Reverse Engineering of Inductive Fault Current Limiters

J M Pina, P Suárez, M Ventim Neves, A Álvarez and A L Rodrigues

1Centre of Technology and Systems
Faculdade de Ciências e Tecnologia, Nova University of Lisbon
Monte de Caparica, 2829-516 Caparica, Portugal

2“Benito Mahedero” Group of Electrical Applications of Superconductors
Escuela de Ingenierías Industriales, University of Extremadura
Avenida de Elvas s/n, 06006 Badajoz, Spain

E-mail: jmmp@fct.unl.pt

Abstract. The inductive fault current limiter is less compact and harder to scale to high voltage networks than the resistive one. Nevertheless, its simple construction and mechanical robustness make it attractive in low voltage grids. Thus, it might be an enabling technology for the advent of microgrids, low voltage networks with dispersed generation, controllable loads and energy storage. A new methodology for reverse engineering of inductive fault current limiters based on the independent analysis of iron cores and HTS cylinders is presented in this paper. Their electromagnetic characteristics are used to predict the devices’ hysteresis loops and consequently their dynamic behavior. Previous models based on the separate analysis of the limiters’ components were already derived, e.g. in transformer like equivalent models. Nevertheless, the assumptions usually made may limit these models’ application, as shown in the paper. The proposed methodology obviates these limitations. Results are validated through simulations.

1. Introduction
Inductive fault current limiters (FCL) using high temperature superconducting materials (HTS) have been suggested almost two decades ago [1] and tested with success [2, 3]. It consists in a primary coil magnetically linked with a superconducting cylinder, and its principle of operation was extensively described elsewhere [4-6]. Some of its advantages include the absence of current leads or the adjustment of limiting impedance through primary’s number of turns. Nevertheless, its high weight and volume, when compared with e.g. resistive FCLs, caused by the presence of iron cores or the difficulty to scale them to high voltage networks led to the decrease in interest in this type of limiter. Despite all this, their simplicity of construction and robustness make them attractive in systems as microgrids, low voltage networks with dispersed generation, controllable loads and energy storage [7] (which can also include other superconducting technologies, as SMES – Superconducting Magnetic Energy Storage - or flywheels with superconducting bearings).

Inductive FCLs are usually represented by transformer like models due to its operation as a short-circuited transformer, see e.g. [2, 8-11]. Nevertheless, some assumptions made with these models limit its application and they are seldom really used. In this paper, a reverse engineering methodology is

3 To whom any correspondence should be addressed.
presented, based on the hysteresis maximum loop of the FCL. This is set up with experimental data from FCL’s constitutive parts and the knowledge of the grid’s short-circuit current where it will be inserted. This simple methodology allows determining FCL’s dynamic behavior with different materials (iron and HTS), primary coils and grid parameters.

In the next section transformer like models of the inductive FCL are detailed. Section 3 presents the proposed methodology, validated through simulations in section 4. Conclusions are drawn in the last section.

2. Fault current limiter transformer models

A FCL transformer type model is represented in figure 1 where the parameter corresponding to HTS resistance, \( N^2 R_{hts} \), is variable. Usually the parameters of the primary longitudinal branch, \( r_p \) and \( \lambda_p \), respectively primary resistance and leakage flux inductance, as well as the secondary leakage flux inductance, \( N^2 \lambda_{hts} \), are neglected.

Some references characterize the limiter by a time dependent impedance, see e.g. [12-14], corresponding to the parallel association of the model’s transversal branch and the HTS resistance, where the latter is time dependent. This considers HTS resistance to change with time, which, although really happens, is due to its dependence on current, magnetic field and temperature, not on time itself.

Other limitations arise with these models, and that might be the reason why they are seldom really applied. In fact, they do not usually take into account iron core saturation and the device hysteresis, which determine the limiter’s dynamic response. These characteristics, saturation and hysteresis, should be incorporated in the models, although increasing its complexity. This is one of the motivations for the limiter’s model proposed in this paper, based on its hysteresis maximum loop.

3. Reverse engineering methodology

The simple reverse engineering methodology proposed in the paper is based on the determination of the limiter’s hysteresis maximum loop that relates primary current, \( i_{line} \), to linked flux, \( \Psi_{fcl} \). The dynamic behavior of the device is then simulated based on this loop.

