FAULT CURRENT LIMITERS BASED ON HIGH TEMPERATURE SUPERCONDUCTORS

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Abstract: **The Fault-current limiters based on high temperature superconductors offer a solution for controlling fault-current levels on utility distribution and transmission networks. These fault current limiters, unlike reactors or high-impedance transformers, will limit fault currents without adding impedance to the circuit during normal operation. Development of superconducting fault-current limiters is pursued by several utilities.**

Keywords: **high-temperature superconductors, faults, feeder, current limitation, system protection, fault current limiter.**

1. Introduction

The Fault current limiter (FCL) is a power apparatus suppressing the fault current by generating the limiting impedance when the fault occurs into electric power system. For fault current limiter, it is important to choose the optimum limiting impedance properly according to the purpose of the introduction of FCL, the installed location of the fault current limiter in the power system [2], [3]. Electric power system designers often face fault-current problems when expanding existing buses. Larger transformers result in higher fault-duty levels, forcing the replacement of existing bus work and switchgear not rated for the new fault duty. Alternatively, the existing bus can be broken and served by two or more smaller transformers. Another alternative is use of a single, large, high-impedance transformer, resulting in degraded voltage regulation for all the customers on the bus. The classic trade off between fault control, bus capacity, and system stiffness has persisted for decades.

Superconductors offer a way to break through system design constraints by presenting the impedance to the electrical system that varies depending on operating conditions. The development of high temperature superconductors (HTS) enables the development of economical FCL. Superconducting fault current limiters were first studied over twenty years ago. The earliest designs used low temperature superconductors, materials that lose all resistance at temperatures a few degrees above absolute zero.

Operating characteristics of superconducting fault current limiter (SFCL) are shown in Figure 1, where: i_1 – expected fault current without limiter, i_2 – current limited by SFCL without limiter, i_n – nominal current, t_1 – fault, t_2 – the operation of conventional switch, t_3 – SFCL operation.

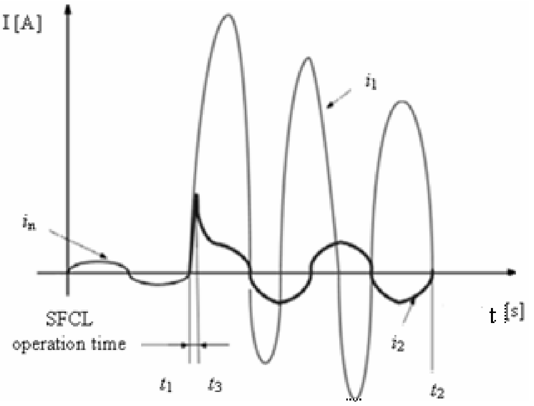

Fig. 1: Operating and currents characteristics of SFCL.

The superconductors' materials are generally cooled with liquid helium, a substance both expensive and difficult to handle.

2. Fault Current Limiter Applications

Fault-current limiters can be applied in a number of distribution or transmission areas. The most direct application of a fault-current limiter is in the main position on a bus (Fig. 2). Benefits of an fault current limiter in this application include the following: the larger transformer can be used to meet increased demand on a bus without breaker upgrades, the low impedance transformer can be used to maintain voltage regulation at the new power level, reduced fault-current flows in the high voltage circuit that feeds the transformer, which minimizes the voltage dip on the upstream high-voltage bus during a fault on the medium-voltage bus.

The fault current limiter can be used to protect individual loads on the bus (Fig. 3). The selective application of small and less expensive limiters can

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be used to protect old or overstressed equipment that is difficult to replace, such as underground cables or transformers in vaults.

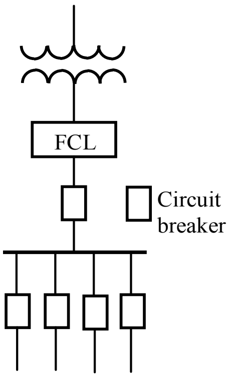

Fig. 2: Fault-current limiter in the main position. The fault-current limiter FCL protects the entire bus.

