Design and Testing of 230 V Inductive Type of Superconducting Fault Current Limiter With an Open Core

Janusz Kozak, Tadeusz Janowski, Sławomir Kozak, Henryk Malinowski, Grzegorz Wojtasiewicz, Beata Kondratowicz-Kucewicz

***Abstract*—A single-phase, 230 V Superconducting Fault Current Limiter using two Bi2223 HTS tubes with the total critical current 2.5 kA situated in vacuum insulated cryostat has been described in this paper. We designed and manufactured the inductive SFCL with an open core as core shielded type acquired the optimal design parameters by using Finite Element Method. We tested the limiter performances at liquid nitrogen temperature 77 K. We proved that the performances of properly designed limiter with open core could be comparable to the limiter with closed core.**

***Index Terms*—HTS tube, open core, superconducting fault current limiter**

I. Introduction

The Superconducting Fault Current Limiters use the natural ability of rapid shifting from the normal to the resistive state due to their critical current value exciding. There are two main types of SFCLs being used for current limitation. One is the inductive or shielded core type and the other the resistive type [1]. The resistive type of SFCL is based on double non-inductive spirals [2] or superconducting bars [3]. Fault current flow directly across the superconducting element causing fast conductive heating. In inductive limiter ceramic superconducting tube acts as shorted secondary winding. Primary winding causes permanent ohmic and inductive losses because is conventionally made of copper wire. Below the activation current limiter operates as current transformer, after fault acts as choke. The inductive does not need the current leads. Nearly no impedance during normal operation, quick and automatic recovery makes this limiter very attractive in power systems.

Manuscript received October 5, 2004. This work was supported by The State Committee for Scientific Research (KBN) under grant: 4 T10A 071 25.
J. Kozak, S. Kozak, H. Malinowski, G. Wojtasiewicz, B. Kondratowicz-Kucewicz are with the Electrotechnical Institute in Warsaw, Laboratory of Superconducting Technology in Lublin, Nadbystrzycka 38A, 20-618 Lublin, Poland (e-mail: januszk@asppect.pl, slawko@eltecol.pol.lublin.pl, henmal@eltecol.pol.lublin.pl, grzegorzw@eltecol.pol.lublin.pl, beatak@weber.pol.lublin.pl)

T. Janowski is with the Lublin University of Technology, Nadbystrzycka 38A, 20-618 Lublin, Poland (phone: +48 81 5381289, fax: +48 81 5253694: (e-mail: tadeuszj@eltecol.pol.lublin.pl).

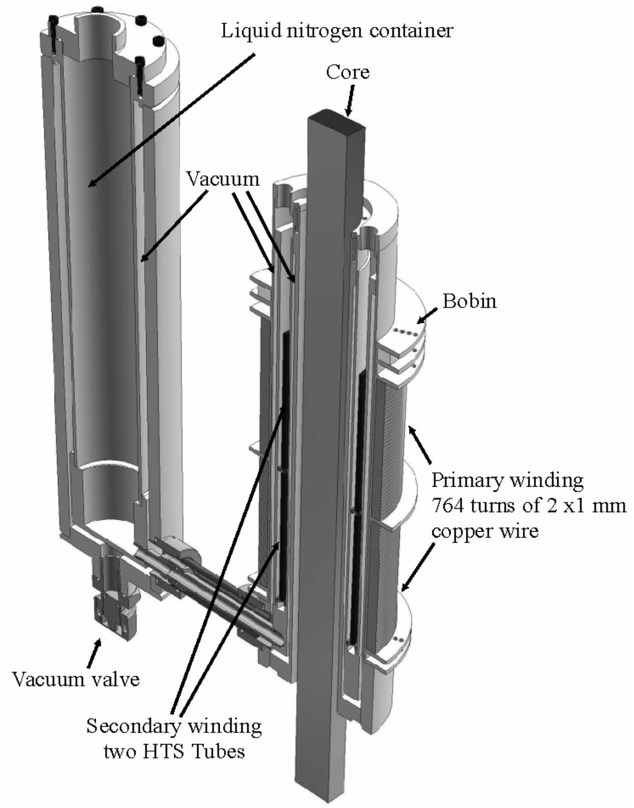

Fig. 1. Structure of investigated inductive SFCL.

