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Simulation of electrical, magnetic and thermal properties of inductive fault current limiters made of YBCO ceramic superconductors

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Abstract

The fault current limiter (FCL) is a device capable of limiting currents in electrical networks during fault conditions. In this device, the acting element is a high temperature superconductor (HTS) ring made of ceramic material. The inductive FCL consists of a primary normal metal coil coupled via a ferromagnetic core to a secondary short-circuited superconducting coil assembled in the form of a set of HTS rings or cylinders. In the normal conditions of the protected circuit, the superconducting rings are in the superconducting state. Under fault conditions, the secondary superconducting coil becomes resistive. As a result, in normal operation, the impedance of the FCL is much less, while in the current limiting mode, the impedance is higher than the impedance of the network. A 12 kVA inductive closed core type HTS FCL with melt textured YBCO ring was developed and tested. The current limiting properties of the FCL were investigated experimentally and the results were compared with those of computer modeling. The quench behavior of the YBCO HTS ring has strong influence on the current limiting properties of the FCL. For the description of transient and quasi-stationary processes of the FCL, the authors have developed a model and a numerical simulation, which consist of coupled electromagnetic and thermal processes, can handle the influence of the hot-spots generated in the HTS, and the non-linear characteristics of the magnetic core. The model provides the various operational modes of the FCL due to material properties observed in the experiments, and enables the determination of main dimensions of the device including those of the magnetic circuit. Due to the very good agreement between the experimental and calculated results, the model can directly be used for the engineering design of inductive type HTS fault current limiters.

Keywords: Electrical properties; Magnetic properties; Thermal properties; Oxide superconductors; Fault current limiters

1. Introduction

The fault current limiter (FCL) is a device capable of limiting currents in electrical networks during fault conditions. In this device, the acting element is a high temperature superconductor (HTS) ring made of ceramic material. The inductive FCL consists of a primary normal metal coil coupled via a ferromagnetic core to a secondary short-circuited superconducting coil assembled in the form of a set of HTS rings or cylinders.

A 12 kVA inductive closed core type HTS FCL with melt textured YBCO ceramic ring was developed and tested in our previous paper.[1]

This report focused on the investigation of the current limiting properties of the FCL tests and the results were compared with those of computer modeling. Our model described the transient and quasi-stationary processes by the model and a numerical simulation of the coupled electromagnetic and thermal effects.

2. Basic theory of the FCL model

A proper description of the non-linear voltage–current (*V*–*I*) relation of the HTS material is necessary for an accurate analysis of the superconducting fault current limiters.

For designing the inductive type FCL with HTS YBCO ceramic ring(s), it is important to know their non-linear voltage–current characteristics because it is determinant for the operation of the fault current limiters.

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For the description of the superconducting-normal transition, two models are proposed and used usually:[2,3]

1. Ideal switch model (ISM);
2. Extended switch model (ESM).

In the present paper, we show a unified non-linear specific resistivity ($\rho(I,T)$) function modeling of HTS. This model takes into account the temperature- and current-dependency of the resistance in a wide range below and above the critical current. The voltage–current characteristic of the FCL can be determined from the $\rho(i,\ T)$ resistivity function of the HTS material.

The temperature-dependent critical current $i_c(T)$ is given as follows:[4]

$$i_c(T) = i_{c0}\left(1-\left(\frac{T}{T_c}\right)^2\right)\left(1-\left(\frac{T}{T_c}\right)^4\right)^{1/2} \tag{1}$$

where i_{c0} is the critical current at 0 K, T and T_c are the actual and the critical temperatures of the HTS material.

Fig. 1. shows the critical current–temperature characteristic between 0 and 110 K. In our case, the critical current is zero above the critical temperature ($T_c = 93$ K) and $i_{c0} = 1000$ A at the LN$_2$ temperature.

In our inductive type HTS FCL model, a non-linear function is selected to achieve the resistance of superconductor material. This function is based on the fast transition from the superconducting state to the resistive or normal state by exceeding the temperature-dependent critical current.

