Properties Comparison of Superconducting Fault Current Limiters with Closed and Open Core

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

***Abstract*— Recently, the high-Tc superconducting fault current limiter (SFCL) has been studied worldwide to be classified into a resistive, inductive and hybrid type. HTSFCL of an inductive type seems to be the most prospective due to the simple design (construction) of the secondary superconducting winding in the form of the ceramic type made of BSCCO and for the reduction of current leads. In the inductive type of SFCL, ferromagnetic cores for magnetic flux are applied, however open cores are also taken into consideration that make the construction more simple. The results of experimental and computational investigation of the inductive SFCL parameters have been presented in the paper.**

***Index Terms*— High-Tc SFCL, Superconducting tube, Iron core**

I. Introduction

SUPERCINDUCTING fault current limiters (SFCL) are one of the most promising devices for transmission and distribution of electrical energy due to low nominal losses, rapid reaction times to fault currents and an automatic response without external trigger mechanisms.

This paper describes the physical models of the inductive-type screened iron core limiter that has been performed and investigated in the Cryoelectromagnet Laboratory and Technical University of Lublin. The aim of the work has been to carry out static impedance test of several types of inductive SFCL models in order to consider their current limitation conditions. The described models differ from each other on primary windings, superconducting tubes and the type of the magnetic circuit - open and closed.

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II. Inductive SFCL Operation

Inductive superconducting fault current limiter has been designed as the transformer with shorted secondary winding in the form of HTS tube [1]. Under normal operation such winding is in superconducting state and it acts as the magnetic shield of the core. Magnetic induction in axial cross-section in superconducting state of the limiter is shown in Fig. 1. Under fault, magnetically induced shielding current exceeds the critical value of superconducting tube and the transition to the resistive state will occur. This allows magnetic field to penetrate the iron core that will proceed to increase of the limiter's impedance. Magnetic induction in the resistive state of the limiter is shown in Fig. 2 [1], [2].

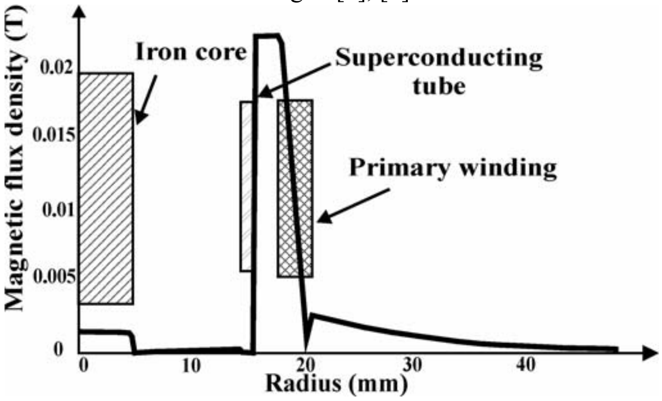

Fig. 1. Magnetic induction in axial cross-section in superconducting state of the limiter.

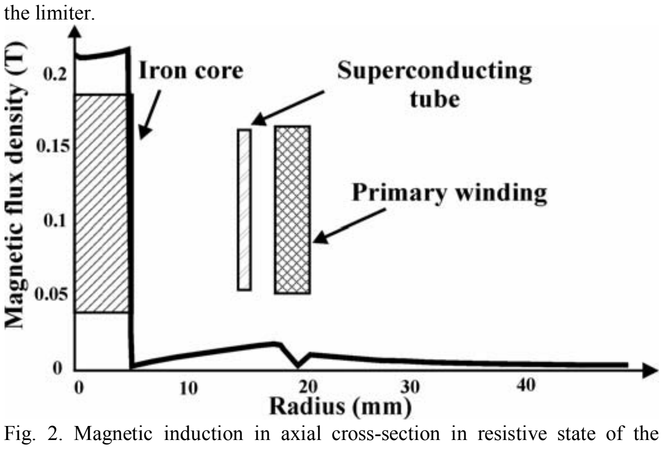

Fig. 2. Magnetic induction in axial cross-section in resistive state of the limiter.

The operation principle of the inductive SFCL with open iron core is the same as SFCL with closed iron core. For load current values lower than critical current value of superconducting secondary winding the limiter operates as the current transformer whereas it behaves like a voltage transformer in case the current exceeds the value of critical current [3].