The hysteresis loops are built with data from the constitutive parts of the limiter, namely from the HTS cylinder and iron core. This is useful in predicting the behavior of the limiter with different irons or HTS materials.

3.1. Determination of the HTS cylinder maximum current

The key HTS characteristic is its maximum transport current, rather than its critical one, as these are quite different. The measurement system is depicted in figure 2, where a Rogowski coil is used to determine total current through its surface, \( i_{tot} \). Since current in the primary winding, \( i_{line} \), is known, current in the HTS cross section, \( i_{hts} \), is simply

\[
i_{hts} = i_{tot} - i_{line}
\]

The maximum value of \( i_{hts} \) is defined as \( i_{hts}^* \).
3.2. Determination of the iron core coil’s characteristic

The iron core coil’s characteristic, i.e., the relationship between primary’s current, $i_{\text{line}}$, and linked flux, $\Psi_0$, can be modeled analytically as

$$
\Psi_0(i_{\text{line}}) = a \cdot N \cdot i_{\text{line}} + \frac{b \cdot N \cdot i_{\text{line}}}{c + d \cdot N \cdot i_{\text{line}}} \tag{2}
$$

where $N$ is the primary number of turns and parameters $a$, $b$, $c$ and $d$ are determined by fitting from measurements. This relationship is plotted in figure 3. Linked flux is derived from measurements by

$$
\Psi_0(t) = \frac{N}{N_p} \int_{0}^{t} u_p(\tau) d\tau \tag{3}
$$

where $u_p$ is the measured voltage at the terminals of a $N_p$ turns pick-up coil.

3.3. Setting of the FCL’s hysteresis loop

The current limiter hysteresis loop is built from data determined in the previous subsections. The ascending and descending branches cross the current axis at $\pm I_{hts}^*/N$, since this is the maximum line current that the device can shield. The branches are determined using an auxiliary function, $f$, from the iron characteristic, see figure 4, as

$$
\lambda_g(i_{\text{line}}) = \Psi_0(i_{\text{line}} - f(i_{\text{line}})) \tag{4}
$$

$$
\lambda_f(i_{\text{line}}) = \Psi_0(i_{\text{line}} + f(i_{\text{line}})) \tag{5}
$$

where $\lambda_g$ and $\lambda_f$ are respectively the ascending and the descending branches of the hysteresis loop. Auxiliary function $f$ is sinusoidal and is plotted in figure 5. Is zero at $i_{\text{line}} = \pm I_{sc}$, where $I_{sc}$ is the grid short-circuit current, and is $I_{hts}^*/N$ at $i_{\text{line}} = \pm I_{hts}^*/N$. Thus, $f$ is defined as

$$
f(i_{\text{line}}) = \frac{I_{hts}^*/N}{\cos \left( \frac{\pi}{2} \frac{i_{\text{line}}}{I_{hts}^*/N} \right)} \times \cos \left( \frac{\pi}{2} \frac{i_{\text{line}}}{I_{sc}} \right) \tag{6}
$$
3.4. Determination of the limiter’s dynamic behavior

After setting up the FCL hysteresis loop, it is used to obtain the grid line current’s dynamic behavior under a fault. The circuit used to model a single-phase grid with a FCL is represented in Figure 6. It is built by a voltage source, \( u_{\text{grid}} \), a resistor that models line resistance, \( R_{\text{line}} \), and a load, \( Z_{\text{load}} \), which is short-circuited by an ideal switch when fault occurs.

**Figure 6.** Electrical circuit used to determine limiter’s dynamic behavior under a fault.

### 3.4.1. Circuit equations

Under a fault, the voltage at the load is zero and the circuit response is described by

\[
\frac{\partial \Psi_{\text{fcl}}}{\partial i_{\text{line}}} = \frac{\partial u_{\text{grid}}}{\partial i_{\text{line}}} + \frac{\partial u_{\text{grid}}}{\partial i_{\text{line}}} \frac{\partial i_{\text{line}}}{\partial t} \frac{\partial i_{\text{line}}}{\partial t} + \frac{\partial u_{\text{grid}}}{\partial i_{\text{line}}} \frac{\partial i_{\text{line}}}{\partial t}
\]

that is

\[
\frac{\partial i_{\text{line}}}{\partial t} = \frac{\partial i_{\text{line}}}{\partial t} \left( u_{\text{grid}} - R_{\text{line}} \cdot i_{\text{line}} \right)
\]