Previous measurements and tests[1] have already shown the hysteretic behavior of the HTS FCL caused by the characteristic of YBCO HTS ceramic material.

Consequently, this descriptive function of the resistance to be constructed should account for:

- the dependence on the critical current;
- the dependence on critical temperature;
- fast transition;
- the hysteretic behavior.

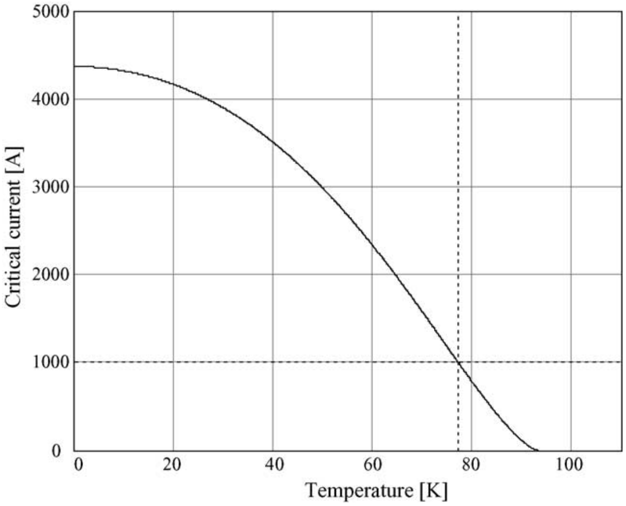


Fig. 1. The critical current–temperature characteristic.

Considering the above requirements, we have constructed the $\rho(i,\ T)$ function.

So, the basic function for the HTS resistivity is defined by:

$$s(x) = \frac{pe^x - e^{-x}}{e^x + e^{-x}} \tag{2}$$

where the $s(x)$ function is the modification of hyperbolic tangent. The p parameter controlled the jumping of the $s(x)$ hyperbolic function.

The expression of $s(x)$ gives a jump function with the variable I_c, where p and x are adjustable fitting parameters. By changing these parameters, we can adjust the superconductor resistivity characteristics in a wide range, which enables the incorporation of hysteretic properties.

Fig. 2 shows the temperature- and current-dependent resistivity of the YBCO ceramic HTS ring as follows:

$$\rho(i,\ T) = \rho(T)\left[\frac{s\left((|i| - i_c(T))/c\right) + 1}{p}\right] \tag{3}$$

where $\rho(T)$ is the temperature-dependent resistivity, $s\left(\frac{|i|-i_c(T)}{c}\right)$ is the $s(x)$ form, where the x is $\frac{|i|-i_c(T)}{c}$ and p is the above mentioned parameter, i is the current in the superconductor ring, $i_c(T)$ is the temperature-dependent critical current and c the gradient factor in the term $\frac{|i|-i_c(T)}{c}$.

Eq. (3) is a new model in the calculation of FCL operation: (3) for $\rho(i,\ T)$ combines the known expression (1) for $i_c(T)$

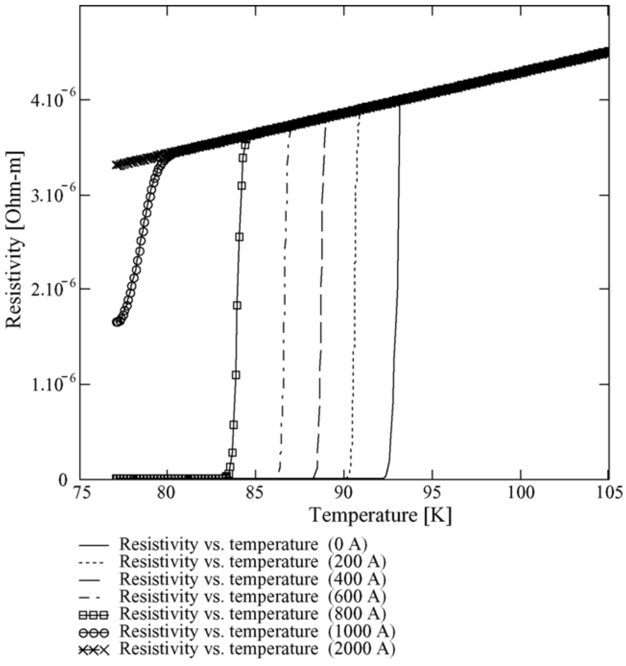


Fig. 2. The resistivity ($\rho(i,\ T)$) of the HTS ring vs. temperature in different current.

with the new function (2) of $s(x)$ for the calculation of the resistivity of the superconductor.

