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EMTDC Modeling Method of Resistive type Superconducting Fault Current Limiter

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***Abstract*—An effective modeling and simulation scheme of a resistive type Superconducting Fault Current Limiter (SFCL) using PSCAD/EMTDC is proposed in this paper. In case of High Temperature Superconducting (HTS) resistive type fault current limiter, current limiting is implemented by the ultra-fast transition characteristics from the superconducting (non-resistive) state to the normal (resistive) state by overstepping the critical current density. The states can generally be divided into three sub-states: the superconducting state, the quench state and the recovery state, respectively.**

In order to provide alternative application schemes of a resistive type SFCL, an effective modeling and simulation method of the SFCL is necessary. For that purpose, in this study, an actual experiment based component model is developed and applied for the simulation of the real resistive type SFCL using PSCAD/EMTDC.

The proposed simulation scheme can be implemented to the grid system readily under various system conditions including sort of faults and the system capacity as well. The simulation results demonstrate the effectiveness of the proposed model and simulation scheme.

1. INTRODUCTION

Recently, increases in the installed capacity and the interconnection of the transmission networks lead to very high short-circuit currents. It is very important to protect the electric power system from high short-circuit current. The present techniques use circuit breakers, however, since their principle is to cut the current at its zero crossing, all the components above the fault have to withstand the destructive effects of the high short-circuit currents for a period of at least 3 ~ 5 cycles. An attractive device is a current limiter which clips the fault current and reduces the electromechanical stress on the network. In addition, the reduction of the fault duration provided by the limiter should increase the power transmission capability and improve the dynamic stability as well [1].

Conventional copper-based current limiters can cause voltage instability in the electrical system by adding reactance to the system. This forces the utility to add capacitance to the system to counter-balance the reactive element. One of well-known limiters is the ultra-fast fuse. Nevertheless, no conventional current limiter is suitable for high voltage, above tens of kV. Fortunately, utilities can reduce or eliminate the cost of upgrades to circuit breakers and fuses by installing Superconducting Fault Current Limiter (SFCL) [2].

The SFCLs, in contrast to current limiting reactors or high impedance transformers, are capable of limiting short circuit currents without adding considerable voltage-drop and energy-loss to power systems during normal operation. Under fault conditions, a resistance is automatically inserted into the power grid to limit the peak short-circuit current by transition from the superconducting state to the normal state, the quench. Further advantages, like fail safe operation and quick recovery, make SFCL very attractive, especially for rapidly expanding power systems with higher short-circuit capacities.

There are typical three types in a SFCL, a resistive type, an inductive type and a hybrid type. The most developed SFCL is the resistive type. Still at the prototype stage, some realizations have already shown satisfying operation at significant power levels. It is expected that the resistive type SFCL of the superconducting power devices will be commercialized quickly in the future [3]. The resistive type SFCL consists of a low inductance superconducting coil and a switch, which are inserted in series in the line. The switch isolates the fault and suppresses the heating of the coil after its quench. In case of resistive type SFCL, the characteristic of the resistances those are occurred from quench to recovery is very important for the real system applications. It is, however, very difficult to analyze the characteristics of the SFCL under various real world system conditions due to the limitation of the physical SFCL and real power systems.

For the purpose of providing an alternative scheme, an *effective modeling and simulation* method of a resistive type SFCL using PSCAD/EMTDC is proposed in this paper. An actual experiment based component model is developed and applied for the simulation of the real resistive type SFCL using PSCAD/EMTDC. The proposed simulation scheme can be implemented to the hypothetical grid system readily under various system conditions including sort of faults and the system capacity as well. The simulation results demonstrate the effectiveness of the proposed model and simulation technique.