Discretizing this equation (using Euler’s method) results in the following value of the line current at time \( t = (k+1) \cdot \Delta t \), \( k = 0, 1, \ldots \), where \( \Delta t \) is the sampling period:

\[
i_{\text{line}}^{k+1} = i_{\text{line}}^k + \frac{\partial i_{\text{line}}}{\partial t} \left|_{i_{\text{line}}^k} \right. \left( u_{\text{grid}} - R_{\text{line}} \cdot i_{\text{line}}^k \right) \Delta t
\]

The previous equation shows that current value at iteration \( k + 1 \) depends naturally on the values of voltage and current at previous iteration, \( u_{\text{grid}}^k \) and \( i_{\text{line}}^k \), and on the excursion in the \( i_{\text{line}} \cdot \Psi_{\text{fcl}} \) plane.
3.4.2. Derivation of the $i_{\text{line}|\Psi_{fcl}}$ excursion. In order to determine the excursion in the $i_{\text{line}|\Psi_{fcl}}$ plane, or, equivalently, the derivative $\frac{di_{\text{line}}}{d\Psi_{fcl}}$ at iteration $k$, a simple algorithm is used. It assumes that if the operation point is somewhere outside the ascending or descending branches, then it follows an horizontal path until it achieves one of the branches. This means that FCL limitation is only effective at the branches (mainly on the steepest regions) and its inductance is neglected outside it. After that it will proceed on the corresponding branch. This can be stated as:

1. If $i_{\text{line}}^k > i_{\text{line}}^{k-1}$ (current is increasing) and $\Psi_{fcl}(i_{\text{line}}^k) > \lambda_g(i_{\text{line}}^k)$ (operation point is outside the ascending branch), then current is only limited by line resistance:

$$\Psi_{fcl}^{k+1} = \Psi_{fcl}^k$$
$$i_{\text{line}}^{k+1} = \frac{u_{\text{grid}}^{k+1}}{R_{\text{line}}}$$

(10)

2. If $i_{\text{line}}^k > i_{\text{line}}^{k-1}$ and $\Psi_{fcl}(i_{\text{line}}^k) = \lambda_g(i_{\text{line}}^k)$ (operation point is on the ascending branch), then

$$i_{\text{line}}^{k+1} = i_{\text{line}}^k + \frac{di_{\text{line}}}{d\lambda_g} \left( \left( \frac{u_{\text{grid}}}{R_{\text{line}}} - i_{\text{line}}^k \right) \Delta t \right)$$
$$\Psi_{fcl}^{k+1} = \lambda_g(i_{\text{line}}^{k+1})$$

(11)

3. If $i_{\text{line}}^k < i_{\text{line}}^{k-1}$ (current is decreasing) and $\Psi_{fcl}(i_{\text{line}}^k) < \lambda_f(i_{\text{line}}^k)$ (operation point is outside the descending branch), then current is only limited by line resistance as in (10).

4. If $i_{\text{line}}^k < i_{\text{line}}^{k-1}$ and $\Psi_{fcl}(i_{\text{line}}^k) = \lambda_f(i_{\text{line}}^k)$ (operation point is on the descending branch), then

$$i_{\text{line}}^{k+1} = i_{\text{line}}^k + \frac{di_{\text{line}}}{d\lambda_f} \left( \left( \frac{u_{\text{grid}}}{R_{\text{line}}} - i_{\text{line}}^k \right) \Delta t \right)$$
$$\Psi_{fcl}^{k+1} = \lambda_f(i_{\text{line}}^{k+1})$$

(12)

The derivatives $\frac{d\lambda_f}{di_{\text{line}}}$ and $\frac{d\lambda_g}{di_{\text{line}}}$ are calculated analytically from (2), (4) and (5).

4. Simulation results

In order to demonstrate and validate the proposed methodology, several simulations were carried out with the finite elements software Flux2D from Cedrat Company. These included iron cores with different characteristics (different materials, open and closed cores), primary coils with different number of turns and different HTS materials. The proposed reverse engineering methodology was applied and then the limiters’ dynamic behaviors were compared with the ones obtained by simulations of the full devices.