II. Principle of Operation

During the normal operation the resistance of superconducting secondary winding is equal zero, and the magnetic flux does not penetrate the iron core because the superconducting tube acts as magnetic screen. Resistance of primary winding and the leakage inductance determine the impedance of the limiter [4]. The voltage on the limiter in superconducting state is very low. When the fault occur the increasing current exceed the critical value of the superconducting element then resistance of secondary winding is reflected into the circuit, and the magnetic flux penetrates the iron core increasing the impedance of limiter. Rapid increase of impedance in the circuit limits the fault current.

TABLE I
SFCL PARAMETERS

Primary winding			
Number of turns		764	turns
Wire diameter		2 x 1.0	mm
Height		200	mm
Inner diameter		86	mm
Outer diameter		102	mm
Secondary winding			
HTS tubes		2 x CST 60/100.2	BSCCO 2223
I_c		2500	A
T_c		108	K
Height		200	mm
Inner diameter		59	mm
Outer diameter		64	mm
Magnetic cores			
Open core R700-30			
Dimension (W x D x H)		30 x 30 x 700	mm
Open core R600-30			
Dimension (W x D x H)		30 x 30 x 600	mm
Open core R500-30			
Dimension (W x D x H)		30 x 30 x 500	mm
Closed core RZC 70/450 -30			
Window (W x H)		70 x 450	mm
Cross - section		30 x 30	mm
SFCL			
U_n		2.19	V
I_n		1.3	A
$I_{activation}$		3.27	A
R700-30	$I_{limitation}$	9.2	A
	I_{peak}	34	A
R600-30	$I_{limitation}$	9.3	A
	I_{peak}	35	A
R500-30	$I_{limitation}$	9.4	A
	I_{peak}	36	A
RZC 70/450-30	$I_{limitation}$	9.0	A
	I_{peak}	32	A
$U_{limitation}$		230	V
Cryostat			
Material		ERTALON 6SA	
Insulator		vacuum	
Capacity of LN_2 container		0.8	dm^3

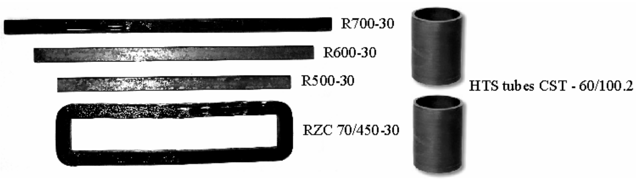

Fig. 2. Cores and HTS tubes used in experiment [5].

The voltage of primary winding in resistive state should have appropriate value for the expected current limitation. The voltage on the limiter depends mainly on the structure of the limiter, number of primary winding turns, distance between the windings and size of the core. A very fast operation of the SFCL enables first current peak limitation which is the most dangerous for the system.

According to the expectations of SFCL parameters the peak current $I_{peak} < 10\ I_{rated}$ and $I_{activation} = 2.5\ I_{rated}$. In succeeding periods the current value should not exceed the $I_{limitation} = 3\ I_{rated}$ [6].

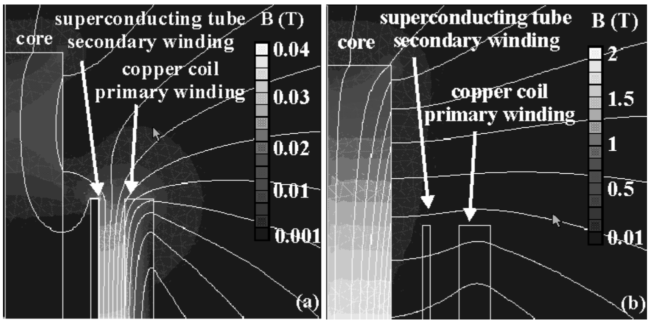

Fig. 3. (a) Magnetic field distribution in superconducting state, (b) magnetic field distribution in resistive state.