2. BASIC PRINCIPLE OF SFCL

Fig.1 shows a simplified phase diagram of superconducting state. It is divided into three regions namely, the "superconducting region" ($\rho = 0$), the "flux-flow region" ($\rho = \rho(j)$), and the "normal conducting region" ($\rho =$ constant). The most straightforward concept of an SFCL is the resistive one, in which the superconductor is directly connected in series to the line. The cross-section of the superconductor is so determined that at I_n the superconductor is operated inside the superconducting state, where its interference with the electrical network is negligible. Even though, for ac applications the superconductor has a certain reactance and exhibits ac-losses. Both depend very strongly on the geometry of the superconductor, and can be minimized by optimal conductor-architecture.

For SFCL application the superconducting-materials have to meet three requirements : (1) low ac-losses in normal operation to minimize cooling costs, (2) high mechanical strength to withstand the thermo-mechanical and magnetic forces during the limitation process, and (3) good thermal stability to avoid excessive heating at "hot-spot", which may develop during the limitation process and can lead to a burn-through of the superconductor.

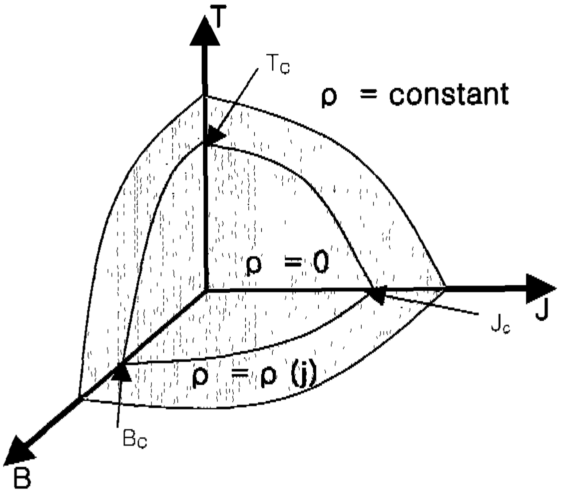

Fig. 1. Simplified phase diagram of superconducting state

The SFCL based on Low Temperature Superconductor (LTS) usually utilize "ac=wire", where LTS filaments are embedded in a normal conducting matrix. These materials are of good mechanical quality and exhibit low ac-losses. Because of their low specific heat, high thermal conductivity and high j_c, hot sports spread very fast, even at j values below j_c. Thus in case of a "quench", a rather homogeneous heating of the conductor is guaranteed. The LTS based SFCLs are usually of the "fast heating" type.

Due to the ceramic nature of the HTS, conductors with sufficiently low ac-losses for arbitrary directions of the magnetic field have not been demonstrated. Most HTS are fabricated in tapes or plates or tubes. Ac-losses are usually minimized by decreasing the conductor dimensions transverse to the local magnetic field. The rather brittle HTS needs to be mechanically stabilized, e.g. by supporting substrate, which might be metallic or insulating. HTS, in contrast to LTS, are very poor thermal conductors, and at 77K have rather high specific heat, thus, hot-spots spread very slowly or even contract if j drops below j_c. In such a case, the whole grid voltage would drop across a decreasing part of the conductor, which eventually will lead to a burn-through in the HTS.

A common measure to reduce the problem is the application of a normal conducting "electrical bypass". Thus allowing the current to bypass the hot-spot. Most HTS components for SFCL are composites, comprising the HTS, a mechanical substrate or supports, and an electrical bypass. The current limiting performance of the composites largely depends on the parameters critical current density, I-V characteristics, thermal conductivity, thermal mass, and bypass. Among HTS there are three major material systems under intensive research for SFCL application: i.e. Bi2223-wires, YBCO-films, and Bi2212-bulk.

