Physical and Numerical Models of Superconducting Fault Current Limiters

Sławomir Kozak and Tadeusz Janowski

***Abstract*— The physical and numerical models of the inductive type superconducting fault current limiter (SFCL) were made. The physical models consist of superconducting Bi2223 tubes (diameter = 0.059 m, height = 0.05 m and critical current at 77 K = 625 A), iron cores (cross-section area = 0.02 m x 0.02 m and 0.02 m x 0.03 m) and the plastic cryostat with copper primary winding (236 turns). The voltage-current characteristics of these physical models were used for verification of the geometry and properties of regions in numerical model of SFCL. The numerical model using the magnetodynamics physical domain of the CAD package FLUX2D coupled with circuit equations was used to analyze the influence of selected parameters on SFCL voltage-current characteristics. The paper shows that the changes of the iron core and the superconducting tube geometry influence these characteristics significantly.**

***Index Terms*— SFCL, Numerical model, FEM-circuit, FLUX2D.**

I. Introduction

Short-circuit current levels can be 20 times larger than the rated current [1], [2]. All electrical equipment exposed to the short-circuit current must be designed to withstand in particular the mechanical forces under fault conditions, which are generally proportional to the square of current. The superconducting fault current limiters (SFCL) can be used to limit the short-circuit current level in electrical transmission and distribution networks to 5 (or less) times of rated current level [1] [3]. These fault current limiters, unlike reactors or high-impedance transformers, will limit the fault current without adding impedance to the circuit during normal operation [4], [5]. In one concept of SFCL – series resistive limiter, the superconductor is inserted in the circuit directly [2], [1]. During a fault, the fault current pushes the superconductor into a resistive state and a resistance, which limits the fault current, appears in the circuit. Another concept – inductive limiter [2], [1] works like transformer with a shorted superconducting secondary winding. The impedance of this limiter under standard operation conditions is nearly zero, since the zero impedance of the secondary superconducting winding is reflected to the primary. In the event of a fault, the resistance in the secondary is reflected into the circuit and limits the fault current.

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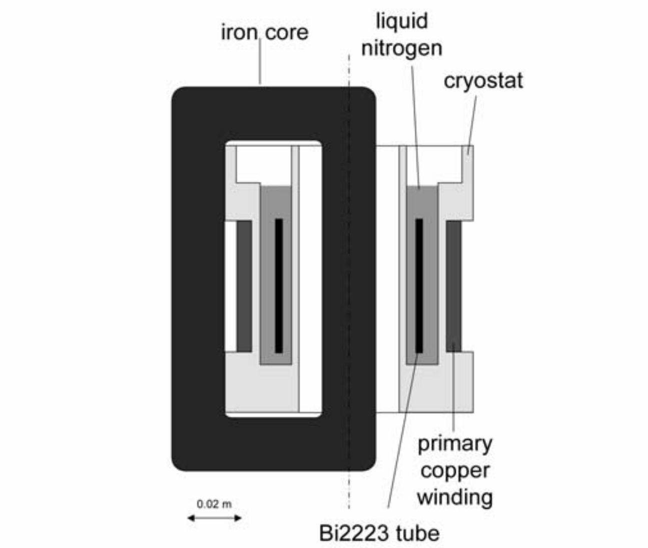

Fig. 1 Inductive superconducting fault current limiter.

II. Inductive Superconducting Fault Current Limiter

Fig. 1 presents one of two physical models of inductive SFCL made in the Laboratory of Cryoelectromagnets in Lublin [6], [7]. These SFCLs work like transformers. They have copper primary windings and secondary windings made with superconducting tubes. In normal operation, the field from the copper primary windings does not penetrate the superconducting tube. Under fault conditions, the current induced in the superconducting tubes is sufficient to drive them normal and the magnetic field links the iron cores.

The main components of these SFCLs are:

1. superconducting (Bi2223) tubes, inner diameter = 0.059 m, height = 0.05 m, thickness = 0.0025 m, critical current = 625 A at 77 K,
2. plastic cryostat for nitrogen with primary copper windings (236 turns),
3. iron cores with height of window = 0.103 m, breadth of window = 0.036 m, and cross-sections:
    a. 0.02 m x 0.02 m [6],

b. 0.02 m x 0.03 m.