The resistivity of the superconductor ring is given by:

$$R_{\mathrm{sc}}(i, T) = \rho(i, T)\frac{l}{A} \tag{4}$$

where l the average length and A the cross-sectional area of the HTS ring.

3. Modeling of the inductive type HTS FCL

The FCL impedance can be calculated using the calculation methods of a transformer with a short-circuited secondary coil, where the short-circuited secondary coil is the superconductor ring. So, we can use the calculation methods of the parameters of conventional reactors and transformers.

The model provides the various operational modes of the FCL due to material properties observed in the experiments, and enables the determination of main dimensions of the device including those of the magnetic circuit (Fig. 3(a)).

The main flux Φ_0, the primary Φ_{sl} and secondary Φ_{s2} leakage flux of the fault current limiter shown in Fig. 3(a) and (b) shows the analog equivalent circuit of the FCL magnetic circuit, where R_{m} is the magnetic resistance and U_{m} is the magnetomotive force, respectively.

The elements of the analog equivalent circuit can be calculated from the dimensions and the property of the magnetic core and coil of the FCL.

For the determination of the parameters of electrical equivalent circuit,[5] we have used the analog magnetic equivalent circuit.

The stationary and transient behaviors of the FCL and the superconductor can be described by the following differential equation system:

$$U = R_1 i_1 + L_{\mathrm{s1}}\frac{\mathrm{d}i_1}{\mathrm{d}t} + L_{\mathrm{m}}\frac{\mathrm{d}i_{\mathrm{m}}}{\mathrm{d}t} \tag{5}$$

$$0 = L_{\mathrm{m}}\frac{\mathrm{d}i_{\mathrm{m}}}{\mathrm{d}t} + L_{\mathrm{s2}}\frac{\mathrm{d}i_2}{\mathrm{d}t} + R_{\mathrm{sc}} i_2 \tag{6}$$

$$0 = i_1 + i_2 + i_{\mathrm{m}} \tag{7}$$

$$0 = R_2 {i_2}^2 + c_{\mathrm{v}} V\frac{\mathrm{d}T}{\mathrm{d}t} + Ah(T - T_{\mathrm{cool}}) \tag{8}$$

where R_1 is the resistance of primary coil; L_{s1} is the leakage inductance of primary coil; L_{m} is the inductivity of the main field; L_{s2} is the reduced leakage inductance of the secondary coil (SC ring); R_{sc} transferred to primary resistance of the secondary coil (in the calculation of the acting non-linear resistance element represents the short-circuited HTS secondary coil (ring)); i_1, i_2 and i_{m} is the primary, reduced secondary and main field current, respectively.

The resistance of the superconductor, R_{sc} in (6) can be divided into two parts, viz. one representing the hot-spot part and the other one representing the superconducting part ($R_{\mathrm{sc}} = R_{\mathrm{sc\_hot\text{-}spot}} + R_{\mathrm{sc\_other}}$). The thermal Eq. (8) also can be divided into two parts, which describe:

1. temperature change in the hot-spot;
2. temperature change in other superconductor part.

The propagation of the normal zone is neglected. The solution of the differential equation system gives the primary (i_1), secondary (i_2) and main field (i_{m}) currents and the temperature of the hot-spot ($T_{\mathrm{hot\text{-}spot}}$) and the other superconductor (T_{other}) parts.

