

INFLUENCE OF HEATING OF INDUCTIVE SUPERCONDUCTING FAULT CURRENT LIMITER WINDINGS ON CURRENT LIMITING PERFORMANCE

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Abstract. One of the types of superconducting fault current limiters are inductive. Windings in these limiters are made of second generation superconducting tapes (HTS 2G). Large resistance in resistive state and large currents flowing by the limiter windings during the fault cause the dissipate significant amounts of power and strong heating of the windings, which causes increase in impedance of the limiter. We discuss the influence of the windings heating on the value of limiting short circuit current.

Keywords: inductive superconducting fault current limiter, HTS tape, heating of HTS tape

Wpływ nagrzewania się uzwojeń nadprzewodnikowego ogranicznika prądu na wydajność ograniczania prądu

Streszczenie. Jednym z typów nadprzewodnikowych ograniczników prądu są ograniczniki typu indukcyjnego. Ich uzwojenia wykonane są z taśmy nadprzewodnikowej drugiej generacji (2G). Duża rezystancja w stanie rezystywnym i duże wartości prądów zwarciovych powodują wydzielanie dużych ilości energii i silne nagrzewanie uzwojeń, które powoduje wzrost impedancji ogranicznika. W artykule omówiono wpływ nagrzewania się uzwojeń na wydajność ograniczania prądów zwarciovych.

Słowa kluczowe: nadprzewodnikowy ogranicznik prądu typu indukcyjnego, taśma HTS, nagrzewanie taśmy HTS

Introduction

The growing demand for electricity requires better quality and reliability of its supply. The application of devices that limit possible short circuits makes possible the reduction of the required short-circuit strength of the system elements and ensure the reduction of its costs. Special features of high temperature superconductors make it possible to build superconducting fault current limiters (SFCL) with parameters which cannot be achieved by using conventional materials [4]. One of the types SFCLs are inductive fault current limiters. There are three basic constructions of the inductive type SFCLs: limiter with an open magnetic core [3], with a close core [1] and coreless SFCL [4]. During normal operation impedance of the SFCL is nearly zero, but during short circuit the rapid increase of impedance of the SFCL reduces the short current in the circuit.

The most dangerous are the short circuits occur when voltage is passing through zero, because surge current and the dynamic forces reach the maximum values. Therefore very important is to limit the current at the time less than a quarter of the period (time < 5 ms).

1. Experiment

The coreless inductive type fault current limiter were used in the experiment (Fig. 1.).

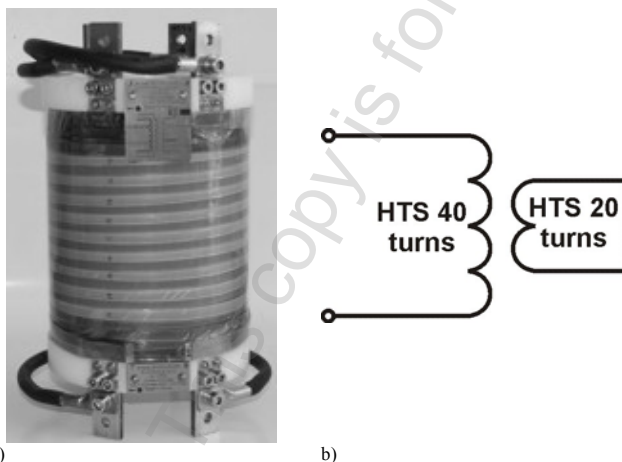


Fig. 1. a) Superconducting fault current limiter, b) diagram of SFCL
Rys. 1. a) Nadprzewodnikowy ogranicznik prądu, b) schemat ideowy ogranicznika

Figure 2 show experimental setup and diagram of experimental setup. Experiments were conducted for three different supply voltages (U_s) in the circuit with and without SFCL to compare the values of the surge currents in order to estimate the percentage rate of limiting current for different short circuit currents. Experimental short circuits are caused when the voltage is crossing zero.

The properties of the power source and SFCL are presented in table 1.

