Tests results and analysis of inductive superconducting fault current limiter with Bi-2223 tube and HTS tape as secondary winding

J Kozak¹, ², T Janowski³, S Kozak¹, G Wojtasiewicz¹ and B Glowacki⁴
¹Electrotechnical Institute in Warsaw, Nadbystrzycka 38A, 20-618 Lublin, Poland
²CERN, Accelerator Technology Department, Geneva, Switzerland
³Lublin University of Technology, Nadbystrzycka 38A, 20-618 Lublin, Poland
⁴University of Cambridge, Pembroke Street, CB23QZ, United Kingdom
E-mail: januszk@asppect.pl

Abstract. The Superconducting Fault Current Limiters are very attractive devices for the electrical power network. The performance comparison of inductive SFCL with three different secondary windings are presented in this paper. As secondary windings we used Bi-2223 tube, HTS tape and HTS tape parallel rings. We proved that the limiting capabilities of the SFCL with different windings are comparable, and the windings made of HTS tape are less expensive and more mechanically stable then HTS tubes. We proposed two method of implementation of shorted secondary winding. The experimental results show that HTS tube can be successfully substitute by cheaper shorted winding made of HTS tape.

1. Introduction
Fault currents result from power surges caused by lightning and short circuits. These surges can cause serious damage to grid equipment and cause circuit breakers to shut down the affected parts of the system. Serious faults can generate current surges of more than 30 times the normal operating current can cause current flow to arc uncontrollably within the breaker, hindering its effectiveness and even destroying it and other utility or customer equipment [1]. A Fault Current Limiter is a device placed in electric network to limit the peak current in the event of fault. When the fault occur the increasing current exceed the critical value of the HTS element causing a rapid increase of impedance in the circuit, which limit the value of the fault current [2].

2. Inductive SFCL-principle of operation
Inductive superconducting fault current limiter, SFCL, consists of two coaxial windings and magnetic core. The primary winding connected in series to the circuit is conventionally made of copper wire the secondary is made of superconductor. During the normal conditions, Figure 1a, SFCL is almost invisible for the circuit until the current value is below the critical current of superconductor. 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. During the normal operation resistance of primary winding and the leakage inductance determines the impedance of the limiter. The voltage of the limiter in superconducting state is very low. When the fault occurs, Figure
1b, the increasing current exceed the critical value of the superconducting element then resistance of secondary superconducting winding is reflected into the circuit, and as a consequence the magnetic flux penetrates the iron core increasing the impedance of limiter. Rapid increase of impedance in the circuit limits the value of the fault current [3].

Figure 1. Principle of operation of SFCL: a) Iron core screened by HTS tube – invisible for magnetic flux in superconducting state; b) Magnetic flux penetrates iron core in resistive state.

3. Concept of SFCL

3.1. Primary winding
Primary winding made of copper wire is directly connected to the protected circuit therefore an increase of number of turns leads to increase the resistance of the limiter which induced permanent ohmic losses. These losses could be reduced by using larger cross - section of wire but it also increases leakage reactance. The height of the primary coil is equal the secondary coil \((h = 100 \text{ mm})\). The inner diameter was defined by the cryostat dimensions \((d_{\text{int}} = 82 \text{ mm})\). Number of turns in presented model was calculated on the basis of the core parameters to operate in the utility grid \(U = 230 \text{ V}\) and is equal \(n_1 = 764\) turns.

3.2. Iron core
The iron core is not magnetized in normal operation, but the core cross – section is determined by the HTS tube inner diameter and should be as large as possible. We used standard transformer core made of silicon sheet steel. The mass of the core was about 4 kg.

Figure 2. SFCL elements: a) Primary winding; b) Iron core; c) HTS tube CST 60-100.2 [4]; d) 10 turns of AMSC Bi-2223 Multifilamentary Conductor; e) 10 rings made of AMSC Bi-2223 High Strength Wire [5].