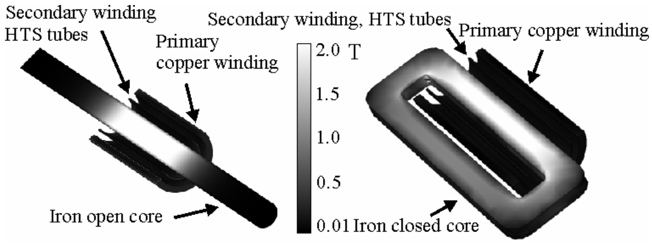

Fig. 4. Comparison of magnetic field distribution of SFCL with open and closed core.

III. DESIGN

The inductive SFCLs consist of two coaxial windings and magnetic core. Size of the core is comparable with the one of a transformer. Inductive SFCLs can be divided into limiters with closed and open core. The primary winding made of copper wire is connected in series to the circuit. The secondary winding (HTS tube) is cooled by liquid nitrogen. The bobbin and the cryostat are made of plastic ERTALON 6 SA to avoid eddy currents. Fig. 1 shows the cross-section of vacuum insulated cryostat of investigated limiter with liquid nitrogen container. For the fast calculation of limiter parameters such as dimensions of primary winding and core computer program was written. Program calculates the optimal wire diameter of primary winding based on HTS tube parameters and number of desired turns to achieve the minimal impedance of limiter in superconducting state. The low impedance during normal operation is significant regarding voltage drop on limiter and heat losses. Based on *B-H* curve and dimensions of the core the *V-I* characteristic is also calculated. The inductive SFCL was designed to work at 230 V. Critical current of secondary winding I_c = 2.5 kA. Primary winding 764 turns consists of two parts 382 turns each, winded 2 x 1mm each part copper wire to achieve lower resistance. Liquid nitrogen container has capacity 0.8 dm^3. For the experiment we used cores made of grain oriented strips ET 51-27, thickness = 0.27 mm. We used three open cores and one closed core.

IV. MAGNETIC FIELD DISTRIBUTION

After the pre-calculations using our program (SFCL Calculator) the model in software based on FEM was analysed.

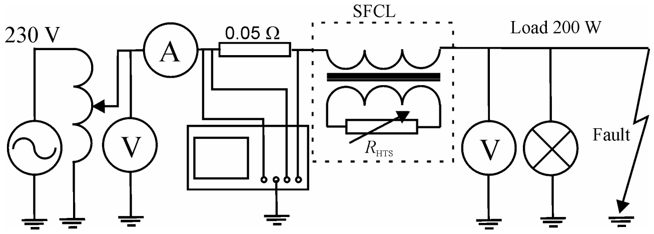

Fig. 5. Experimental circuit.