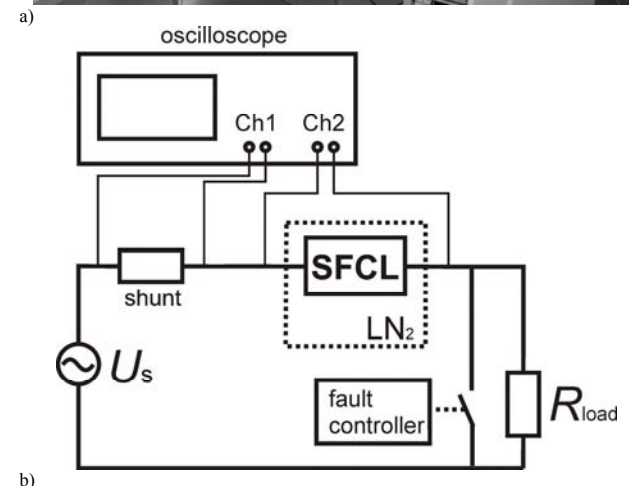
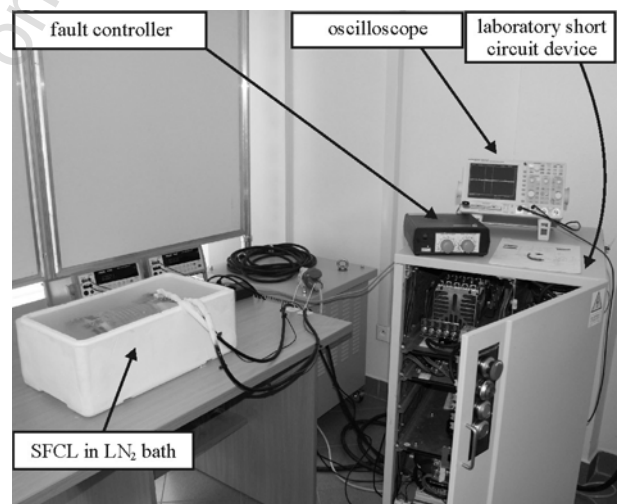


Fig. 2. a) Experimental setup, b) diagram of experimental setup
Rys. 2. a) Układ pomiarowy, b) schemat układu pomiarowego

Characteristic property of this type limiter is that in normal state both of windings are in superconducting state, their resistance is equal zero. Therefore impedance is also equal zero. During the short circuit when current exceeds critical value the windings resistance is increased. Additional as results growing of the secondary winding resistance, inductance of the primary winding is increase. This phenomenon causes that SFCL acts as a impedance coil.

Figure 3 show current in the circuit during short circuit with and without superconducting fault current limiter for three supply voltages 20 V, 30 V and 40 V.

In all three cases shows that the largest short-circuit current values are in the first half period, the next maxima have less values. This confirms that the most important is the first 5 ms of a short-circuit. For a better presentation of issue, first full period (20 ms) of short-circuit will be analyzed.

Table 1. Properties of power supply and superconductor fault current limiter
Tabela 1. Parametry źródła zasilania i nadprzewodnikowego ogranicznika prądu

supply voltage U_s	max. 40 V	
internal resistance	0,094 Ω	
number of primary turns	40	
number of secondary turns	20	
superconducting tape used to made limiter windings	SF12050 (SuperPower)	
	critical current at 77 K	270 A
	critical temperature	90 K
	resistance 1 m tape at 295 K	0,51 Ω
	width	12 mm
thickness	0,055 mm	

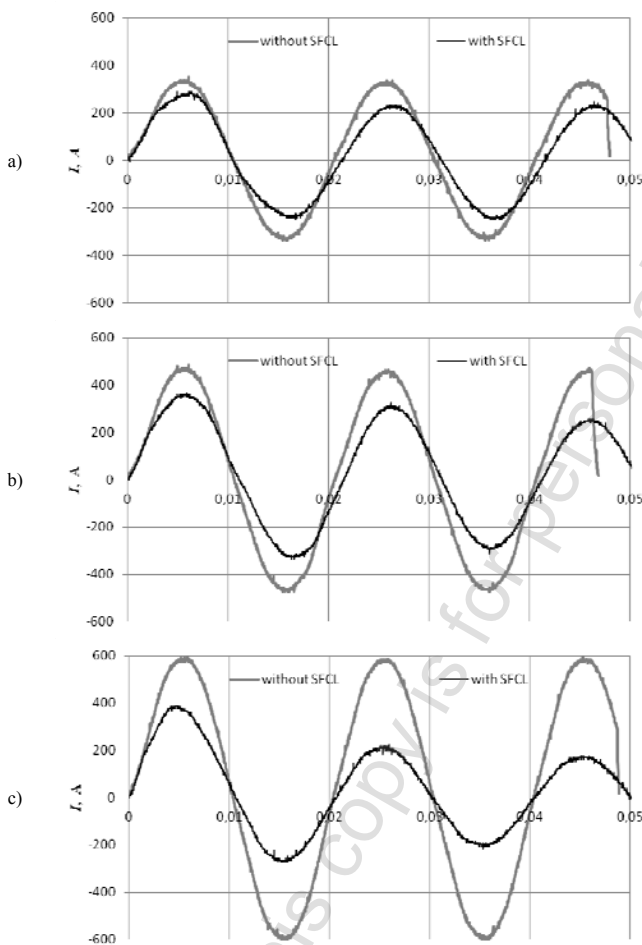


Fig. 3. Traces of the fault current for circuit with and without SFCL for the three supply voltages: a) 20 V, b) 30 V and c) 40 V
Rys. 3. Przebiegi prądów zwarciovych dla obwodu z ogranicznikiem i bez ogranicznika dla trzech napięć źródła: a) 20 V, b) 30 V and c) 40 V

In table 2 we show comparison limiting current by SFCL for each of the three values of voltages.