Such a limiter would require only a small load current rating but would deliver the following benefits: separate buses can be tied together without a large increase in the fault duty on either bus, during a fault, a large voltage drop across the limiter maintains voltage level on the unfaulted bus, the paralleled transformers result in low system impedance and good voltage regulation; tap-changing transformers can be avoided, excess capacity of each bus is available to both buses, thus making better use of the transformer rating.

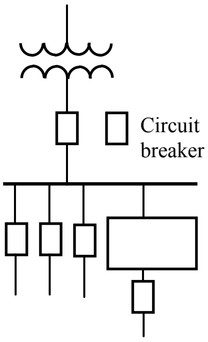

Fig. 3: Fault-current limiter in the feeder position. The fault-current limiter FCL protects an individual circuit on the bus. Underrated equipment can be selectively protected as needed in this manner.

The FCL find numerous applications as it offers these benefits: avoid equipment damage; avoid equipment replacement, higher breaker rating; use lower fault rated equipment, avoid series reactors; avoid split buses, opening bus-tie breakers; higher system reliability when bus tie breakers are closed; use lower impedance transformers; reduce voltage dip on adjacent feeders; enhance grid stability.

3. Fault-Current Limiter concepts

3.1. The Series Resistive Limiter

The simplest superconducting limiter concept, the series resistive limiter, exploits the nonlinear resistance of superconductors in a direct way. The superconductor is inserted in the circuit. For a full-load current of I_{FL}, the superconductor would be designed to have a critical current of $2I_{FL}$ or $3I_{FL}$. During a fault, the fault current pushes the superconductor into a resistive state and resistance R appears in the circuit.

The superconductor in its resistive state can also be used as a trigger coil, pushing the bulk of the fault current through a resistor or inductor. The advantage of this configuration, shown in Fig. 4, is that it limits the energy that must be absorbed by the superconductor.

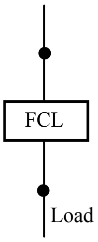

Fig. 4: Fault-current limiter with HTS trigger coil.

The fault-current limiter (FCL) normally is a short across the copper inductive or resistive element *Z*. During a fault, the resistance developed in the limiter shunts the current through *Z*, which absorbs most of the fault energy.

The trigger coil approach is appropriate for transmission line applications, where tens of megawatt-seconds would be absorbed in a series resistive limiter. The trigger coil configuration also allows an impedance of any phase angle, from purely resistive to almost purely inductive, to be inserted in the line.

A resistive FCL limits the fault current by its increased resistance when the HTS wire transitions to its normal state during a fault. The key parameters impacting the resistive FCL design are fault current (I_{lim}), fault duration (Δt) and permissible temperature rise (ΔT) of the HTS elements. These variables are related in through the following equations:

$$R = \frac{V_0}{I_{\lim}} = \frac{\rho \cdot L}{t \cdot w}; \quad I_{\lim} = t \cdot w\sqrt{\frac{C_p \cdot \Delta T}{\rho \cdot \Delta t}} \qquad (1)$$

where: R is FCL resistance during fault, V_0 is system rms voltage, L - length of HTS current limiting elements, ΔT - maximum permissible temperature rise, Δt - maximum fault duration (hold time) ρ, t, w - resistivity, thickness and width of HTS, C_p - effective specific heat of HTS and stabilizer.

Solving these equations, one can derive the minimum conductor volume given below for a series FCL. The required conductor volume (*Vol)* is independent of conductor resistivity.

$$Vol = \frac{I_{\lim} \cdot V_0 \, dt}{C_p \cdot \Delta T}. \qquad (2)$$

The series limiter employs a coil in series with the load and limits current by its increased resistance during the current limiting phase. This design is best for a single fault current limiting action, with resetting after the several minutes required cooling it down to its pre-fault temperature.

This FCL requires wire current density, high resistively stabilizer and higher heat removal capability and the cold temperature. It is most suitable for a single fault limiting event with recovery after multiple minutes of cool-down.

3.2. The Inductive Limiter

This concept uses a resistive limiter on a transformer secondary, with the primary in series in the circuit. This concept, illustrated in Fig. 5, yields a limiter suitable for high-current circuits (I_L>1000 A). One phase of the limiter is shown. A copper winding (W_{Cu}) is inserted in the circuit and is coupled to an HTS winding W_{HTS}. During normal operation, the zero impedance is reflected to the primary.