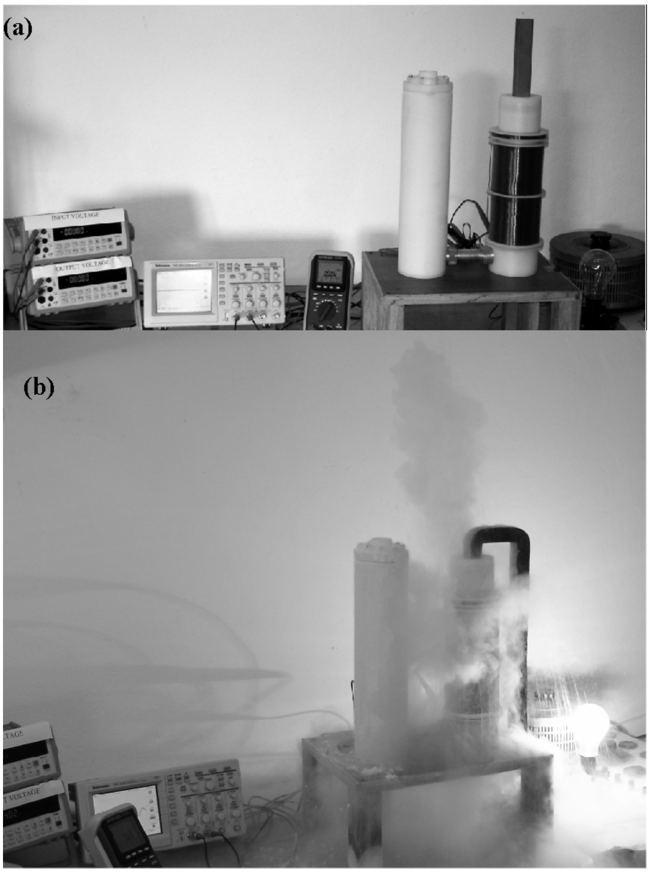

Fig. 6. (a) Experimental circuit for the SFCL investigation, (b) nitrogen evaporation after fault (fault duration 1s).

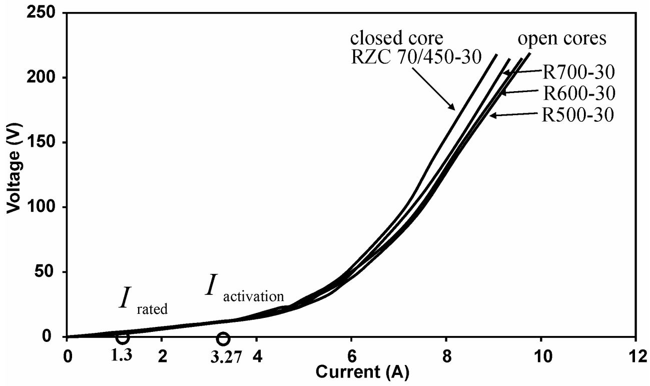

Fig. 7. Comparison of *V-I* characteristic of SFCL with closed and open cores.

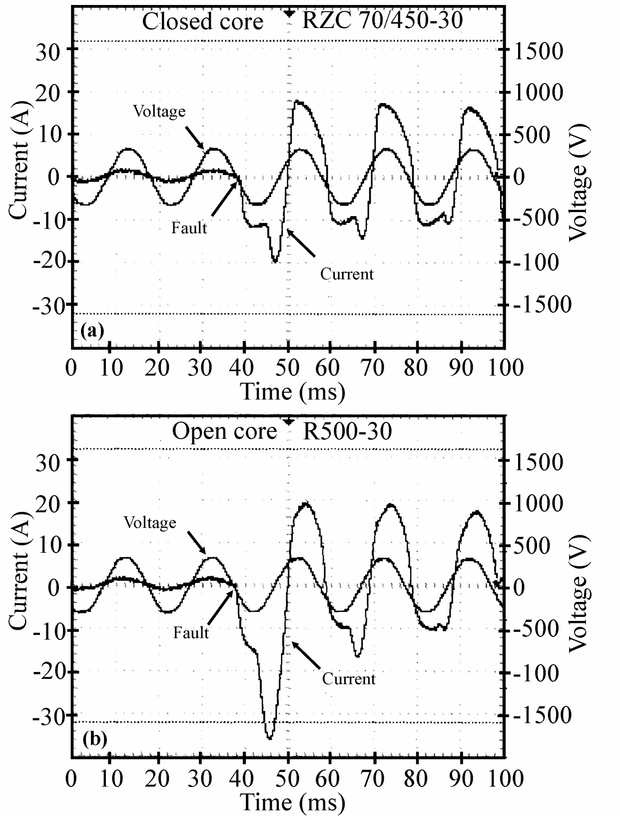

Fig. 8. Voltage and current courses during fault (a) closed core (b) open core. Fault - 0.5 ms after zero crossing by voltage course.