Table 2. Comparison of the surge current and percentage limiting current for three different U_s values
Tabela 2. Porównanie pierwszego maksimum prądu zwarciovego i procentowego ograniczenia prądu dla trzech różnych U_s wartości

U_s, V_{rms}	i_p, A^*	i_{pSFCL}, A^{**}	$(i_p - i_{pSFCL}) / i_p, \%$
20	334	280	16,2
30	471	360	23,6
40	600	376	37,3

* surge current without SFCL
** surge current with SFCL

2. Analysis

Figure 4 shows traces current and voltage on SFCL on first 20 ms short-circuit for each of the three voltages. Based on these waveforms can be estimated how influence is on the limiting current by each of the windings. Below we described shortly each of tested cases.

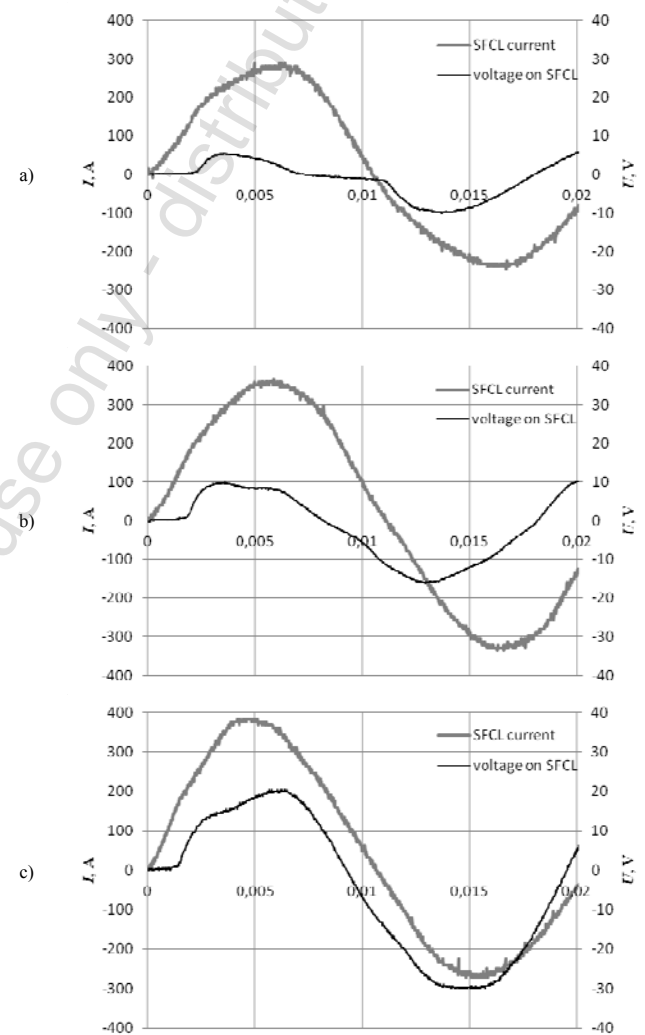


Fig. 4. Traces of the SFCL current, and voltage on SFCL during first 20 ms after fault for three power supply voltages: a) 20V, b) 30V and c) 40V
Rys. 4. Przebiegi prądu zwarciovego i napięcia na ograniczniku podczas pierwszych 20 ms zwarcia dla trzech napięć zasilania: a) 20V, b) 30V and c) 40V

1. first case (for $U_s = 20$ V):

Maximal value of current is 280 A. This is slightly higher value than critical current (270 A). Therefore resistance of primary winding is still close to zero (dependence of resistance on the current is described by empirical equation (1)). SFCL has a transmission 2 to 1 so the current in secondary winding is nearly twice greater than primary current and reaches a value much greater than the critical. And when resistance of secondary winding increases, in-

ductance of current limiter also increases. So the current is limited by a reactance.

2. second case (for $U_S = 30$ V):
Primary current reaches 360 A so in this case both of the windings have resistance. Current is limiting by the reactance and resistance of primary winding [2].
3. third case (for $U_S = 40$ V):
Maximal value of current in the circuit reaches 380 A. This value is similar to second case. But voltage has much larger value than for the previous case. This indicates that the resistance of the windings reaches a much greater value than for $U_S = 30$ V. This phenomenon is caused by heating windings and thermal increase of resistance.