Resistance developed in the HTS winding during a fault is reflected to the primary and limits the fault. The inductive limiter can be modeled as a transformer.

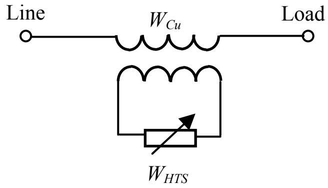

Fig. 5: Inductive fault current limiter.

The impedance of this limiter in the steady state is nearly zero, since the zero impedance of the secondary (HTS) winding is reflected to the primary. In the event of a fault, the large current in the circuit induces a large current in the secondary and the winding loses superconductivity. The resistance in the secondary is reflected into the circuit and limits the fault.

3.3. The Shunt Resistive Limiter

The shunt limiter concept uses a warm resistor (or inductor) in parallel with the HTS coil and this can be bulky. During normal operation, the resistance of the HTS coil is essentially zero and steady-state current flows through it. However, during a fault, if the resistance of the HTS coil increases to a high enough value, most of the current is diverted through the warm resistor. This limiter could be designed to withstand several fault limiting events within a safe upper limit of the HTS coil temperature. Once the fault is cleared, steady-state current can continue to flow without excessive heating in the HTS coil because it remains in the superconducting temperature range. Preliminary analysis shows that the shunt limiter HTS coil requires about 10 % more HTS wire than the series limiter.

The shunt limiter employs an inductor in parallel with the HTS coils. Once the HTS coil transitions to its normal state, fault current is limited by the impedance of the external inductor. An advantage of the shunt limiter is that with proper design, it could withstand multiple closely timed current limiting events.

3.4. The Series-Parallel Resistive Limiter

As shown in Figure 6, the fault-current limiter is formed by connecting four superconducting coils in a series-parallel configuration so the total inductance is minimized.

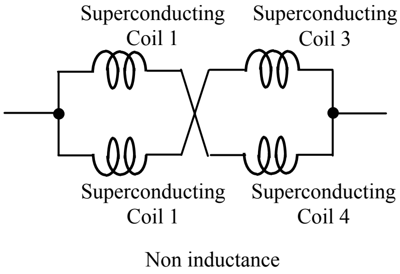

Fig. 6: Configuration of superconducting coils.

One set of coils is used for each phase of the device, and limiting is accomplished by quenching the coils.

4. Modelling

4.1. Generalities

The model uses data from superconducting YBCO samples thick films on YSZ substrate. The data takes the form of E (electric field) - J (current densities) as well R (Resistivity) – T (Temperature) characteristics to room temperature and beyond.

The current waveform and other system parameters such as superconductor temperature and magnetic field are calculated by an iterative process. Due to the nature of FCL devices, thermal conduction into the substrate is considered and a prediction of the material temperature throughout the limiting period is made. The superconductor is considered as a single homogenous element at present; future revisions will include some degree of in homogeneity into the model in order to ascertain the significance of manufacturing imperfections. Additionally, depending on configuration, the magnetic field applied to the material may change. Both factors influence the voltage drop across the FCL and hence the current through it. Thus one limiting cycle involves an excursion over the *E*-*J*-*B*-*T* plane. To attempt to predict the current-time waveform analytically would be difficult if not impossible. The superconductor is modeled in Matlab - Simulink within the overall model as a single block with three inputs: *J*, *B* and *T* (corresponding to the current density, magnetic field and temperature) and two outputs corresponding to the specific heat capacity (modeled as a function of temperature) and electric field strength E appearing across the sample. The line and load impedances are modelled as lumped parameter models using Laplace transform to represent the transfer functions relating to the imaginary and real parts of their impedances [1].

For example, a line with 0,1 ohms resistance and 1 mH inductance will have an impedance of 0,1+0,001 $j\omega$, where j is the complex operator. The laplacian operator $s=\sigma+j\omega$ allow us to model the line transfer function as:

$$\frac{1}{sL+R}. \tag{3}$$

4.2. Heat flow

Heat flow through the FCL is modelled in two ways: Heat flow from top surface of film and Heat flow into substrate.