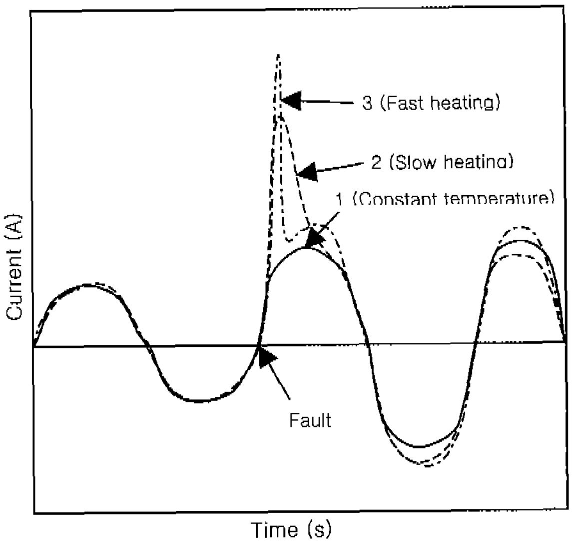

Fig. 2. Different limiting behaviors realized by mainly varying the conductor length

3. THEORETICAL MODEL OF SFCL

3.1. Parameterization of I-V characteristics

The E(j) characteristics can be practically described by subdividing it into three regions. In each of the three regions E(j) is approximated by a power law.

"Superconducting" region:

$$E^{(1)}(j,T)=E_c\left(\frac{j}{j_c(T)}\right)^{\alpha(T)} \tag{1}$$

with j_c the critical current density defined at $E_C = 1\mu V/cm$ (see Figure 1). $j_c(T)$ is fitted to experimental data. The exponent α (T) is given by:

$\alpha(T)=\max[\beta,\alpha'(T)]$,with

$$\alpha'(T)=\frac{\log(E_0/E_c)}{\log\left[\left(\frac{j_c(77K)}{j_c(T)}\right)^{(1-1/\beta)}\left(\frac{E_0}{E_c}\right)^{1/\alpha(77K)}\right]} \tag{2}$$

"Flux flow" region:

$$E^{(2)}(j,T)=E_0\left(\frac{E_c}{E_0}\right)^{\beta/\alpha(77K)}\frac{j_c(77K)}{j_c(T)}\left(\frac{j}{j_c(77K)}\right)^{\beta} \tag{3}$$

Normal conducting region:

$$E^{(3)}(j,T)=\rho(T_c)\cdot\frac{T}{T_c}j \tag{4}$$

where ρ is the normal resistivity and T_C is the critical temperature of the HTS.

3.2. HTS composite

The HTS composite is modeled as a parallel connection of the HTS-material and the normal conducting bypass. The composite was assumed to be homogeneous along its length. Therefore, heat dissipated in the superconductor (and normal conducting bypass) will be transferred to the liquid nitrogen bath (and/or the substrate) in the direction perpendicular to the current direction only. The heat diffusion can thus be described with the one dimensional differential equation:

$$c\frac{\partial T}{\partial t}=\frac{\partial}{\partial_X}\left(\kappa\frac{\partial T}{\partial_X}\right)+E\cdot j \tag{5}$$

3.3. Recovery time

Another important feature of the SFCL is the time after which the HTS can resume normal operation, i.e. the so-called "Recovery time". This time depends on the thermal mass of the composite, the resistance of the bypass and the limitation time. Of course, it also depends on the percentage of I_n with which the device will be loaded immediately following the fault. Usually the recovery time will be in the other of a few seconds.

However, the SFCL can be designed so that it can operate again immediately after the limitation action, i.e. zero recovery time. There are two approaches: First, the so-called constant temperature design, where the HTS during limitation stays essentially at constant temperature and thus in the superconducting state. As second approach, the so-called "operation recovery" can be realized, if the warmed HTS-component can recover to its superconducting state under nominal current, I_n (or partial I_n, if sufficient for operation). The former approach needs a very large thermal mass (e.g. realized via very long conductor). For the latter a very good bypass system and an optimized heat transfer away from the SFCL-component plays a crucial role.

3.4 Overload capability

Most classical power system devices allow for a certain overload capability at the expense of increases losses and maybe accelerated ageing.

