MODEL OF CALCULATING THE RESPONSE OF A SUPERCONDUCTING FAULT CURRENT LIMITER IN THE ELECTRICAL GRID

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ABSTRACT

A model for calculating the response of the current limiter based on high-temperature superconductors (HTS) is presented. The model is based on the use of an approximate curve of a superconducting assembly of a current limiter resistance to energy in the form of heat generated in it at the moment of short circuit (SC) in the calculation of current flowing through the device. This dependence is a universal characteristic of superconducting fault current limiters (SFCL) and can be approximated by a power function. The step-by-step, in time, calculation of the heat released allows to determine the current flowing at a given mains voltage and, thus, describe the SFCL response parameters.


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1. INTRODUCTION

Currently, there is an accelerated increase in the electrical load on the electric power industry facilities commensurate with the growth of megacities and enlargement of power grids. In the process of designing and operating such grids, the question of their protection from the growing values of short-circuit current rises. They actually become the limiting factor for the development of electrical systems [1-3]. The higher is the fault current, the higher will be the cost of all equipment since the necessity to build new electrical power systems takes account of short-circuit currents in the network sizing calculation.

The field of superconductivity began with the discovery by H. Kamerlingh-Onnes in 1911 that mercury wire at 4.2 K had zero electrical resistance. Zero resistance implied transmission of current at any distance with no losses, the production of large magnetic fields, or because a superconducting loop could carry current indefinitely storage of energy. These applications were not realized because, as was quickly discovered, the superconductors reverted to normal
conductors at a relatively low current density, called the critical current density, $J_c$, or in a relatively low magnetic field, called the critical field, $H_c$ [4].

At the moment, current-limiting reactors, transformers with split windings, as well as sectioning and automatic grid division systems in emergency situations are used to combat SCA. A current-limiting reactor is physically large and may not be able to fit physically in retrofit applications or locations with little real estate. The reactor adds continuous conductor resistive losses during normal operation, imposes a regulating voltage drop and blocks VARs transfer out of generators [5]. For smaller devices that operate in fields with amplitudes that are comparable to the self-field of the conductors, it is necessary to estimate the critical current of the device by considering the local self-field effects of the superconducting material [6].

Against this background of the mentioned, freestanding and promising current limiting device is a system based on high-temperature superconductors [7, 8]. The response of such devices is based on the properties of the HTS material to conduct a significant current without resistance, and when the critical current $J_c$ is reached, to transit to the resistive state. Such a principle of operation is implemented directly by resistive SFCL, which are installed in series in normal operation mode of the grid, do not add any load on the grid, and response in case of SC occurs within a few microseconds [9]. The SFCLs of resistive type are simply a length of superconductor. The current density of superconductor would exceed the critical current density $J_c$ when there is a fault [1–3; 10]. The absence of induction losses is ensured by the use of a bifilar winding of a superconductor in a SFCL.

The basic element of the fault current limiting device is a transformer connected in series and having a non-linear resistance in the secondary winding circuit. Note that as this non-linear resistance can be used any low-impedance fast-acting switching device, e.g. superconducting commutation elements, cryotrons, fuse-links, explosive IS-limiters etc. The fault current limitation is realized by breaking the transformer secondary winding circuit [10].

Over the past 15 years, a range of current-limiting devices have been developed in the world [11–14]. Further implementation of such systems is limited by both technological problems of using superconductors and complexity of calculating the response process of SFCL in various power grids [15–17]. In this paper, we propose a computational model for evaluating the response of SFCL based on the dependence of the resistance of a device on the thermal energy released in it.

2. MATERIALS & EXPERIMENTAL PROCEDURES

2.1. Model description

The process of resistive SFCL response is primarily determined by the magnitude of the critical current of the used superconductor, the architecture of the superconducting wire and its length [18]. The critical current of a superconductor is defined as the current at which the transition of the superconductor to the normal state begins. Accordingly, this value determines which part of the current front will trigger the current limiter.

The traditional means for limiting faults for higher continuous current systems has fallen into a number of approaches:
1. Addition of a current limiting reactor to reduce fault currents within system capabilities,
2. Open a system tie to eliminate some of the sources of fault current,
3. Upgrade the switchgear and other over duties equipment to higher ratings, beyond the fault spectrum [19].
The architecture and the length of the conductor in the device determines the behavior of the device after response, since the current flows not through the superconductor, but through the metal stabilizing coatings [20–22]. The electrical conductivity and heat capacity of the coatings, as well as the length of the conductor, determine the resistance of the SFCL in the resistive state [23]. Calculation of these characteristics is quite a difficult task, but from the experiment it is possible to isolate cumulative characteristics that reflect the characteristics described above as a whole. This characteristic is the dependence of the specific (along the length) resistance of the device \( r \) on the thermal energy \( q \) released in it (Figure 1).

\[
\frac{r_{FCL}}{q} = b \times q^n,
\]

(1)

where \( r_{FCL} \) is resistance (Ohm / m) arising as the result of the transition of HTS to the non-superconducting state; \( q \) is energy (kJ / m), released on the SFCL, \( b \) and \( n \) are constants, in this case equal to 0.01 and 0.48, respectively. The power dependence does not accurately describe the experimental data in the low-energy region, which will be described below.