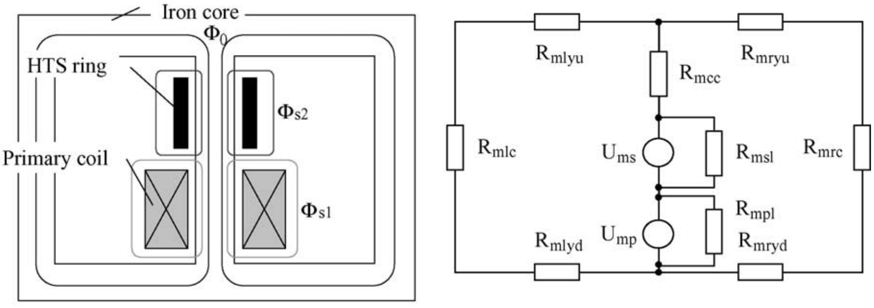
4. Calculation and experimental results

4.1. Current limitation—regular operation

In one of our papers,[1] we showed the experimental results of the short circuit tests, and we performed a calculation with this experimental arrangement. The comparison of the measurement and the calculation data are show in Fig. 4.

Fig. 4 shows the measured (a) and calculated (b) time functions of the current and the voltage of the FCL.

The investigation shows that the calculation data are in accordance with the measured data, the deviation is below 10%. Thus, our model provides a good representation of the electrical and thermal processes in inductive type HTS FCL and YBCO ceramic ring under the steady-state and the transient states. The activation, the operation and the recovery



(a) (b)

Fig. 3. The FCL magnetic core and its analog equivalent circuit.

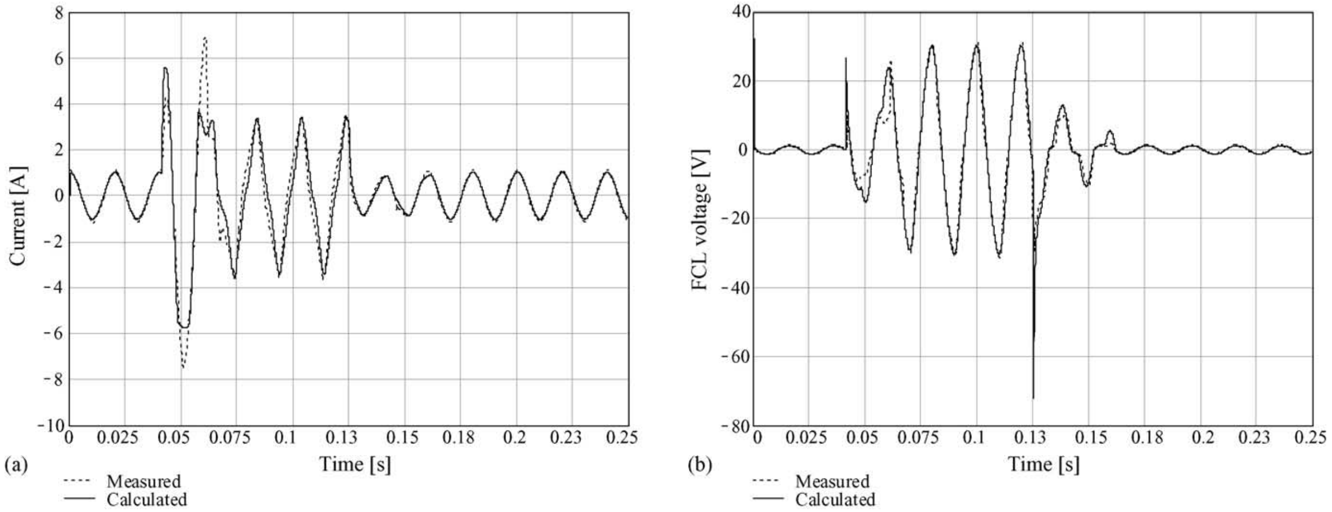


Fig. 4. The measured and calculated time function of the current (a) and voltage of the FCL (b).

processes are the same in the results of the calculation method and the measuring.

The figures below show the calculated currents (primary, main field and secondary currents) of the HTS fault current limiter (Fig. 5) and the temperature of the HTS ring (Fig. 6).

