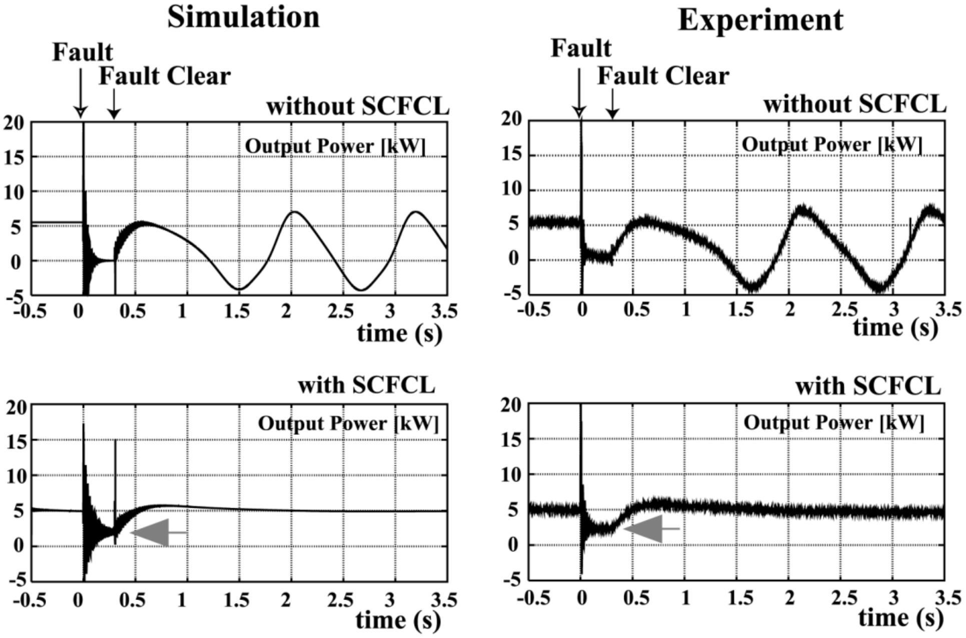

Fig. 8. Output power of the generator at the fault and after the fault line removal.

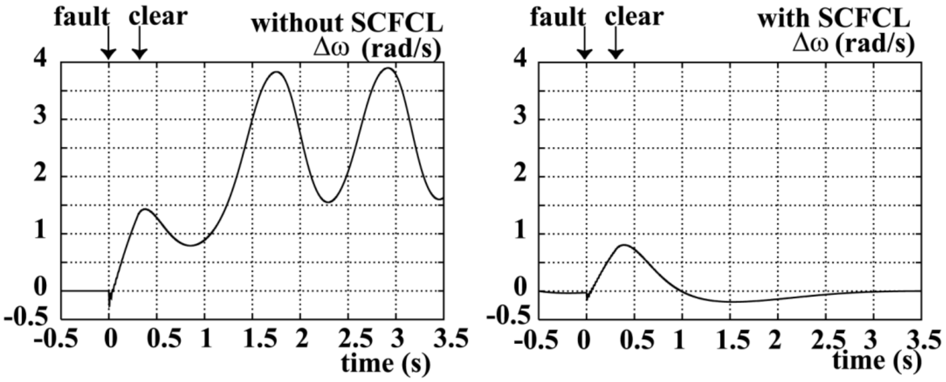

Fig. 9. Simulation result of deviation $\Delta\omega$ of angular velocity of the generator rotor at the fault.

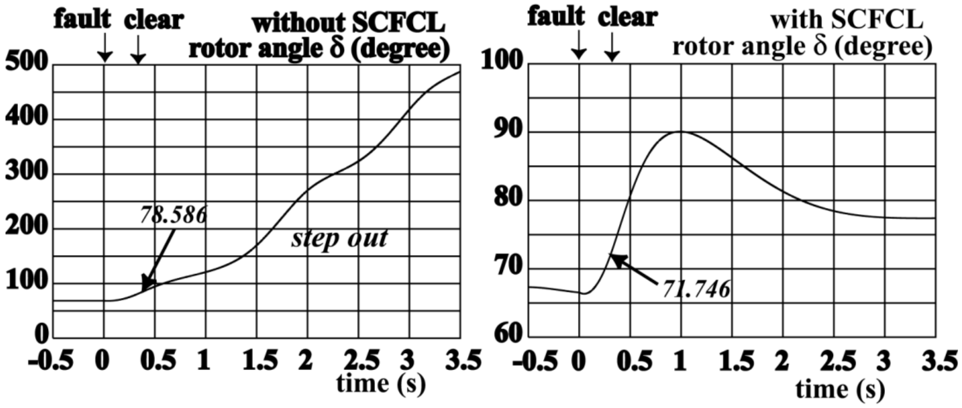

Fig. 10. Simulation result of rotor angle of the generator at the fault.

The generator rotor angle (base phase is the d-axis of the infinite bus voltage) is calculated by the simulation as shown in Fig. 10. Without SCFCL, the rotor angle at the fault line removal is 78.586 degrees, and after that, the generator goes to step out. Due to the SCFCL current limiting operation, the rotor angle at that time is 71.746 degrees and the generator goes to new stable operating point with the rotor angle of 77.5 degrees.

IV. CONCLUSION

A simulation model of a SCFCL of transformer type was proposed based on the experimental results using trial one. By use of the model, the simulation studies were performed on one-machine infinite bus system with parallel transmission lines including 3-phase SCFCL, which corresponds to the experimental system. The simulation results agree well with the experimental ones.

Power system operating characteristics of the SCFCL were investigated and discussed by simulation results. It is shown that the SCFCL's make critical clearing time longer and improve the system stability. The SCFCL can keep the generator terminal voltage and output power to a certain extent during the fault. Then it suppresses the acceleration of the generator rotor during the current limiting operation.

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