SCOPE - B2

FINITE ELEMENT METHOD IN MAGNETIC FIELD ANALYSIS OF THE INDUCTIVE SUPERCONDUCTING FAULT CURRENT LIMITER WITH AN OPEN CORE.

Janusz Kozak, Tadeusz Janowski

Electrotechnical Institute in Warsaw, Cryoelectromagnets Laboratory in Lublin, Nadbystrzycka 38A, 20-618 Lublin, Poland, e-mail: januszk@eltecol.pol.lublin.pl.

Lublin University of Technology, Nadbystrzycka 38A, 20-618 Lublin, Poland, fax: +48 81 5253694,
e-mail: tadeuszj@eltecol.pol.lublin.pl.

ABSTRACT

The Superconducting Fault Current Limiter is a device placed in electric network to limit the peak current in the event of fault. In inductive SFCL the high temperature superconducting tubes are used as secondary winding. Primary winding is conventionally made of copper wire. The magnetic field distribution analysis is significant to elaborate proper operation of the limiter. The FEM is irrevocable at designing stage to calculate the electrical parameters of the SFCL in resistive and superconducting state. During the normal operation the resistance of superconducting winding is equal zero, and the magnetic flux does not penetrate the iron core because the superconducting tube acts as magnetic screen. The impedance of SFCL is nearly zero. When the fault occurs the increasing current exceed the critical value of the HTS element then resistance of secondary winding is reflected into the circuit, and the magnetic flux penetrates the iron core increasing the impedance of limiter. The voltage on the limiter depends mainly on the structure of the limiter, its geometrical dimensions, number of primary winding turns, distance between the windings and size of the core. The influence of many different parameters on the SFCL operation makes the analytical calculation very complicated and inaccurate. The Finite Element Method offers the possibility of analysis very close to the reality. Results of numerical analysis of superconducting inductive fault current limiter with an open core based on the FEM have been described in this paper.

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J Kozak, T Janowski

Electrotechnical Institute in Warsaw, Poland, Lublin University of Technology, Poland

INTRODUCTION

The Superconducting Fault Current Limiter is a device placed in electric network to limit the peak current in the event of fault, Waynet et al (1). SFCLs are designed to react to and absorb unanticipated power surges in the utility grid, preventing loss of power to consumers or damage to utility grid equipment, Bitterman (2). In inductive SFCL the high temperature superconducting tubes are used as secondary winding. Primary winding is conventionally made of copper wire. The magnetic field distribution analysis is significant to elaborate proper operation of the limiter. The FEM is irrevocable at designing stage to calculate the electrical parameters of the SFCL in resistive and superconducting state.

PRINCIPLE OF OPERATION

During the normal operation the resistance of superconducting winding is equal zero, and the magnetic flux does not penetrate the iron core because the superconducting tube acts as magnetic screen. The impedance of SFCL is nearly zero and the voltage on the limiter in superconducting state is very low.

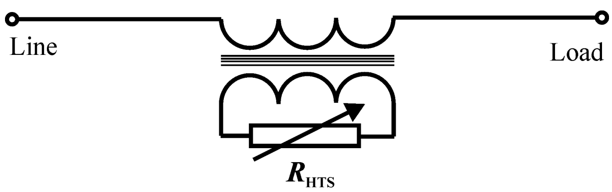

Figure 1: Equivalent circuit of SFCL

When the fault occurs the increasing current exceed the critical value of the HTS element then resistance of secondary winding is reflected into the circuit, and the magnetic flux penetrates the iron core increasing the impedance of limiter. Fast increase of impedance in the circuit limits the value of the fault current. The voltage of primary winding in resistive state of secondary winding should have appropriate value for the expected current limitation. The voltage on the limiter depends mainly on the structure of the limiter, its geometrical dimensions, number of primary winding turns, distance between the windings and size of the core. The influence of many different parameters on the SFCL operation makes the analytical calculation very complicated and inaccurate. The Finite Element Method offers the possibility of analysis very close to the reality.

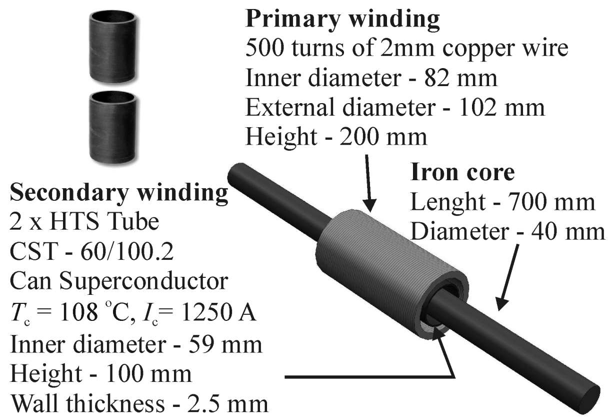

Figure 2: Structure of the SFCL shown without cryostat

The above model of SFCL with an open core was proposed as limiter, which can fulfil the following expectations:
- U_N = 230 V
- I_{rated} = 2 A
- $I_{activation}$ = 2.5 I_{rated}
- $I_{limitation}$ < 4 I_{rated}
- low voltage on SFCL in superconducting state.

