System Studies of the Superconducting Fault Current Limiter in Electrical Distribution Grids

Lin Ye, *Member, IEEE*, M. Majoros, T. Coombs, and A. M. Campbell

***Abstract*—A superconducting fault current limiter (SFCL) in series with a downstream circuit breaker could provide a viable solution to controlling fault current levels in electrical distribution networks. In order to integrate the SFCL into power grids, we need a way to conveniently predict the performance of the SFCL in a given scenario. In this paper, short circuit analysis based on the electromagnetic transient program was used to investigate the operational behavior of the SFCL installed in an electrical distribution grid. System studies show that the SFCL can not only limit the fault current to an acceptable value, but also mitigate the voltage sag. The transient recovery voltage (TRV) could be remarkably damped and improved by the presence of the SFCL after the circuit breaker is opened to clear the fault.**

***Index Terms*—Circuit breaker (CB), electrical distribution grid, electromagnetic transient program (EMTP), superconducting fault current limiter (SFCL), transient recovery voltage (TRV).**

I. Introduction

When electric power systems are expanded and become more interconnected, the fault current levels increase beyond the capabilities of the existing equipment, leaving circuit breakers and other substation components in over-duty conditions. The short circuit current containing extremely high energy will damage electrical equipment. All the equipment has to have a short circuit rating capable of withstanding this level. Typically, circuit breakers open automatically in three to six cycles when a fault occurs. However, circuit breakers, sometimes, cannot handle the intense level of faults, so they fail to break. Traditionally, handling these increasing fault currents often requires the costly replacement of substation equipment or the imposition of changes in the configuration by splitting power system that may lead to decreased operational flexibility and lower reliability. An alternative is to use Fault Current Limiters (FCLs) to reduce the fault current to a lower, acceptable level so that the existing switchgear can still be used to protect the power grid [1].

FCLs utilizing superconducting materials which are capable of providing instantaneous (sub cycle) current limitation abilities, can prevent the buildup of fault currents and have been studied for years [2]. In particular, a superconducting fault current limiter (SFCL) will be operating in a superconducting state and is basically invisible to the power grid because no major energy loss and voltage drop will be developed across the device during normal operation. In the event of a fault, the SFCL will produce a certain value of an impedance within a few milliseconds due to the loss of superconductivity, and insert it into the circuit, thus reducing the fault currents to levels that circuit breakers can handle.

Being a promising application of superconductors, the SFCL is considered to be one of the innovative devices of FACTS in electric power systems. The application of the SFCL would not only decrease the stresses on devices but also offer a higher interconnection to secure the network. This is a very effective means to enhance the system stability and power quality in terms of availability and voltage drop, which is a real need today [3], [4]. Several types of SFCL have been considered which are based on different superconducting materials and designs. From the point of view of power systems, the resistive SFCL is preferable because it increases the decay speed of the fault current by reducing the time constant of the decay component of the fault currents, and can also make the system less inductive [5].

Distribution systems have been designed and built as passive unidirectional systems to accept generation or bulk supplies from transmission grids or substations. The short circuit current is just limited by the impedance of various system components through which the fault currents will flow. These paths very much depend upon the interconnection of the system. Thus, integration of the SFCL could offer an effective solution to controlling fault current levels in distribution grids.

However, the SFCL has no interrupting ability, the circuit breaker is required in series to interrupt the fault current which is limited upstream by the SFCL. To achieve a successful interruption, the circuit breaker must withstand TRV without re-igniting the arc between the contacts. It is paramount to investigate the behavior of the breaking duty imposed on a circuit breaker connected with an SFCL. The aim of the paper is to examine the behavior of incorporating the resistive SFCL into the distribution grid and look at the potential beneficial effect of the SFCL in reducing the circuit breaker's transient recovery voltage (TRV).

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L. Ye was with the Department of Electrical Engineering, CAU, Beijing 100083, China. He is also with the Interdisciplinary Research Center (IRC) in Superconductivity, Cavendish Laboratory, Department of Engineering, University of Cambridge, Cambridge CB3 0HE, U.K. (e-mail: yl@cau.edu.cn; ly231@cam.ac.uk).

M. Majoros is with the Laboratories for Applied Superconductivity and Magnetism, Ohio State University, Columbus, OH 43210 USA.