Fig. 3 shows the experimental system used in the investigation.

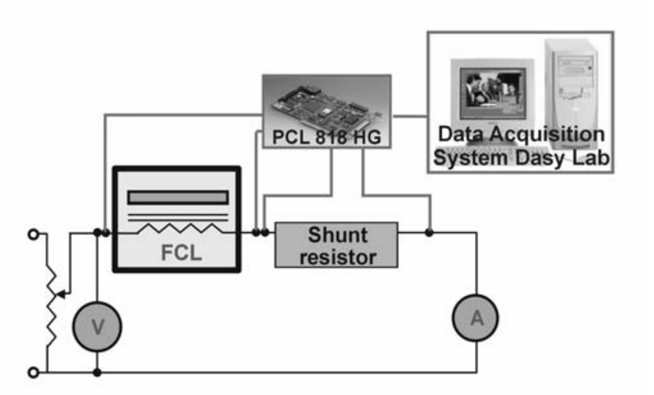

Fig. 3. The experimental circuit diagram.

III. The SFCL Model with Closed Core and 112A HTS Tube

The constructed model consists of the closed iron core, normal conducting primary copper winding and a secondary winding of superconducting material Bi2223. The SFCL model is presented in Fig. 4. The parameters of the model are shown in Table I.

TABLE I
PARAMETERS OF MODEL

Primary Cu winding			
1	Diameter of conductor	0.7 mm	
	Number of turns	112	
	Height of winding	14 mm	
	Inner diameter of winding	26 mm	
	Limiting current	1 A	
2	Diameter of conductor	0.7 mm	
	Number of turns	448	
	Height of winding	14 mm	
	Inner diameter of winding	26 mm	
	Limiting current	0.25 A	
Secondary SC winding (BSCCO 2223 tube)			
Critical temperature		108 K	
Inner diameter		15 mm	
Height		15 mm	
Wall thickness (approx.)		1.5 mm	
I_c in tangential direction (77 K)		112 A	
Magnetic core (silicon steel plates)			
Core type		plated	tape-wound
Cross – section		10 mm x 10 mm	10 mm x10 mm
Height of core limb		45 mm	49 mm
Width of core window		40 mm	11 mm

The measurements were carried out for models with various number of primary winding turns and different magnetic cores. *V-I* characteristics of this model are shown in Fig. 5 and Fig. 6 [4].

The charts presented above show that SFCL with tape-wound closed core for both 112 and 448 turns of primary winding is more efficient than the limiter with plated closed core.

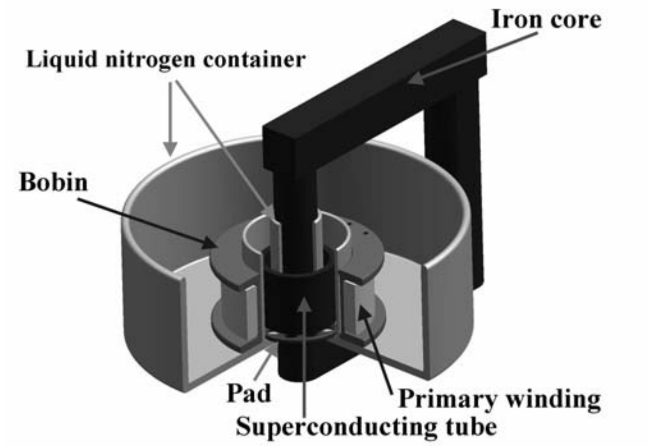

Fig. 4. The inductive SFCL model view.

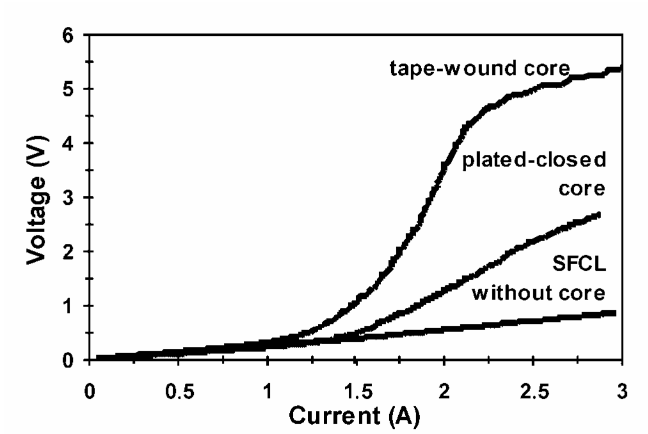

Fig. 5. *V-I* characteristic of SFCL model with 112 turns of primary winding.