In superconducting state the value of magnetic flux density is about 0.04 T due to shielding effect of high temperature superconducting tube Fig. 3(a). When the induced current in secondary winding exceeds its critical value the flux penetrates iron core and magnetic flux density rapidly grows to 2 T Fig. 3(a). Fig. 4 shows differences between magnetic field distributions in SFCL with open and closed core which has significant influence on *V-I* characteristic and limiting capability of the superconducting fault current limiter.

V. Experimental Results

In experimental circuit shown in Fig. 5 the Superconducting Fault Current Limiter was investigated. Fig. 6(a) shows the measurements equipment and inductive superconducting fault current limiter with open core. The nitrogen evaporation after fault is shown in Fig. 6(b).

The distance between the windings has considerable influence on voltage on the SFCL. The distance is determined mainly by the thickness of the cryostat's walls, (Fig. 1). In our model the distance between primary and secondary winding is 11 mm. The core cross-section is crucial for the obtaining steep *V-I* characteristic, the larger cross-section the higher voltage on the SFCL in resistive state. The above *V-I* characteristics (Fig. 7) prove that SFCL with open core assures comparable operation to the limiter with closed core. This model has been designed to operate at mains voltage 230 V and activation current 3.27 A. The first current pulse, the most dangerous for the system has the largest value due to aperiodic component of short current. The small peak on the first half-period is caused by the core transition to the saturation state.

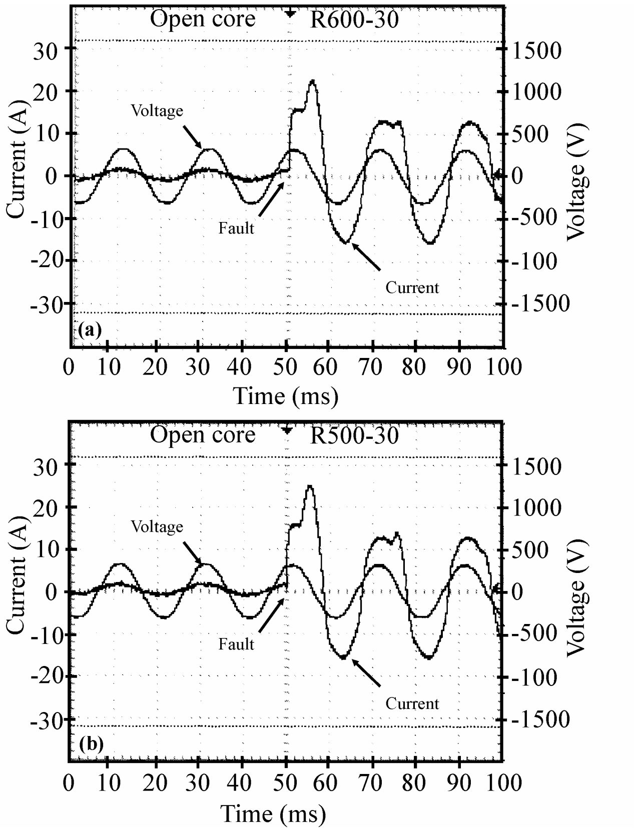

Fig.9. Voltage and current courses during fault (a) open core R600-30 (b) open core R500-30. Fault - 4 ms after zero crossing by voltage course.