In optimum designs, I_n of the SFCL will be just below the critical current (at nominal operation temperature) of the HTS. There are two ways to allow for an operation above this I_n. First, applying a good conducting bypass system will allow to run the device in normal operation 10-20 % above I_n. Secondly, by reducing the operating temperature, the critical current will increase and thus the rated current can be increased by the same factor. In both cases the overloading will be at the expenses of increased losses. In the latter case, a certain time is needed for the cooling system to reduce the temperature, however, a large overload; even a factor of 2 can be realized.

3.5 Transient behavior –inrush current

In case of transient overloads, the behavior of the SFCL depends very much on the time of the transient and again on the design, e.g. the bypass system. Generally it can be said, that the SFCL will not react to currents less than 2 times I_n, if this transient overload lasts less than a second. Currents above 3 time I_n will be limited. Whether the device will immediately go back to normal operation depends on the duration of the transient and on the design of the by pass system. If the duration is above 100 [ms], the SFCL will essentially behave as under a fault as described above. When designed for "operational recovery", the device will go back to normal operation without opening the circuit, as long as the transient does not exceed several seconds [4]-[7].

4. SIMULATION OF RESISTIVE TYPE SFCL

In this paper, three cases: single line to ground fault, three lines to ground fault and 3 phase short-circuit, are simulated and the results are given.

Table 1 shows the simulation parameters. For this simulation, a utility that the rated voltage is 6600[V] and the rated current is 200[A], are considered. The resistance curve of SFCLs is fitted to experimental *R*(*T*. *I*) curves of SFCLs using YBCO film.

In addition, we are developed Resistive type SFCL EMTDC component by using fitted equations. As given in Fig. 3, the EMTDC component of resistive type SFCL consists of one input and output. The input is current and the output is resistance.

TABLE I Simulation conditions

Duration of Simulation	1.0 [sec]
Duration of Fault	0.3 [sec]
Time of First Breaker operation	0.264 [sec]
Time of 2nd Breaker operation	0.664 [sec]
Line-to-Line Voltage	4.67 [kV]
V_{RMS}	3.81 [kV]
Line Current	0.2 [kA]
Fault Resistance	0.5 [Ω]
Critical Current	2 [kA]