The experimental investigations of these inductive SFCLs were made.

III. FEM-Circuit Numerical Model of Inductive SFCL

A FEM-circuit (FEM – Finite Element Method) numerical model of the inductive SFCL was made using the magnetodynamics (MD) physical domain of the CAD package FLUX2D [8] (Fig. 2) coupled with circuit equations [9] (Fig. 3). Real 3D geometry of inductive SFCL was replaced by simplified 2D geometry.

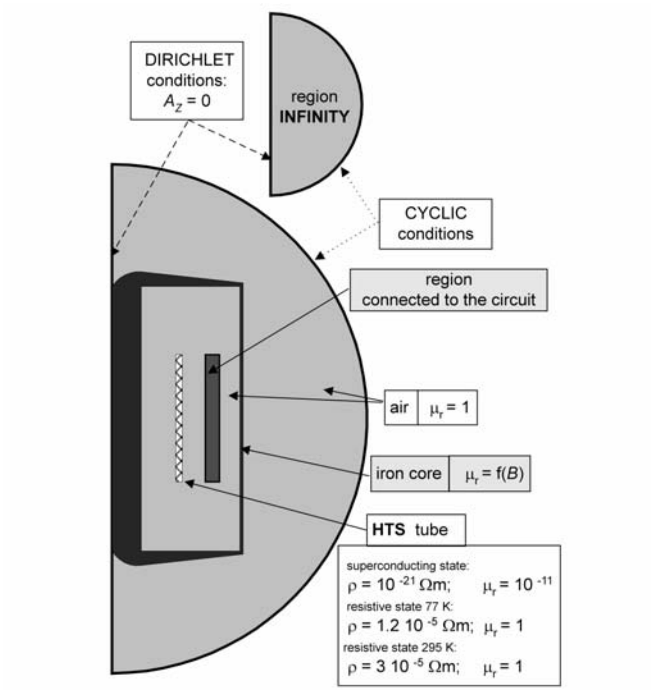

Fig. 2. Geometry and region properties diagram in FEM part of numerical model of inductive SFCL – FLUX2D.

The numerical model consists of 6 regions and 4 boundaries (Fig. 2) where the following boundary conditions are defined:

- CYCLIC – boundary on "air" and "infinity" regions,
- DIRICHLET – axis of symmetry.

Fig. 4 presents voltage-current characteristics of 2 physical models of limiters (with 2 cm x 2 cm and 2 cm x 3 cm iron core cross-section) and respective characteristics of the numerical models in the superconducting and resistive states. The characteristics of the physical models are placed between the superconducting state and the resistive state characteristics of the numerical models (Fig. 4). For currents up to 1 A the superconducting state *V-I* characteristics of numerical model almost fit the physical model *V-I* characteristics. For current above 4 A the physical model *V-I* characteristics start to be very close to the resistive state *V-I* characteristics of numerical model. The theoretical characteristics of limiters are drawn under assumption that Bi2223 tube is in superconducting state if the effective current in it is less then 625 A (2.65 A in primary winding) and in resistive state if the effective current is above 625 A.

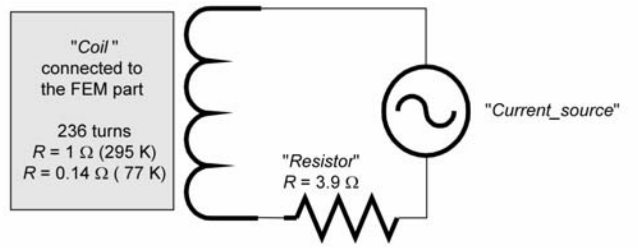

Fig. 3. Diagram of circuit part of numerical model of inductive SFCL – FLUX2D.