T. Coombs and A. M. Campbell are with the Interdisciplinary Research Center (IRC) in Superconductivity, Cavendish Laboratory, Department of Engineering, University of Cambridge, Cambridge CB3 0HE, U.K..

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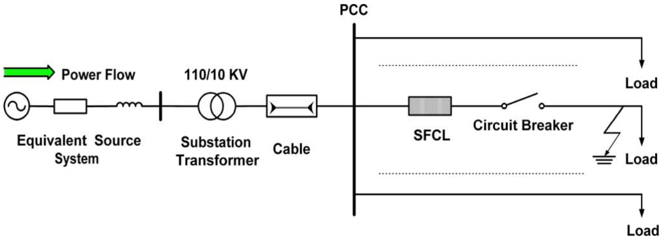

Fig. 1. Diagram of a typical electrical distribution system.

II. INTEGRATION OF A RESISTIVE SFCL IN AN ELECTRICAL DISTRIBUTION SYSTEM

The majority of distribution systems are operated in a radial configuration because of the simplicity of operation and the economy of the overcurrent protection. Both of the advantages are due to the fact that in any branch of a radial system, power only flows in one direction. The most prevalent distribution voltage class is 10-15 kV in power systems. The systems have continuous current ratings less than or equal to 600 amps and fault current ratings less than 20 kA [5]. For a distribution level SFCL, heat management is less of a problem than it is for transmission systems. Thus the SFCL is more practical to be first put in action in distribution systems [6].

It can be expected that there will be interactions between the SFCL and power system when the SFCL is placed in the power grid. In order to evaluate the integration behavior of the SFCL in power grids, we setup a unidirectional distribution system in the latest version of the electromagnetic transient program, which is considered to be a universal program system for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature. With this digital program, complex networks and control systems of arbitrary structure can be simulated.

A typical distribution system is represented in Fig. 1. The source impedance is seen from the secondary winding of the substation system's step-down transformer, and it includes the transformer impedance and the upstream short-circuit impedance. A number of parallel feeders are connected to the point of common coupling (PCC) which is the path from the source to the load. The bus is supplied by a substation transformer from an 110 kV network. We analyse a phase-to-ground fault because nearly 90% of the faults in distribution networks are single-phase short circuits.

III. DISTRIBUTION GRID MODELING AND SIMULATIONS

The Alternative Transient Program (ATP) version of Electromagnetic Transient Program (EMTP) and ATPDraw [7], one of the universal digital simulation programs for the analysis of power system transients, was chosen to carry out the investigation. The upstream source system is modeled as an infinite bus and the source impedance is composed of an equivalent resistance and inductance connected to the local distribution substation. The feeder was composed of cables, the SFCL and a circuit breaker connected between load and source. The cable can be modeled as a π-circuit with inductance and capacitance per unit length. To properly account for linear load damping, the overall load is modeled as an uncoupled, lumped series R, L, C branch with a power factor of 0.886. A fault simulation switch at the load side is closed to create a single phase-to-ground short-circuit. After three cycles, the circuit breaker opened to clear the fault to recover the normal operation state. The circuit breaker is modeled as an ideal time-controlled switch and a parallel capacitance. After a successful opening, the switch will stay open. We assume the current in the ideal switch is definitely cut and re-strike procedure is neglected.

The transient behavior of the superconducting device can be described by its $\mathrm{E} \sim \mathrm{J}$ characteristic and heating due to the resistive power dissipation in the flux flow and normal state. Under the hypothesis of a massive transition in adiabatic and isothermal condition, heat dissipated in the superconductor will not be transferred to the liquid nitrogen, so the refrigeration by the coolant can be neglected. The resistive type SFCL was programmed to be a nonlinear resistance evolving as a function of time. Making the SFCL model uses the MODELS language [8], which is a general-purpose description of language and algorithmic simulation tool in ATP to represent and study of dynamic systems [9]. Further, ATPDraw assists to create the SFCL electric circuit and edit the icon to be used as a component interactively. The circuit current flow is an input signal to the SFCL model, and the output of the SFCL model is controlled by a TACS (Transient Analysis of Control System) controlled time-dependent resistance. There is an improvement in this resistive SFCL model in the time domain because it considers the evolution of the various parameters such as nonlinear limiting resistance, temperature rise etc. with time [10].