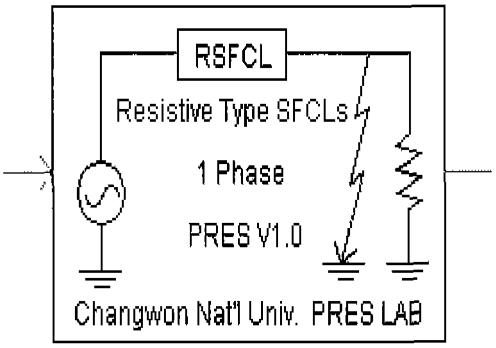

Fig. 3. EMTDC component of resistive type SFCL

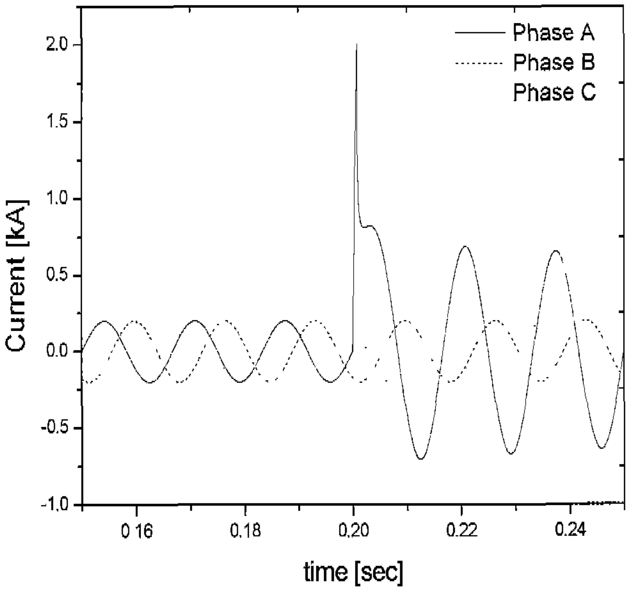

Fig. 4. Waveforms of single line ground fault with SFCL

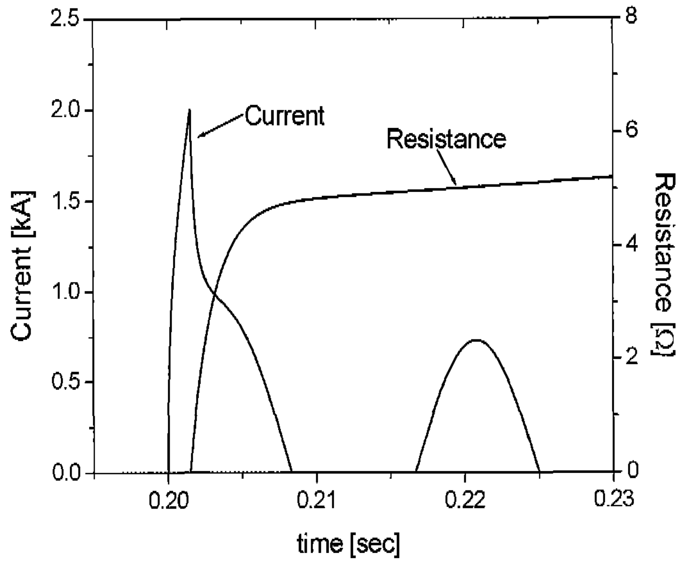

Fig. 5. Waveforms of current and resistance at the quench

Fig. 4 shows the waveforms of single line-to-ground fault with SFCL. The result shows that the current is limited at the 2 [kA] after fault has been occurred. Fig. 5 shows the waveforms of the current and resistance at the quench in detail. When the single line-to-ground fault occurs in utility, the rated current increases over critical current, and SFCLs resistance increases due to the normal conductor resistance (quench).

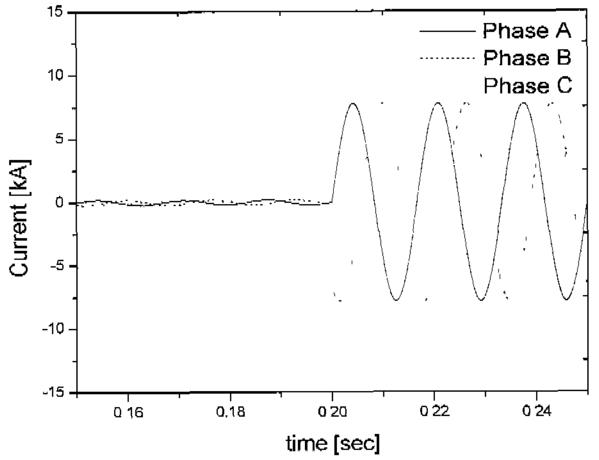

Fig. 6. Waveforms of the three line-to-ground fault current without SFCL

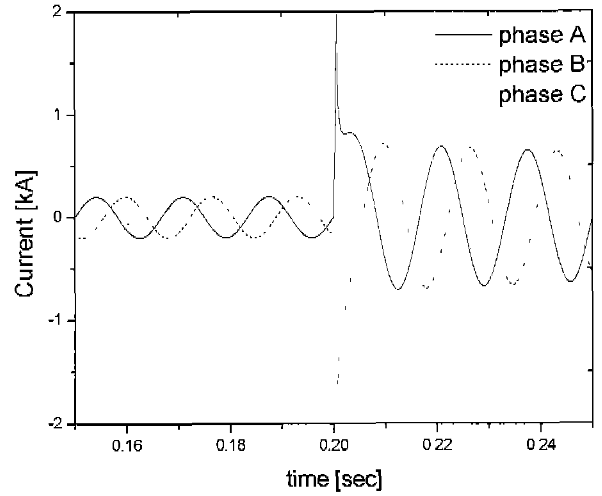

Fig. 7. Waveforms of three line-to-ground fault current with SFCL

Fig. 6 and Fig. 7 represent the current waveform of three line-to-ground fault in the 3-phase power system without and with resistive type SFCL, respectively. It is confirmed that the fault current is limited to under 1[kA] from 5[kA].