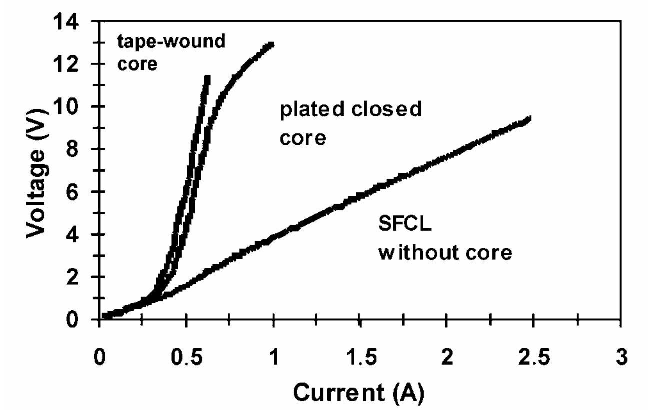

Fig. 6. *V-I* characteristic of SFCL model with 448 turns of primary winding.

IV. THE SFCL MODEL WITH OPEN CORE AND 112A HTS TUBE

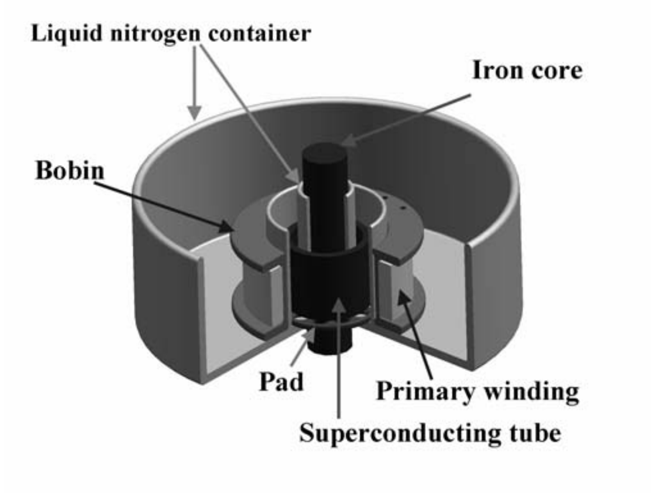

Fig.7. View of the model of SFCL with open core.

Superconducting fault current limiter with open core has been conventional type of inductive limiter. The design of the limiter shown in Fig. 7 has plenty of advantages: simple structure, light weight, easily removed superconducting tube. Magnetic field generated in large space outside the limiter seems to be one of the disadvantages which leads to the decrease of the quenching time and it can disturb the operation of nearby devices. The parameters of the model are shown in Table II.

The measurements were taken for the models with various number of primary winding turns and different open magnetic cores.

TABLE II
PARAMETERS OF THE MODEL

<table>
<tr><th colspan="6">Primary Cu winding</th></tr>
<tr><td rowspan="5">1</td><td colspan="3">Diameter of conductor</td><td colspan="2">0.7 mm</td></tr>
<tr><td colspan="3">Number of turns</td><td colspan="2">112</td></tr>
<tr><td colspan="3">Height of winding</td><td colspan="2">14 mm</td></tr>
<tr><td colspan="3">Inner diameter of winding</td><td colspan="2">26 mm</td></tr>
<tr><td colspan="3">Limiting current</td><td colspan="2">1 A</td></tr>
<tr><td rowspan="5">2</td><td colspan="3">Diameter of conductor</td><td colspan="2">0.7 mm</td></tr>
<tr><td colspan="3">Number of turns</td><td colspan="2">448</td></tr>
<tr><td colspan="3">Height of winding</td><td colspan="2">14 mm</td></tr>
<tr><td colspan="3">Inner diameter of winding</td><td colspan="2">26 mm</td></tr>
<tr><td colspan="3">Limiting current</td><td colspan="2">0.25 A</td></tr>
<tr><th colspan="6">Secondary SC winding (BSCCO 2223 tube)</th></tr>
<tr><td colspan="4">Critical temperature</td><td colspan="2">108 K</td></tr>
<tr><td colspan="4">Inner diameter</td><td colspan="2">15 mm</td></tr>
<tr><td colspan="4">Height</td><td colspan="2">15 mm</td></tr>
<tr><td colspan="4">Wall thickness (approx.)</td><td colspan="2">1.5 mm</td></tr>
<tr><td colspan="4">I_c in tangential direction (77 K)</td><td colspan="2">112 A</td></tr>
<tr><th colspan="6">Magnetic core (silicon steel plates)</th></tr>
<tr><td colspan="2">Cross – section</td><td>5 mm x 5 mm</td><td>6 mm x 6 mm</td><td>8 mm x 8 mm</td><td>6 mm x 6 mm</td></tr>
<tr><td colspan="2">Height of core limb</td><td>35 mm</td><td>35 mm</td><td>35 mm</td><td>41 mm</td></tr>
</table>