The simulation was carried out with a fault created at $\mathrm{t} = 20$ ms ($\mathrm{t} = 0$ ms at the beginning of the simulation), and the circuit breaker was opened after 3 cycles at $\mathrm{t} = 80$ ms. (*Distribution level circuit breakers typically open in two cycles after receiving the order to open. This plus one cycle delay and sensing time makes the fastest expected distribution level opening time three cycles). The total simulation time was 0.12 s according to the circuit breaker opening time, and the simulation step is 1 μs. The operation current magnitude during normal condition is 350 A. The initial operation temperature is 77 K and critical temperature is 90 K. All calculations were carried out for simple conductors without any support materials. The HTS conductor is assumed to be homogeneous along its length. During normal operation, the SFCL is in superconducting state.

IV. PERFORMANCE OF THE SFCL BASED ON SYSTEM STUDIES

A. Limitation Behavior

In the event of a single-phase short circuit in the load feeder, a very large fault current will pass through the SFCL. After the critical current is exceeded, within the first half cycle, the critical temperature is reached and the transition to the normal conducting state quickly takes place. Fig. 2 and Fig. 3 below show the variation of resistance and temperature rise of the SFCL, as well as currents compared with and without the SFCL. In Figs. 2 and 3, the time scale is not beyond 80 ms for the sake of legibility, and also because the fault has been cleared at this point

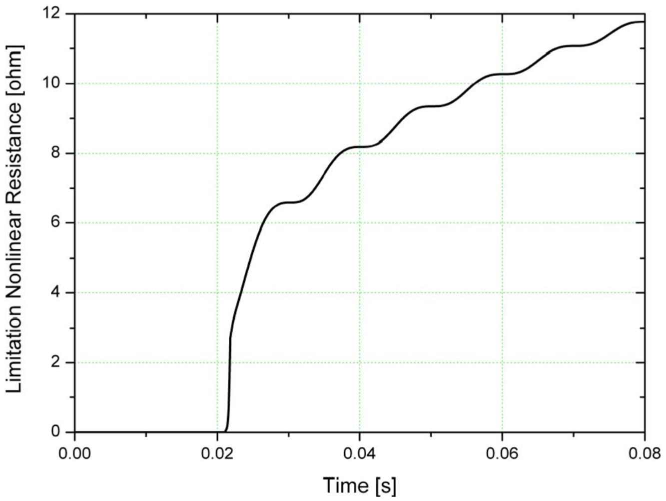

Fig. 2. Nonlinear limiting resistance of the SFCL.

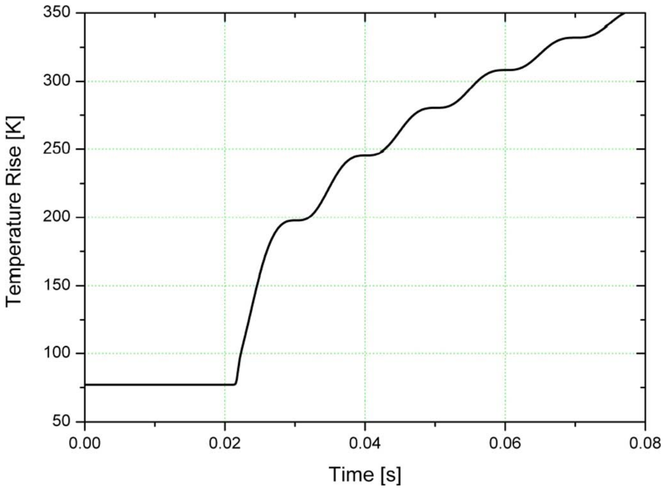

Fig. 3. Temperature rise of the SFCL.