By scaling the curve depending on the length of the conductor, you can get the desired dependencies for different designs of SFCL. Besides, the parallel connection of several conductors with a known \( r(q) \) curve in the SFCL can also be taken into account.

The required curve is obtained in the SFCL response experiment. Using a digital oscilloscope with the appropriate sensors, an alternating voltage \( U \) applied to the device and the current \( I \) passing through it are recorded. The resistance \( r \) of the measured device is determined by the direct ratio of the voltage signal to the current due to the absence of inductance in the device design. Knowing the amount of energy stored in the CLD HTS in the form of heat and using the dependence:

\[
P = U \times I,
\]

(2)

where \( P \) is the power released in the SFCL, it is possible to calculate \( r(q) \) at any time.

3. RESULTS & DISCUSSION

Using the obtained dependence, it is possible to make a step-by-step calculation of the SFCL behavior using the algorithm presented in Figure 2.
Model of Calculating The Response of A Superconducting Fault Current Limiter In The Electrical Grid

![Diagram](http://www.iaeme.com/IJMET/index.asp 725 editor@iaeme.com)

**Figure 2.** The scheme of the algorithm for calculating the SFCL response.

The essence of the calculation is that a sinusoidal voltage is applied with an amplitude $U_{\text{peak}}$ to a device with a known $R(Q)$ dependence. At each time step, the value of the released power:

$$P = \frac{U^2}{R_{\text{FCL}}} \cdot \Delta t,$$

is calculated from the previous resistance value. The specifics of the superconducting fault current limiter response are taken into account as follows:

1. when $I < I_c$, the resistance of the SFCL is equal to zero, and it does not affect the magnitude of the SC current (calculation uses the estimate of the resistance of the SFCL connection contacts, estimated at $R_0 = 0.23 \, \Omega$);

2. when $I > I_c$, the resistance of the SFCL begins to grow according to the power law:

$$R_{\text{FCL}} = b \cdot Q^n,$$

and it should already be taken into account when calculating the value of SC current.

Before reaching $I = I_c Q = 0$, but at the time of reaching $I > I_c$ (first $\Delta t$), HTS transfers into a non-superconducting state and the initial $\Delta Q$ is selected, which must be set independently, and the variation of the initial $\Delta Q$ does not affect the result. Having obtained the power, the energy released in the current time interval $\Delta Q$ is calculated, which is then added to the energy obtained earlier by $Q$. In this approach, an adiabatic approximation is used, which is valid for SFCL, the cooling element of which is the volume of liquid nitrogen. With the response of the device, the conductor heats very quickly, and liquid nitrogen is replaced by a gas nitrogen film [24, 25]. In such a case, a gas film is formed around the conductor, which prevents the coolant from effectively removing heat, which forms quite adiabatic conditions for the SFCL response.

Using the value of the total energy, using the curve $R(Q)$, the resistance of the superconducting assembly is calculated, and, further, the current $I(t)$ that is flowing at SFCL. The obtained current limiting curve for the considered $R(Q)$ dependence is shown in Figure 3, along with the experimentally obtained dependence.
There is a good agreement of the calculated values with the experimental values. The accuracy of the coincidence of the curves was 17%. A significant contribution to the error was made by the difference in the first half period. As mentioned above, in this area the description of the power function of the curve $R(Q)$ also occurs with a significant error. It is worth noting that attempts to use more complex functions to describe $R(Q)$, which dramatically reduces this error, led to a decrease in the simulated current peak in the first half period. This is due to the peculiarities of the transition of the superconductor to the normal state, which is neglected in this approach in favor of the simplicity of the model.

5. CONCLUSION

This work presents a model for calculating the behavior of a superconducting fault current limiter in the event of a short circuit current in the power grid. The model uses the universal dependence $r(q)$ describing the heating of the superconductor after the device transition to the normal state to calculate the limited short circuit current. The considered model has sufficient accuracy and ease of calculation. The ability to scale the dependence $r(q)$, measured for a single conductor, for other SFCL structures (conductor lengths in it) makes this model an indispensable tool for grid engineers to calculate the use of superconducting fault current limiters.

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