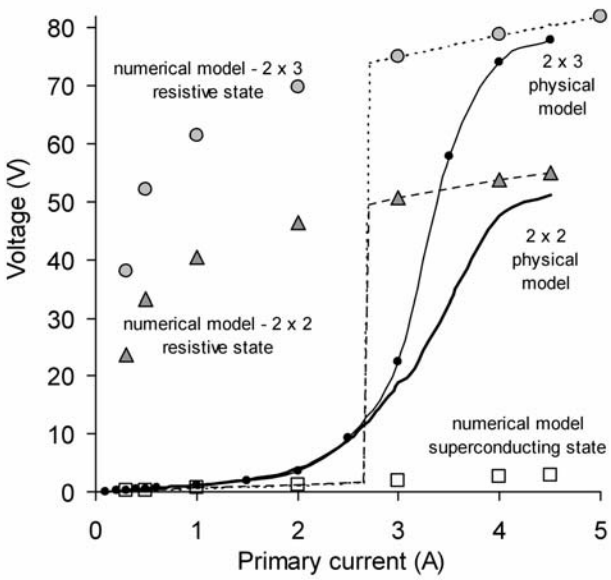

Fig. 4. *V-I* characteristics of physical models with 2 cm x 2 cm and 2 cm x 3 cm iron core cross-sections and respective numerical model characteristics in superconducting state and resistive state at 77 K.

As it can be concluded from Fig. 4, the rated current of these limiters should be set to 1-1.5 A and then the limited current can be equal to 5-7.5 A. (5 times the rated current). It shows that the comparison of physical model *V-I* characteristics of limiters can be substituted by the comparison of numerical model in superconducting and resistive states. To obtain numerical model *V-I* characteristics it is necessary to set the proper geometry, region properties and state (superconducting or resistive) in the FEM part of the numerical model (Fig. 2) and calculate the voltage drop on the limiter for different currents of "Current_source" in the circuit part of the numerical model (Fig. 3). The FEM-circuit numerical model of an inductive SFCL allows examining the influence of construction and electromagnetic parameters on the *V-I* characteristics of limiter. The smaller the voltage drop on the limiter in the superconducting state, the smaller the energy losses generated by the rated current in the limiter. The higher the voltage drop on the limiter in resistive state, the better the reduction of the short-circuit current level during the fault. Then, the voltage drop on the optimal working inductive

SFCL should be minimal as possible in the superconducting state and as large as possible in resistive state.

The related voltage drop $(U\text{-}U_0)/U_0$, where U is the voltage drop on SFCL with different geometry or region properties, U_0 is the voltage drop on SFCL with (0.02 m x 0.02 m iron core) physical model geometry and region properties at respective state (superconducting or resistive) was used to show the influence of the parameters on the *V-I* characteristics of limiter.

IV. Voltage Drop at Limiter vs Breadth of Iron Core Window

Fig. 5 shows the changes in *V-I* characteristics vs the breadth of iron core window. The numbers near the curves show the change (in meters) in breadth of window in comparison to 0.036 m.

The increase of window breadth of 0.005 m, 0.01 m and 0.015 m increases the resistive state *V-I* characteristics by 1% - 3.9% and decreases the superconducting state *V-I* characteristics by 2.3-4.2% (Fig. 5). The changes of both characteristics are small but advantageous.

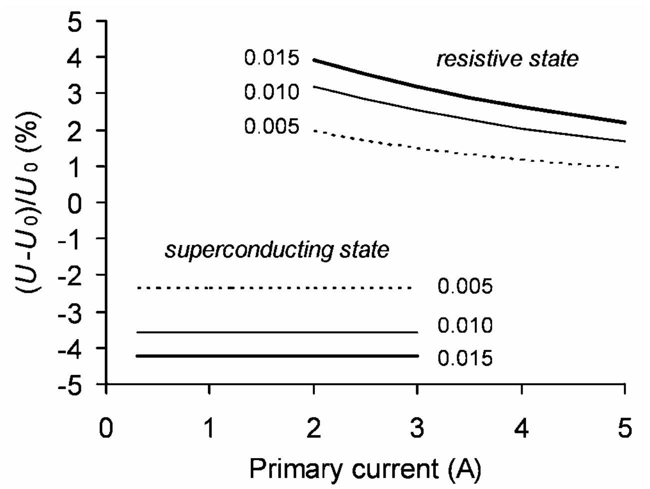

Fig. 5. Changes in *V-I* characteristics vs the breadth of window of iron core in resistive state and superconducting state at 77 K.