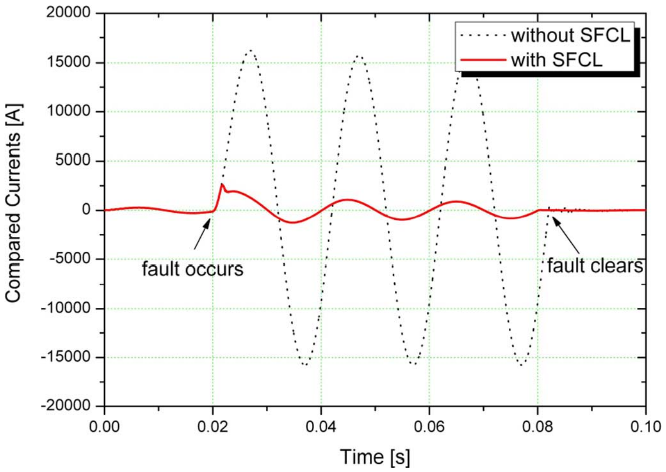

Fig. 4. Compared currents with and without the SFCL.

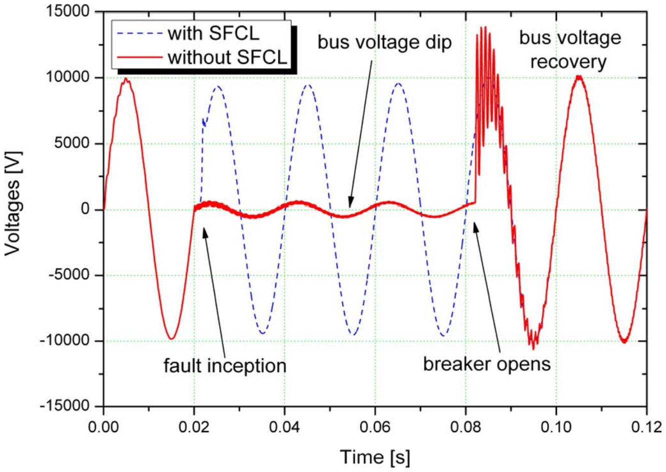

Fig. 5. Bus voltages with and without the SFCL.

and there will be no further increases in temperature and resistance of the SFCL.

Fig. 4 illustrates the short circuit currents with and without the SFCL. After the fault occurred, without the SFCL, the peak value of the fault current reached 18 kA ($\mathrm{I_{sc}}$) in the first half cycle. With the SFCL installed, the maximum short circuit current was limited to 2.6 kA ($\mathrm{I_{limited}}$) within the first half cycle, and in the second cycle, was further reduced to 1.2 kA which is nearly four times the peak value of the normal operating current. The current limiting factor ($\mathrm{I_{sc}/I_{limited}}$) which is the ratio of peak short-circuit current to peak value of the limited short-circuit current within the first half cycle is 7. After quenching, the limitation resistance of the SFCL went up to 10 ohms (Fig. 2) after two cycles of the fault, and the SFCL temperature increased to about 300 K (Fig. 3).

B. Mitigation of Voltage Sag

Fig. 5 shows the evolution of the phase-to-ground voltages on the busbar. Without the SFCL, the voltage of the busbar drops sharply to 10% of the normal voltage after the short circuit, so called voltage collapse. It took nearly one cycle for the voltage level to recover to its normal value with a transient overvoltage after the fault. With the SFCL, the bus voltage level can recover to more than 90% of the normal level when the SFCL's limiting resistance is in the circuit. The normal value can be resumed swiftly after fault clearance.

As can be seen, the SFCL can be regarded as a very useful apparatus preventing the distribution system from voltage decreases, i.e., it makes voltage sag less severe, and can help to recover voltage levels smoothly after the short circuit. Thus, the SFCL can improve both the voltage stability and the reliability of the supply network.

V. CIRCUIT BREAKER TRANSIENT RECOVERY VOLTAGE

A resistive SFCL is basically a variable nonlinear resistance that is installed in series with a circuit breaker in power grids. In the case of a fault, its resistance increases to a certain value at which the fault current is reduced to a level that the circuit breaker can handle. When the circuit breaker attempts to interrupt the limited fault current, an overvoltage is developed across the open contacts as a consequence of switching a circuit breaker or a section-switch etc. This voltage is called Transient Recovery Voltage (TRV) of the circuit breaker, which is imposed across the opening breaker contacts and stresses the gap