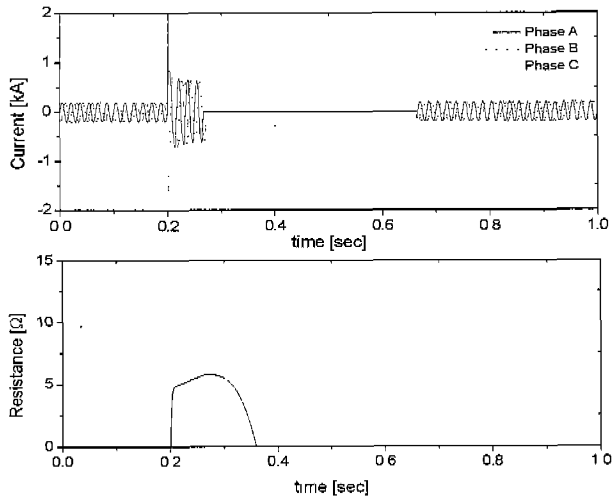

Fig. 8. Three line-to-ground fault current waveforms and the SFCL resistance variations due to circuit breaker operation. (Fault duration 0.2[sec], interruption at 0.264[sec] and reclosing at 0.664[sec]

Fig.8 shows the simulation result of the three line-to-ground fault with circuit breaker operation. Three line-to-ground fault occurred at 0.2 [sec], in this time, the current is exceeded critical current 2[kA], the HTSC starts to heat up. The fault current pushed the superconductor into the resistive state and resistance R appears in the SFCL. That resistance is sufficient to reduce the fault current below the critical current. The circuit-breaker operated at 0.264[sec] after 4 cycle.

Fig.9 shows the S/N transition of resistive type SFCLs with recovery in this simulation. The recovery behavior, which is determined by heat flux within the substrate and into the bath of LN2, is represented by the decay of the resistance. The resistance decrease within = 100 [ms] does not necessarily mean that the complete superconductor has cooled down to a temperature below its critical value, and that the nominal current can be newly carried after = 100 [ms], but it is at least an indication of the cooling process [8].