In this section, simulations with a closed core limiter are presented, see figure 7 for dimensions. The HTS cylinder and primary coil parameters are specified in table 1. HTS material was modeled according to the power law and current density was made independent of flux density.

4.1. Application of the reverse engineering methodology

According to the previous section, the first steps in the reverse engineering methodology consist on measuring HTS maximum current and primary characteristic.

4.1.1. Determination of the HTS cylinder maximum current. A simulation was performed in order to determine the maximum current the HTS can transport, when primary is fed by a sinusoidal current.
This experiment must allow maximum current to be achieved. Simulation results are presented in figure 8, where horizontal paths in the figure correspond to maximum current which is 

\[ I_{\text{hs}}^* = 632 \, \text{A} \]

**Figure 7.** Cross section view of the closed core limiter. All dimensions in millimeters.

### Table 1. HTS cylinder and primary coil parameters.

| HTS cylinder (Bi-2223)                  | Value     |
|----------------------------------------|-----------|
| Critical temperature (K)               | 108       |
| Inner radius (mm)                      | 16.5      |
| Width (mm)                             | 2.5       |
| Height (mm)                            | 48.0      |
| Critical current density at 77 K (A·cm\(^{-2}\)) | 300        |
| Exponent \( n \)                       | 15        |

| Primary coil                           | Value     |
|----------------------------------------|-----------|
| Number of turns                        | 350       |
| Height (mm)                            | 35.0      |

4.1.2. **Determination of the iron core coil’s characteristic.** The iron core coil’s characteristic obtained with a magnetic steel from Flux2D library, reference FLU_M27035A, is presented in figure 9. The primary coil used in simulation is the same that builds the limiter. Using tool `cftool` from MATLAB the following parameters in (2) were obtained:

\[
 a = 7.3421 \times 10^{-6} \quad b = 6.2343 \quad c = 457.8311 \quad d = 25.1627
\]

**Figure 8.** Determination of the HTS cylinder maximum current.  
**Figure 9.** Iron core coil’s characteristic.
4.1.3. Setting of the FCL’s hysteresis loop. Using the proposed methodology, the limiter’s maximum hysteresis loop is set up, see figure 10. It can now be used in the next step to evaluate limiter’s performance.

![Figure 10. Maximum hysteresis loop characterizing the fault current limiter, set up according to the reverse engineering methodology.](image)

4.1.4. Determination of the limiter’s dynamic behavior. The circuit used to evaluate limiter’s performance is the same as in figure 6, with \( u_{\text{grid}} = \sqrt{2} \cdot 50 \cdot \sin(100 \pi \cdot t) \) V, \( R_{\text{line}} = 5 \) Ω and \( I_{\text{sc}} = 10 \) A rms. A short-circuit was applied at \( t = 20 \) ms. The prospective current, \( i_p \), and resulting line current, \( i_{\text{line}} \), are plotted in figure 11, while the excursion in plane \( i_{\text{line}} | \Psi_{\text{fcl}} \) is plotted in figure 12.

![Figure 11. Evolution of current in the circuit, \( i_{\text{line}} \), under a fault. Prospective current, \( i_p \), is also shown. Currents are in amperes.](image)

![Figure 12. Excursion in the plane \( i_{\text{line}} | \Psi_{\text{fcl}} \) under a fault.](image)

4.2. Current limiter finite elements simulation

In order to validate limiter’s behavior obtained previously, simulations were performed with Flux2D. The resulting line current, as well as the excursion in plane \( i_{\text{line}} | \Psi_{\text{fcl}} \), are plotted respectively in figures 13 and 14. The results obtained with reverse engineering methodology are also plotted in those figures for comparison.

5. Conclusions

A reverse engineering methodology for inductive fault current limiters is presented in this paper. It allows determining the dynamic behavior of a particular FCL when inserted into an electrical grid. The methodology is based on measurements of the limiter’s individual parts properties and on knowledge of the grid’s short-circuit current. The latter parameter is not crucial as it may only slightly affects hysteresis loop width near its extreme points and these areas should not be reached by line current. Obtained results are in good accordance with simulations for which this methodology is useful and straightforward to apply in the consequences’ evaluation of different materials (iron and HTS) and primary coils in limiters’ performance. This type of modeling enhances the fact that limited current
should ideally reach $\pm I_{\text{lim}}/N$. An additional, and perhaps most important, advantage in the proposed methodology is the dramatic reduction in computational time required to determine the device’s behavior when comparing with finite elements simulations, namely a few seconds against several hours.