The figures show that the activation of the HTS FCL induce the increased current in the superconductor, which increases the temperature of the hot-spot and the other part of the HTS material. The balance between the two processes and the continuous refrigeration results in the equilibrium state, which results in the stable condition in the temperature and current characteristics.

The recovery processes depend on the temperature and the temperature-dependent critical current combined influence of the superconductor.

4.2. Current limitation—non-regular “sticking in” operation

We observed a new effect in the operation of the FCL due to the YBCO HTS ceramic material with hysteretic behavior. We call this effect *“sticking in”* because over the fault the HTS ring doesn’t recover into the superconducting state, it *“sticks in”* into the normal state. This process is self-maintaining due to the equilibrium of the thermal and electrical processes in the superconductor ring.

The figures below show the *“sticking in”* effect after the fault; Fig. 7 shows the measured (a) and calculated (b) current and voltage curves of the FCL.

The results of the calculation method reproduce the *“sticking in”* effect successfully. The temperature dependence of the hot-spot and non-hot-spot parts of HTS material are shown in Fig. 8.

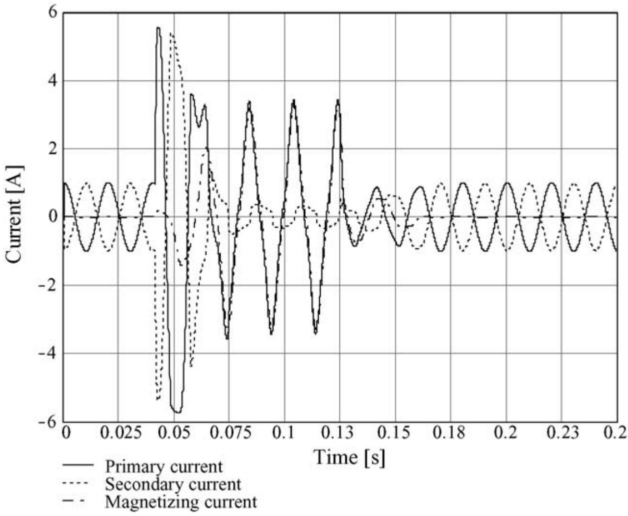


Fig. 5. The time functions of the primary (i_1), the magnetizing (i_m) and the reduced secondary (i_2) currents of the FCL.

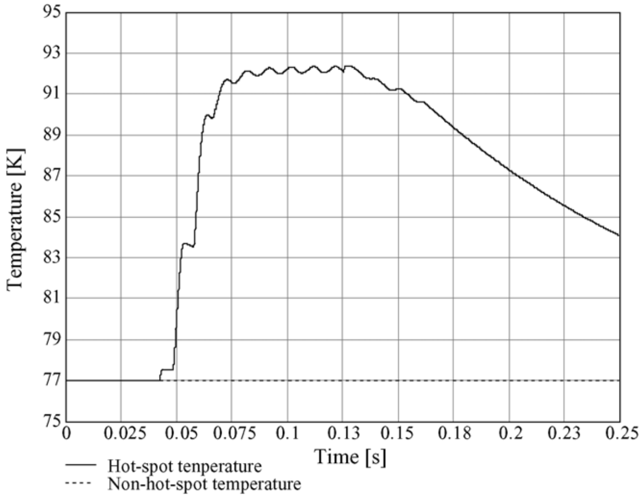


Fig. 6. The calculated temperature of the hot-spot and the other superconductor part.