V. Voltage Drop at Limiter vs Height of Iron Core Window

Fig. 6 shows the changes in the resistive and superconducting state *V-I* characteristics vs. the height of iron core window. The numbers near curves (in meters) show the change in height of window in comparison to 0.103 m. The increase of window height by 0.02 m and 0.04 m decreases the resistive state *V-I* characteristics by 0.7 % - 2.8 % and decreases slightly the superconducting state *V-I* characteristics (~ 0.1 %). The decrease of window height by 0.02 m and 0.04 m increases the resistive state *V-I* characteristics by 1 % - 4.6 % and increases the superconducting state *V-I* characteristics by 0.6 % and by 3.8 %.

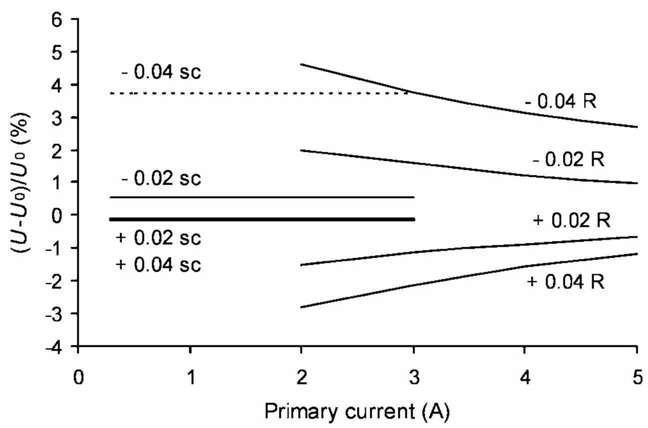

Fig. 6. Changes in *V-I* characteristics vs the height of window of iron core in resistive (R) and superconducting (sc) state at 77 K.

VI. Voltage Drop at Limiter vs Shape of Superconducting Tube

Fig. 7 shows the changes in the resistive and superconducting state *V-I* characteristics vs the shape of the superconducting tube. The numbers near curves show the shape of superconducting tube (height (mm)/thickness (mm)). The superconducting tube of the physical model of inductive SFCL has the shape of 50/2.5 (mm/mm). During the calculation, the shape of tube had a constant cross-section = 125 mm^2.

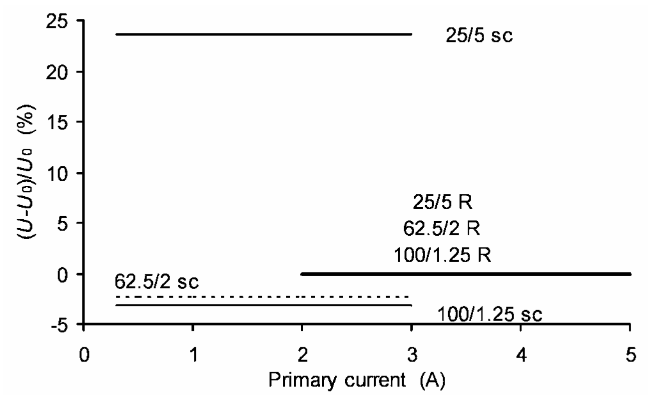

Fig. 7. Changes in resistive (R) and superconducting (sc) state *V-I* characteristics of numerical model vs the shape of superconducting tube (height (mm)/thickness (mm)) at 77 K.

The changes in the shape of the superconducting tube do not influence the *V-I* characteristics of the numerical model of the inductive SFCL in the resistive state at 77 K (Fig. 7). The decrease in the height of the tube to 25 mm increases significantly the voltage drop (23.6 %) in the superconducting state (Fig. 7). The increase in the height of the tube to 62.5 mm and 100 mm decreases the voltage drop by 2.2 % and 3.2 % in the superconducting state respectively (Fig. 7).