The results of the *V-I* measurements are shown in Fig. 8 and Fig. 9.

For the presented case the influence of open magnetic core is more significant for the primary winding with higher number of turns whereas the core's dimension as well as its length do not have considerable impact on current-voltage characteristics.

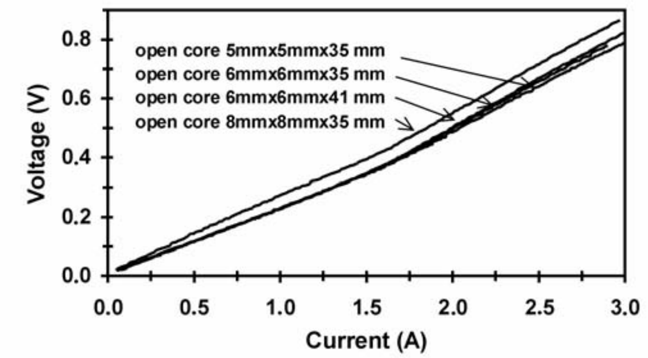

Fig. 8. *V-I* Characteristic of SFCL model with 112 turns of primary winding and 112 A I_c.

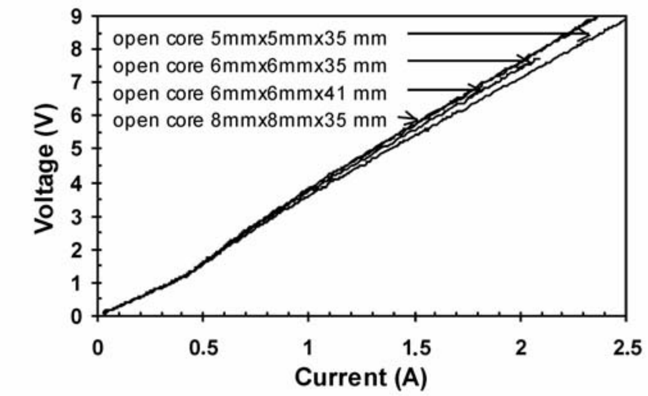

Fig. 9. *V-I* Characteristic of SFCL model with 448 turns of primary winding and 112 A I_c.

V. SFCL MODEL WITH OPEN CORE AND 1210A HTS TUBE

SFCL model with open core and 1210A HTS tube is presented in Fig. 10. Table III shows the parameters of this model. The results of the measurements are shown in Fig. 11. The application of long HTS tube and long open magnetic core significantly influences the efficiency of the limiter. The increase of the number of primary winding turns leads to the higher slope of voltage-current characteristics and therefore the limiter operates more rapidly.

VI. THE INFLUENCE OF CORE TYPE ON THE LIMITING FACTOR

A limiting factor has been introduced by the authors to estimate the current limitation caused by the investigated superconducting limiter.

This factor has been defined as the relation of the voltage at the limiter to the voltage of the ideal shielding (voltage of the limiter without the core).