NUMERICAL ANALYSIS

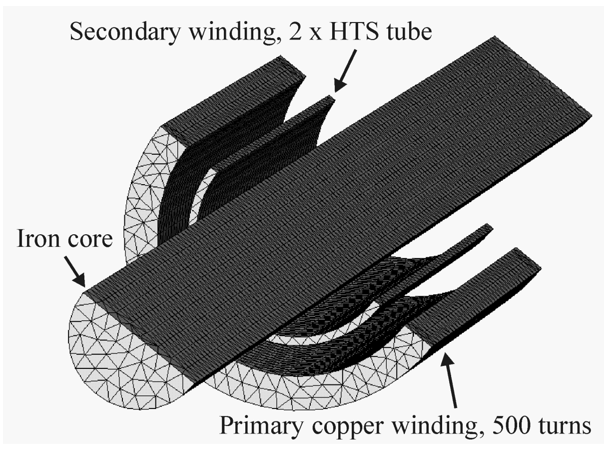

Figure 3: Cross-section of numerical model's of SFCL

After calculations of several models the SFCL structure shown in Figure 2 have been chosen as the most appropriate to assure above conditions. Limiter consists of iron core, primary copper winding and cryostat where the secondary winding is located. Two high-temperature superconducting tubes cooled down in liquid nitrogen act as secondary shorted winding. The magnetic field distribution is very important to calculate the impedance of the SFCL in resistive state because the limiter operates at the core saturation state and magnetic flux occur in surrounding area.

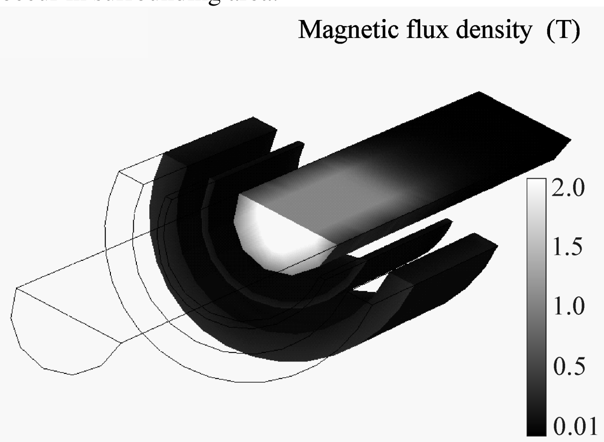

Figure 4: Magnetic field distribution of SFCL with an open core during the fault

Histograms made on surface, which cross the limiter along it's symmetry axis present the spatial magnetic flux density.

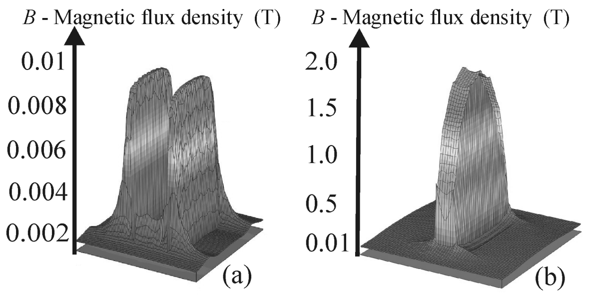

Figure 5: Histograms of magnetic flux density in (a) superconducting and (b) resistive state of SFCL

In superconducting state core is shielded by HTS tubes and the magnetic flux density has the largest value between the windings. After transition to the resistive state magnetic flux penetrate the core causing increase of limiter impedance, which limit the fault current, Janowski and Kozak (3). Obtained *V-I* characteristic shown in Figure 5 assures expected current limitation. The voltage on the limiter in superconducting state U_{sup} = 3.1 V, which is about 1.35% U_N. Investigated SFCL has low losses during normal operation. Superconducting Fault Current limiter with an open core has easily adjustable characteristic by core length extension.

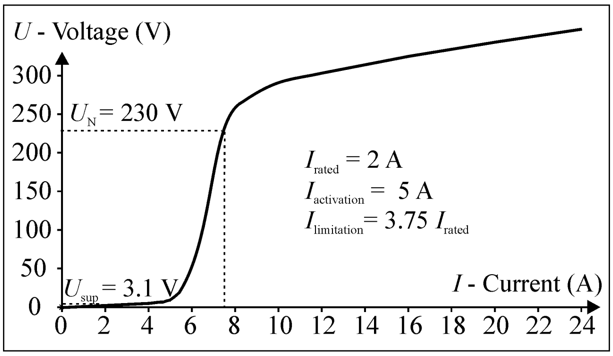

Figure 6: Obtained *V-I* characteristic of SFCL model

Analysis results prove the proper choice of FEM method for solving this problem, because limiter operates at core saturation state. Therefore calculations using analytical or empirical method where infinity magnetic permeability of the core is assumed can significantly differ from real value. It comes from the breakdown of the magnetic field line on border of environment

$$\mu_1 \, tg\alpha_1 = \mu_2 \, tg\alpha_2 \quad (1)$$

where:

α_1, α_2 – angles between magnetic flux lines and the boundary surface

μ_1, μ_2 – environments magnetic permeability

In this case the numerical analysis was irrevocable because of complex dependence of magnetic permeability on magnetic flux density.

CONCLUSION

Results of numerical analysis of superconducting inductive fault current limiter with an open core based on the FEM have been described. The *V-I* characteristics of SFCLs obtained by numerical analysis fulfil the utility network expectations to a great extend. The numerical analysis of magnetic field is very helpful in designing of inductive Superconducting Fault Current Limiter and obtaining the *V-I* characteristic of this device.

REFERENCES

1. Waynet J. A., H. J Boeing H. J., Mielke C. H., Willis J. O. Burley, B. L., 2003.IEEE Trans. Appl. Supercond.,13, 1984-1987

2. Bitterman A., 1999.Superconductor & Cryoelectronics Magazine, 19-23.

3. Janowski T., Kozak J., 2003.XXVI IC-SPETO,1, 119-122