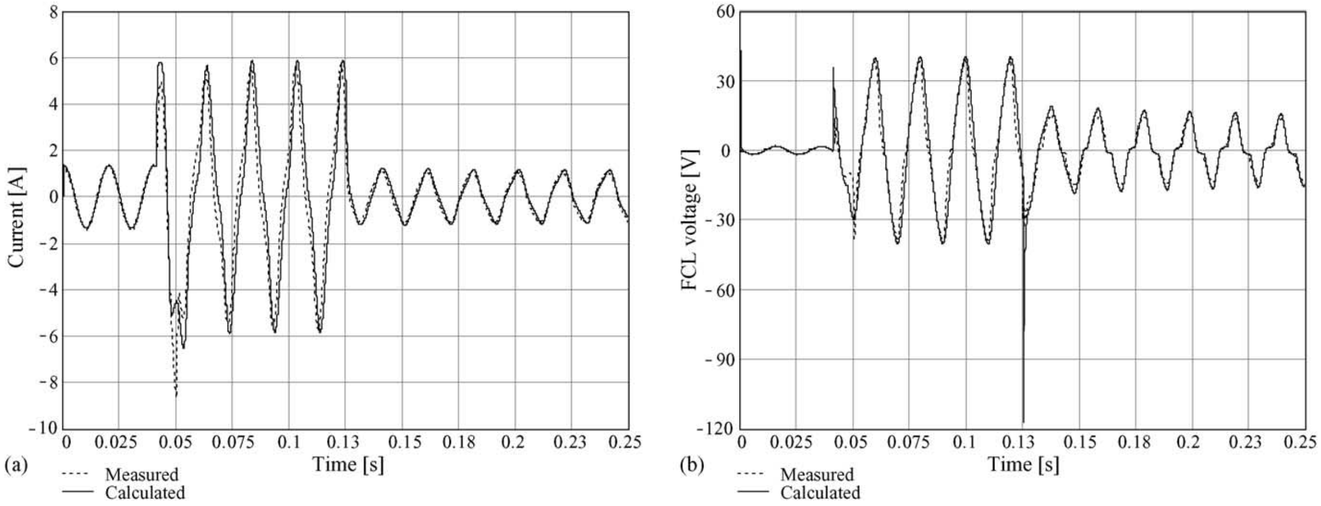


Fig. 7. The time functions of the measured and calculated current (a) and voltage of the FCL (b) with *"sticking in"* effect.

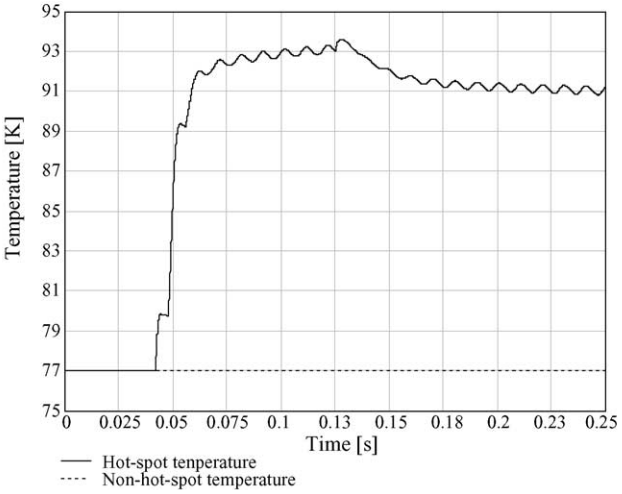


Fig. 8. The calculated temperature of the hot-spot and the other superconductor part in *"sticking in"* effect.

Fig. 8 shows the temperature of the hot-spot part below the critical value (93 K), but the critical current belongs to this temperature ($i_c(T)$) is lower than the actual current in the superconductor ring—so the HTS material is maintained in normal state. This state is stable and this effect in the hot-spot part exists until the current in the HTS material drop off.

5. Conclusions

The current limiting properties of the FCL were investigated experimentally and the results were compared with those of computer modeling:

1. The quench behavior of the YBCO HTS ring has strong influence on the current limiting properties of the FCL.
2. We developed a new extension of the existing model and a numerical simulation, which consists of coupled electromagnetic and thermal processes, can handle the influence of the hot-spots generated in the HTS, and the non-linear characteristics of the magnetic core.
3. This model describes efficiently the operation of the hysteretic inductive type HTS FCL in the steady-state and the transient state. The deviation between the measured and calculated data is below 10%.
4. The model can directly be used for the engineering design of inductive type HTS fault current limiters.

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