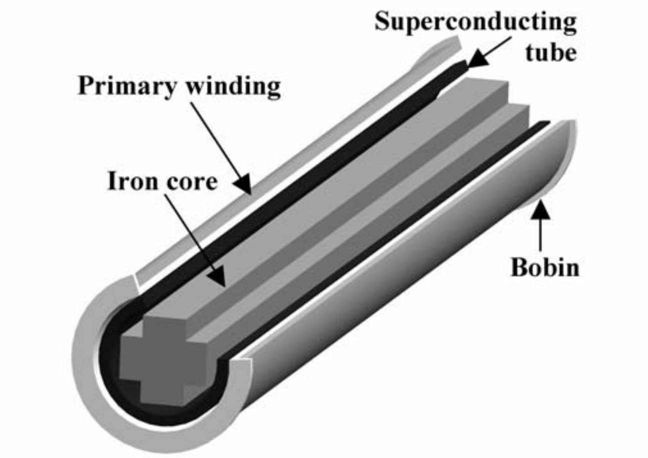

Fig.10. The SFCL model with open core.

TABLE III
PARAMETERS OF MODEL

Primary Cu winding	
Diameter of conductor	0.45 mm
Number of turns	1200
Height of winding	170 mm
Inner diameter of winding	20 mm
Limiting current	1 A
Secondary SC winding (BSCCO 2223 tube)	
Critical temperature	108 K
Inner diameter	18 mm
Height	160 mm
Wall thickness (approx.)	2 mm
Critical current in tangential direction (77 K)	1210 A
Magnetic core (silicon steel plates)	
Cross – section	110 mm^2
Height of core limb	170 mm

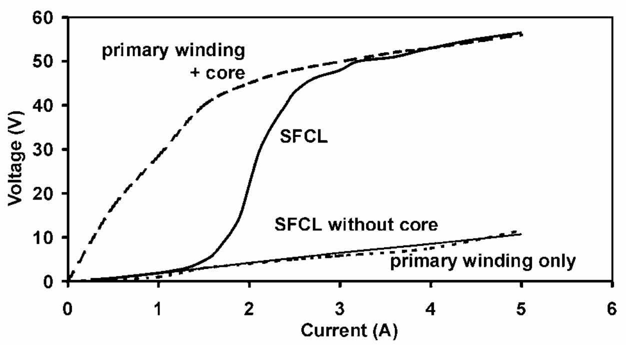

Fig. 11. *V-I* characteristic of SFCL model with open core 1210 A HTS tube.

Fig. 13 shows the limiting factor's changes versus current *I* for the limiter with two types of the core: plated closed core and tape-wound core. The figure shows that SFCL with tape-wound core is more efficient than SFCL with plated closed core at the same current values.

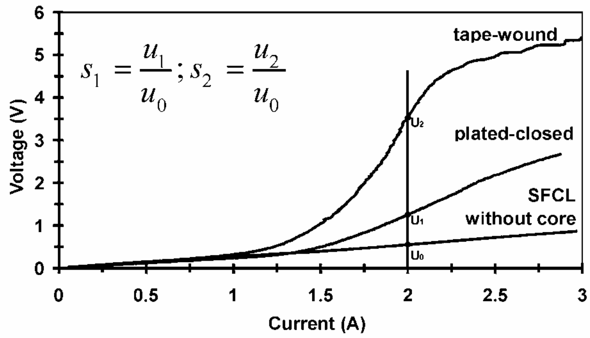

Fig.12. Evaluation of limiting factor S_n for SFCL model.

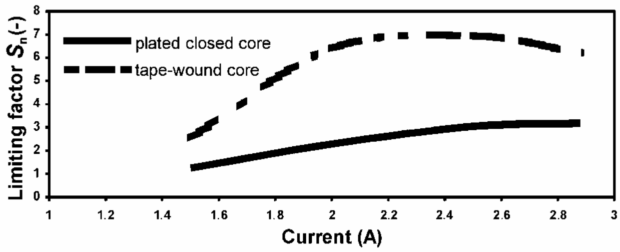

Fig. 13. Limiting factor's changes due to current *I* for two types of core limiters.

VII CONCLUSIONS

1) The parameters of tape-wound core are better than the parameters of the plated core.
2) The increase of number of the primary winding turns causes the growth of the limiter's impedance.
3) Slenderness of the limiter construction highly influences its efficiency in case of the limiter with the open core.
4) The more slender construction of the limiter, the more significant the current limitation effect.
5) The dimensions and the type of iron cores determine inclination of static characteristic to a great extent and the efficiency of fault current limiting.

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