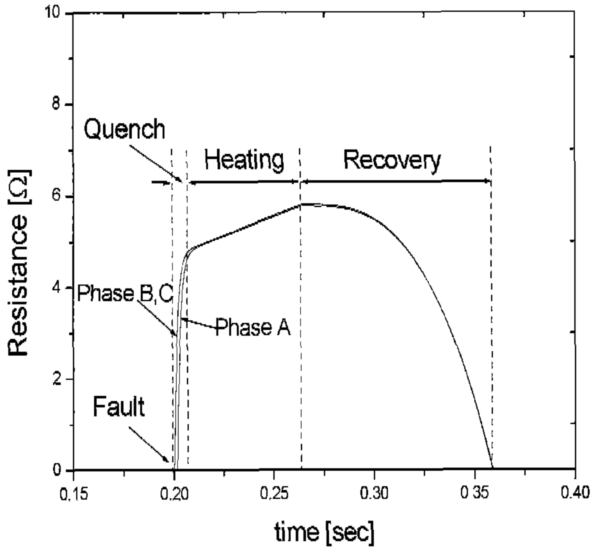

Fig. 9. The S/N transition of resistive type SFCL with recovery

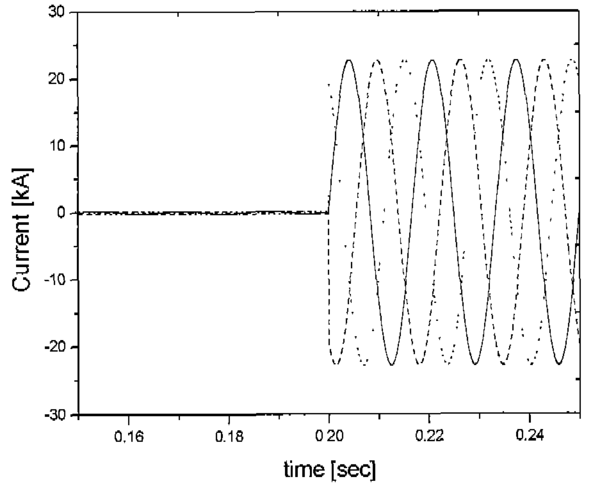

Fig. 10. Waveforms of three phase short-circuit current without SFCL

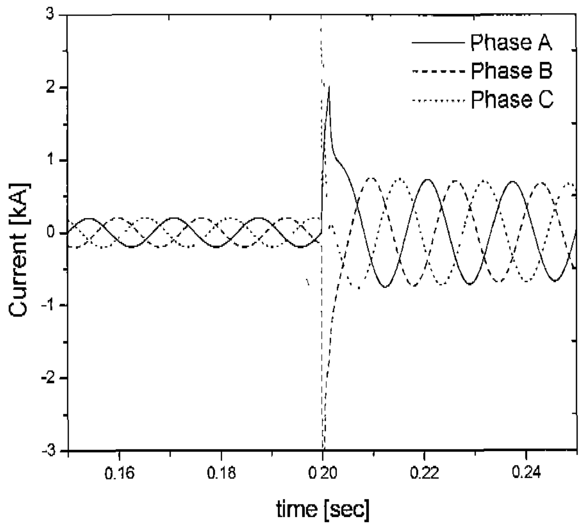

Fig. 11. Waveforms of three phase short-circuit current with SFCL

In the case of three phase short-circuit, the fault current waveform without SFCL shows in Fig.10. The fault current is increases nearly 25 [kA]. However, when the resistive type SFCLs are inserted series in the utility, the short circuit current below 2 [kA] in Fig.11.

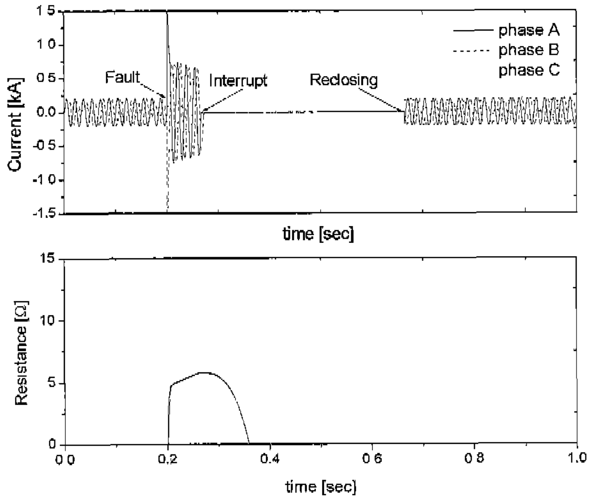

Fig.12. Three Phase short-circuit current waveforms and the SFCL resistance variations due to circuit breaker operation. (Fault duration 0.2[sec], interruption at 0.264[sec] and reclosing at 0.664[sec]

Fig.12. shows the waveforms of three phase short-circuit current waveforms due to the circuit-breaker operation. The three phase short-circuit current is limited below critical current, and circuit breaker operation at 0.246 [sec], reclosing time is 0.646 [sec].

5. CONCLUSION

An effective modeling and simulation scheme of a resistive type SFCL using PSCAD/EMTDC is proposed in this paper. An actual experiment based component model is developed and applied for the simulation of the real resistive type SFCL using PSCAD/EMTDC.

The proposed simulation scheme can be implemented to the grid system readily under various system conditions including sort of faults and the system capacity as well. The simulation results demonstrate the effectiveness of the proposed model and simulation scheme. In addition, the simulation method actually contributes to the time and cost saving for the application study of the SFCLs.

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