Future work includes validation of the methodology by experimental measurements.

**Figure 13.** Comparison between current in the circuit under a fault obtained by reverse engineering methodology and by simulation.

**Figure 14.** Comparison between excursion in the plane $i_{\text{lim}}|\Psi_{\text{fc}}|$ under a fault obtained by reverse engineering methodology and by simulation.

**Acknowledgments**

Authors would like to thank to CTS (Centre of Technology and Systems) from UNINOVA (Instituto de Desenvolvimento de Novas Tecnologias) and to Fundação para a Ciência e a Tecnologia for its financial support.

**References**

[1] Bashkirov Y, Fleishman L, Patsayeva T, Sobolev A and Vdovin A 1991 Current-Limiting Reactor Based on High-$T_c$ Superconductors *IEEE Trans. Mag.* 27 1089-1092.

[2] Paul W, Lakner M, Rhyner J, Unternährer P, Baumann Th, Chen M, Widenhorn L and Guérig A 1997 Test of 1.2 MVA high-$T_c$ superconducting fault current limiter *Supercond. Sci. Technol.* 10 914-918

[3] Kado H, Ichikawa M, Shibuya M, Kojima M, Kawahara M and Matsumura T 2005 Inductive Type Fault Current Limiter Using Bi-2223 Thick Film on MgO Cylinder With Bi-2212 Buffer Layer *IEEE Trans. Appl. Supercond.* 15 2051-2054

[4] Noe M and Steurer M 2007 High-temperature superconductor fault current limiters: concepts, applications and development status *Supercond. Sci. Technol.* 20 R15-R29

[5] Vajda I and Semperger S 2005 Simulation of electrical, magnetic and thermal properties of inductive fault current limiters made of YBCO ceramic superconductors *J. Europ. Ceram. Soc.* 25 2925-2929

[6] Janowski T, Kozak S, Malinowski H, Wojtasiewicz G, Kondratowicz-Kuciewicz B and Kozak J 2003, Properties Comparison of Superconducting Fault Current Limiters With Closed and Open Core *IEEE Trans. Appl. Supercond.* 13 2072-2075

[7] Jiayi H, Chuanwen J and Rong X 2008 A review on distributed energy resources and MicroGrid *Renew. Sust. Energy Rev.* 12 2472-2483

[8] Meerovich V and Sokolovsky V 2007 Thermal regimes of HTS cylinders operating in devices for fault current limitation *Supercond. Sci. Technol.* 20 457-462

[9] Zhang G, Wang Z and Qiu M 2003 The Improved Magnetic Shield Type High $T_c$ Superconducting Fault Current Limiter and the Transient Characteristic Simulation *IEEE Trans. Appl. Supercond.* 13 2112-2115

8
[10] Lee C, Lee S, Hyun O-B and Kuk Ko T 2001 Design and Characteristic Analysis of a Rod Type High-Tc Superconducting Fault Current Limiter Through Electromagnetic Analysis IEEE Trans. Appl. Supercond. 11 2102-2105

[11] Acero J, García-Tabarés L, Bajkó M, Calero J, Granados X, Obradors X and Piñol S 1995 Current Limiter Based on Melt Processed YBCO Bulk Superconductors IEEE Trans. Appl. Supercond. 5 1071-1074

[12] Yamaguchi H and Kataoka T 2008 Current Limiting Characteristics of Transformer Type Superconducting Fault Current Limiter with Shunt Impedance and Inductive Load IEEE Trans. Appl. Supercond. 18 668-671

[13] Zong X, Wang J, Sun J and Wang Y 2003 Study on inductive high-$T_c$ superconducting fault current limiters Physica C 386 522-526

[14] Willén D and Cave J 1995 Short Circuit Test Performance of Inductive High $T_c$ Superconducting Fault Current Limiters IEEE Trans. Appl. Supercond. 5 1047-1050