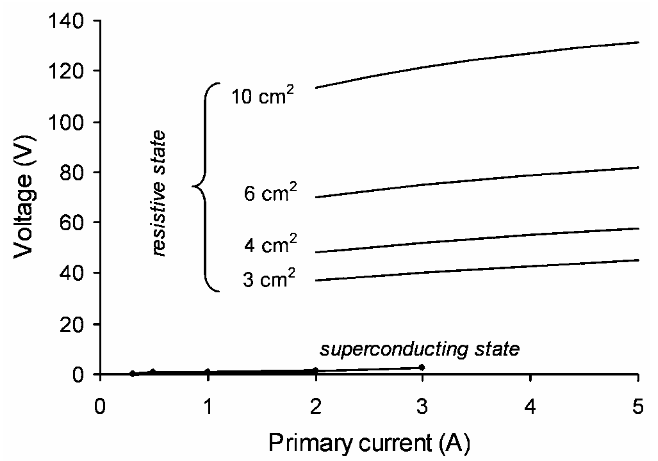

Fig. 8. Changes in resistive and superconducting state *V-I* characteristics of numerical model of inductive SFCL at 77 K vs the cross-section of iron core.

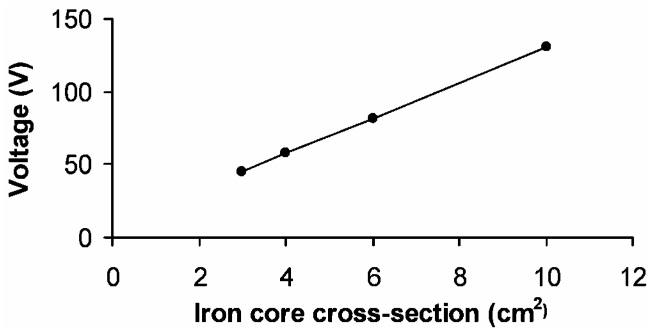

Fig. 9. Voltage drop on inductive SFCL vs iron core cross-section area for current = 5 A at 77 K.

VII. Voltage drop at limiter vs iron core cross-section

Fig. 8 shows the changes in the *V-I* characteristics of the limiter in the resistive and superconducting states vs the cross-sectional area of the iron core. The changes in the iron core cross-section do not influence the *V-I* characteristics of numerical model of the limiter in superconducting state. It can be concluded (Fig. 8) that the iron core cross-sectional area should be as large as possible for the given superconducting tube. In our physical models of limiters presented in the paper only the superconducting tube is cooled to 77 K – the iron core and primary copper winding are placed at room temperature. That arrangement reduces consumption of liquid nitrogen because the iron core losses and resistive copper winding losses do not heat the liquid nitrogen. However, the cryostat and liquid nitrogen vessel significantly reduce (in small limiters) the maximal available cross-sectional area of the iron core. In our limiters the cross-sectional area of iron core = 10 cm^2 is limited by the cryostat. The cross-sectional area could be equal to 27 cm^2 based on the inner diameter of superconducting tube. As the dependence of iron core cross-section on voltage drop at limiter is almost linear (Fig. 9) the increase of area cross-section to 27 cm^2 could increase available voltage drop at limiter by 2.7 times.

VIII. Conclusions

The increase in the breadth of the iron core window has an advantages, but a small influence on both the superconducting and resistive state *V-I* characteristics.

The changes in height of the iron core window have a small and ambivalent influence on superconducting and resistive state *V-I* characteristics.

The height of the superconducting tube should be no less than the height of the copper winding otherwise an increase in the superconducting state *V-I* characteristics appears.

The iron core cross-sectional area has a very strong influence on the *V-I* characteristics of the limiter. The iron core should fill the inner area of superconducting tube as much as possible. By cooling all the components of limiter, it is possible to increase significantly the cross-sectional area of the iron core which otherwise is limited by the cryostat. It is very interesting to investigate if the advantages of significant increase of voltage drop at the limiter are more profitable than the disadvantages of the higher losses in cooling system.

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