The first term is modelled by a simple function relating to the temperature difference between the film and the liquid nitrogen cryogen. The equations vary according to the nucleate or film boiling regime, which can be predicted from the temperature difference between the material surface and the cryogen [3].

The flow into the substrate is modelled as a 20 element diffusion model. This is achieved in Simulink by the use of a state space representation in order to fit in with the laplacian derivative block format expected in Simulink [4].

The addition of an external magnetic field is used in practice to overcome material non-homogeneity by helping the whole material past the superconducting to normal transition (non-homogeneity is a major problem in some designs of limiter). The signal can be derived from other points in the model for a proportional connection (*B* proportional to *I* for series connected coil, or *B* proportional to *E* across the superconductor for a coil connected in parallel with the FCL element.). A switch element can be introduced in the case of a triggered coil type design (where external field is turned on suddenly as soon as a fault is sensed).

Coil inductance is, as in the case of line inductance, modelled by the complex term of a Laplace transform.

4.3. Results of the model

The fault simulation begins with the current I_n flowing for at least one whole cycle. This is 20ms for a 50Hz supply frequency. The fault is then initiated by instantly lowering the load impedance to that expected for a short line fault (SLF). In this case the SLF condition corresponds to If = 200 A peak. Figure 7 shows the current – time waveforms for the first 50 ms of the simulation. The cross sectional area has been kept constant and the limiter lengths are between 3,2 cm (short limiter) and 400 m (long limiter).

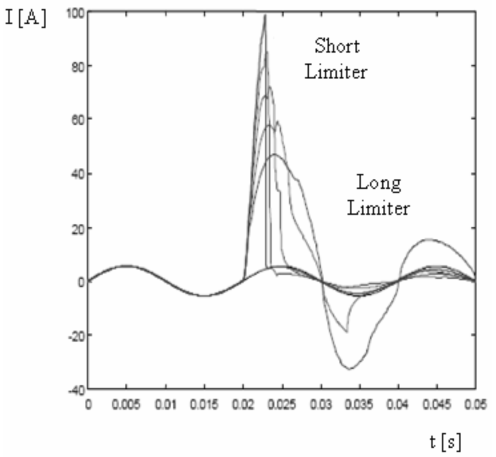

Fig. 7: Current and time for different limiter lengths.

From Figure 8 shows the resultant temperature rise for the same range of limiter sizes.

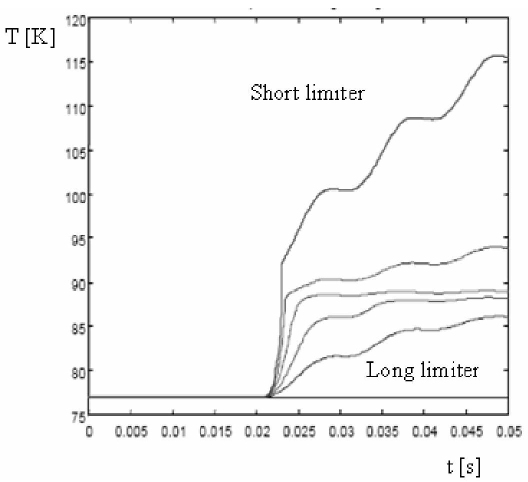

Fig. 8: Predicted temperature rise over fault period.

5. Conclusions

Superconductors offer a way to break through system design constraints by presenting the impedance to the electrical system that varies depending on operating conditions [3].

Resistive fault current limiter limits the fault current by its increased resistance when the high temperature superconductors wire transitions to its normal state during a fault.

The series limiter employs a coil in series with the load and limits current by its increased resistance during the current limiting phase. This FCL requires wire current density, high resistively stabilizer and higher heat removal capability and the cold temperature. This FCL is best for a single fault current limiting action, with resetting after the several minutes.

The shunt limiter employs an inductor in parallel with the high temperature superconducting coils. Once the high temperature superconducting coil transitions to its normal state, fault current is limited by the impedance of the external inductor. The shunt limiter could withstand multiple closely timed current limiting events.

The computer model provides useful information about the predicted current-time waveforms for homogenous film type limiters. The problems associated with material in homogeneity will be addressed in the very near future.

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