3.3. Superconducting secondary windings
We used three types of secondary windings made of two kinds of superconducting tapes and HTS tube. We used 22 turns and rings of the AMSC Bi-2223 multifilamentary conductor \((I_C = 60 \text{ A})\) and 10 turns and rings of AMSC Bi-2223 high strength wire \((I_C = 125 \text{ A})\), Figure 2d.e, to obtain comparable critical current as for the HTS tube CST 60-100.2, Figure 2c. The secondary windings were winded on
non conducting bobbins which has the same dimensions as the superconducting tube (external
diameter $d_{ext} = 64$ mm and height $h = 100$ mm). To connect the HTS tapes we used soft solder and the
overlap in each ring was about 10 mm. Due to the small bending radius and not identical soldering
joints the total critical current was slightly different for each winding. The described fault current
limiter was cooled by liquid nitrogen $T = 77$ K.

4. Nominal current
The critical current of HTS tube was $I_C = 1250$ A, because of that for the maximum operation current
we choose $I_{2max} = 1100$ A to allow some overload capacity. The nominal current of our SFCL thus was
$I_N = I_{2max} \cdot \frac{1}{\sqrt{2}} = 1$ A. Below $I_N$ the impedance of inductive SFCL is mainly given by resistance
of primary coil and leakage inductance [6].

5. Test and discussion
As a protected circuit we used common electric network 230 V, as load the incandescent bulb
(200 W). The test shorts were performed by the relay controlled by electronics, Figure 3. The SFCL
controller was designed and manufactured especially for this experiment. Zero crossing detector with
delay and fault time control for SFCL activation was triggered manually. The moment and the
duration of the fault could be easily adjustable. During experiments we used several of fault times. The
secondary winding was immersed in liquid nitrogen and after faults lasting less than 60 ms the limiter
was able to limit the next fault after several milliseconds. The fault duration longer than few periods
cau sed evaporating large quantities of coolant. Evaporating nitrogen reduced the thermal exchanges to
a great extend and induced current increase the temperature of HTS tube rapidly. About 100 tests were
performed for each winding. The limitation was always smooth without large overvoltages.

![Figure 3. Schematic of experimental circuit.](image)

![Figure 4. a) V-I characteristics comparison of SFCL with different secondary windings b) Average
values of $I_{peak}/I_{rated}$ for all tested secondary windings.](image)
Figure 4a shows the V-I characteristic comparison. The characteristic of SFCL with winding made of 10 turns of AMSC Bi-2223 High Strength Wire has shown the best performance. Also the limiting of the first current peak is the most significant in both cases when the voltage cross zero (0 ms) and when the voltage achieves maximal value (5 ms). Figure 4b shows average values of \( I_{\text{peak}} / I_{\text{rated}} \) for all tested secondary windings.

![Figure 4b](image_url)

Figure 4b shows average values of \( I_{\text{peak}} / I_{\text{rated}} \) for all tested secondary windings.

Figure 5 shows comparison of tested superconducting windings. Fault has been triggered in two different moments exactly when the voltage course cross the zero or 5 ms after. The highest and most dangerous current peak appears when fault is triggered in the moment when the voltage cross the zero. The expected ratio \( I_{\text{peak}} / I_{\text{rated}} < 10 \) was archived only in case with 5 ms delay. However the best limiting performance has been achieved for the 10 turns of AMSC Bi-2223 High Strength Wire. The both secondary windings made as a shorted rings are considerably worst than windings made as normal turns. The limiting capability of SFCL with the winding made of 10 turns of AMSC Bi-2223 High Strength Wire presented on Figure 5 c, d is significantly better than with the superconducting tube (Figure 5 a, b).

6. Conclusions
A SFCL model based on the shielded iron core concept has been built and tested. The single-phase device with a rated power of 230 VA utilizes one Bi-2223 HTS tube or a few turns or rings made of HTS tape. The advantages and disadvantages of three types of secondary windings has been presented in this paper. The tests results show that short winding made of HTS tape, as well as HTS tube, can be successfully used for the realization of inductive SFCL secondary winding.

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