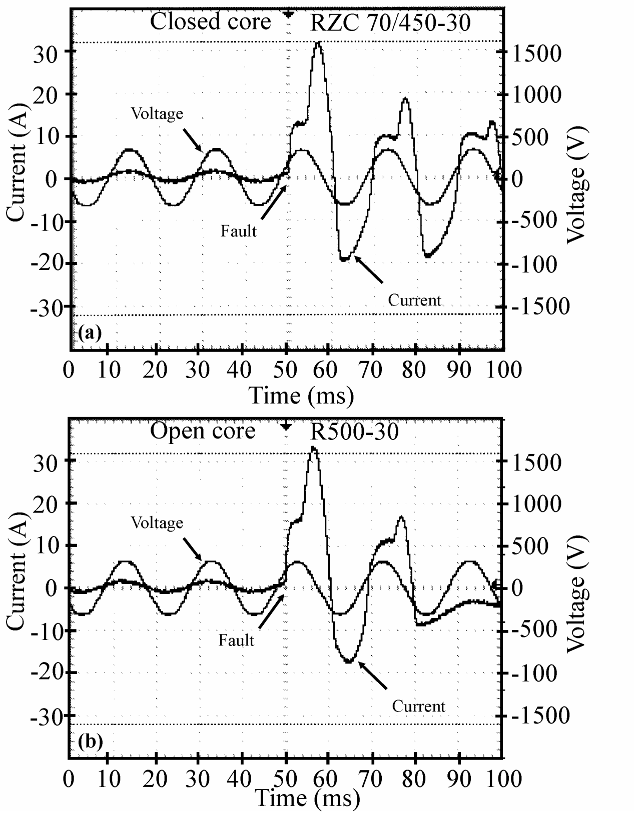

Fig.10. Voltage and current courses during fault (a) closed core RZC 70/450-30 (b) open core R500-30. Fault - 2 ms after zero crossing by voltage course.

The core cross – section should assure that this peak does not exceed ten times rated current. Geometrical dimensions of winding are important in normal operation to achieve as low voltage on limiter as possible. During experiment we used incandescent lamp (200 W) as load. The current in superconducting state was $I = 0.89$ A at 230 V supply voltage. Voltage drop on SFCL in superconducting state was $U_{SFCL} = 1.5$ V. During the fault core plays the key role, its shape, cross – section and material is significant for proper fault current limitation. The comparison of SFCL with open and closed core is shown in Fig. 7. Experimental results prove that it is possible to build the open core SFCL with acceptable parameters but they will never be as good as limiters with closed core Limiting capability of open core SFCL can be improved by extension of the core height. Fig. 8 shows voltage and current courses in circuit during the fault. Comparing the value of peak current of the limiter with closed core Fig. 8(a) and open core Fig. 8(b) which occurs at the same phase of voltage course the closed core design has better performance. Also considering two current courses shown in Fig. 9 the I_{peak} is lower when the open core is higher. Fig.10 shows current waveforms in circuit with SFCL with closed core and open core in different phase than in Fig.8. The small dominance of SFCL with closed core is also noticeable. On the basis of conducted experiments we found that to fulfill power network expectations [6] the closed core design is more promising due to the steeper *V-I* characteristic and better first peak current limitation. The residual flux density has significant influence on the peak current value therefore it is essential to design the magnetic circuit properly to avoid saturation state. In presented model value of the first peak of fault current generated at the identical phase was strongly dependable on the remanence.

VI. Conclusions

The above described experiment supported by computer calculations indicates the meaning of core influence on SFCL operations. The experiments reveal that the limiter with closed core has better parameters then with the open core. However, it is practicable to build open core SFCL with satisfactory parameters provided that slender construction of this device is assured.

References

[1] R. Petranovic, A. M Miri, "Modeling of the Transient Behavior of a Resistive Type high T_c Fault Current Limiter", *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, June 2003, pp.2036-2039.
[2] Nexans. Available: www.nexans.de
[3] Advanced Ceramics. Available: www.aclstafford.co.uk
[4] S. Kozak, T. Janowski, "Physical and Numerical Models of Superconducting Fault Current Limiters". *IEEE Trans. Appl. Supercond.*, vol.13, no. 2, June 2003, pp.2068-2071.
[5] Can Superconductors. Available: www.can.cz
[6] J. N Nielsen, J. J Ostergaard, "Applications of HTS Fault Current Limiters in the Danish Utility Network". Available: www.defu.dk/indhold/elt/superled/1_56.pdf