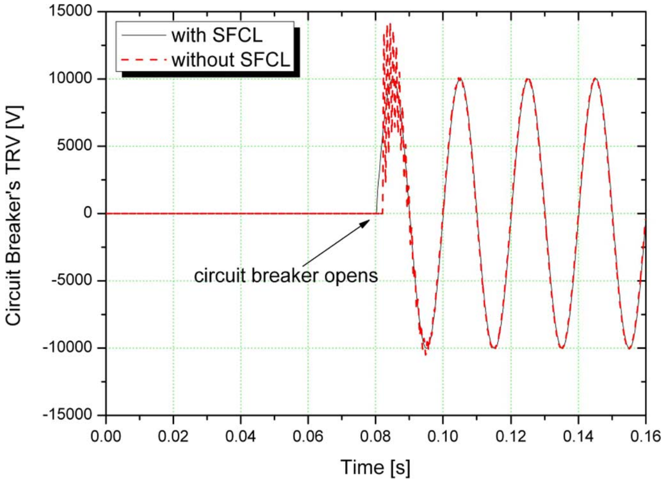

Fig. 6. The circuit breaker transient recovery voltage (TRV) with and without the SFCL.

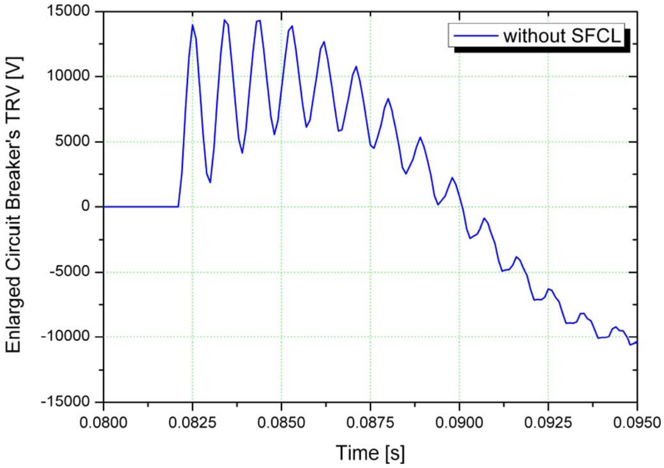

Fig. 7. Enlarged circuit breaker transient recovery voltage (TRV) without the SFCL.

insulation. Circuit breakers might fail to interrupt fault currents when power systems have transient recovery voltage levels, which exceed the rating of circuit breakers. During the process of interrupting the short circuit current, the system oscillates in accordance with its natural frequency and an arc is formed, bridging the gap between the parting contacts.

TRV is considered to be composed of an alternating component at industrial frequency and an oscillatory component with exponential decay. The Rate of Rise of the Transient Recovery Voltage (RRTRV) is an important parameter in the power system operation, specified in Volts per Microsecond $(\mathrm{V}/\mu\mathrm{s})$ in IEEE C37.41 Standard.

Fig. 6 shows the circuit breaker's TRV with and without the SFCL. Fig. 7 is an enlargement of Fig. 6, showing that the transient overvoltage arose after the breaker opened. We will get the value of the RRTVR about 36 $\mathrm{V}/\mu\mathrm{s}$ for the case without the SFCL. When the SFCL is put into action to limit the fault current, the circuit breaker's TRV is strongly damped and the RRTVR is only around 3 $\mathrm{V}/\mu\mathrm{s}$ without the transient phenomena associated with the breaker opening.

VI. CONCLUSIONS AND DISCUSSIONS

In practice the SFCL might be used in distribution systems first. However, the function of the SFCL is only to limit the fault current at a chosen value until the conventional circuit breaker could eliminate the fault. An SFCL in series with a downstream circuit breaker could provide a fast and reliable means of reducing and interrupting increasingly higher short-circuit currents. Transient recovery voltage and transient overvoltage are both remarkably damped and improved by the presence of the SFCL after the circuit breaker is opened to clear the fault. This will thereby extend the breaker's life span and increase the chances of quickly achieving successful fault current interruption. The SFCL can be regarded as a very useful apparatus, shielding the distribution system from voltage decreases.

The SFCL design probably requires that the limited fault current be between three and five times the steady-state current rating. Lower than three times, the SFCL is difficult to design if it is to differentiate a fault due to an overload current from a spike due to an inductance motor starting. Greater than five times and, excessive heating will occur.

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