Note that voltage between 0,005 s and 0,01 s this is component of the voltage on the resistance and reactance of the primary winding (except first case). But between 0 s and 0,005 s voltage is practically only on the SFCL reactance (indirectly on resistance of secondary winding).

So in our experiment, surge current limiting is carried out by a rapid increase of the secondary winding resistance.

We observe a lot of percentage rate of limiting for larger currents (Table 2) because the larger current causes dissipate a lot of power (Joule heat) and stronger heating of the windings in resistive state. This is cause to stronger increase their resistance and limiters impedance. To confirm this assumption, the numerical model was used.

3. Numerical model

It is very difficult to measure the temperature of the windings in a few milliseconds, due to excessively long time to transfer heat from the windings to the temperature sensor and the sensor response time. To determine the temperature changes in the time we used a numerical model. The model was made in the magnetodynamic module of Finite Elements Method program Flux2D. Figure 5 show geometry of the SFCL.

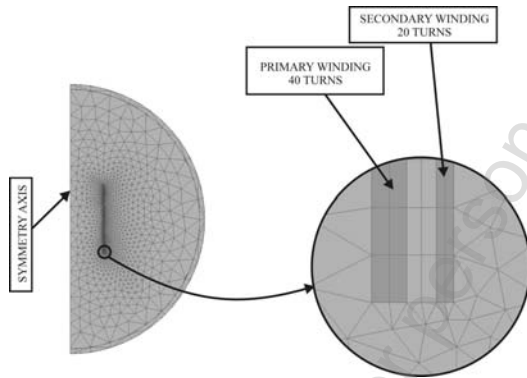


Fig. 5. Geometry of the SFCL made in Flux2D
Rys. 5. Geometria ogranicznika wykonana w programie Flux2D

This module was coupled with an external circuit and thermal module. Dependence of the resistance superconducting tape from the current was described by the Power Law:

$$R(I) = \frac{U_C \frac{1}{n}}{I_C(T)} \left| U_C \left(\frac{I}{I_C(T)} \right)^n \right|^{\frac{n-1}{n}} + R_0 \quad (1)$$

where:

- U_C – critical voltage equal 10^{-4} [V/m],
- $I_C(T)$ – linearity dependence of the critical current on temperature [A],
- n – exponent equal 19,
- R_0 – additional resistance equal 10^{-15} [Ω] (to protect from dividing by zero).

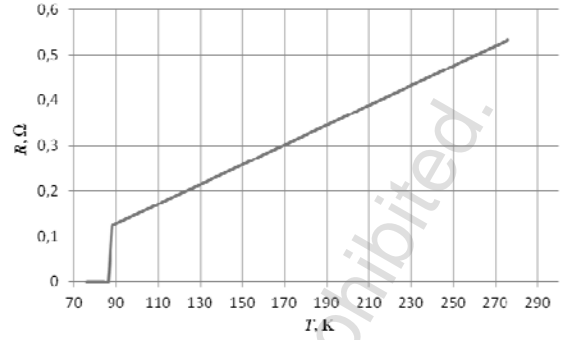


Fig. 6. $R(T)$ curve for 1 meter SF12050 tape
Rys. 6. Charakterystyka $R(T)$ dla 1 metra taśmy SF12050

Additionally, dependence of the windings resistance on temperature is estimated with the temperature variation of the tape resistance (Fig. 7).

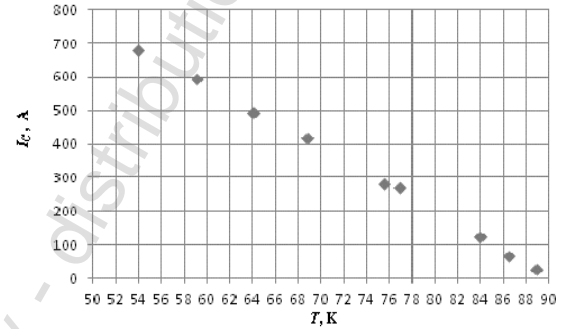


Fig. 7. Critical current SF12050 tape versus temperature [7]
Rys. 7. Zależność prądu krytycznego od temperatury dla taśmy SF12050 [7]

To calculate the temperature of windings following equation was used:

$$T_2 = \frac{RI^2 - SP_{N2}}{mc_v(T)} \Delta t + T_1 \quad (2)$$

where:

- T_2 – calculated temperature [K],
- R – resistance of the winding [Ω],
- I – current flowing by the winding [A],
- S – surface cooled by liquid nitrogen [m^2],
- P_{N2} – power received by the liquid nitrogen from the surface [W/m^2],
- m – mass of the winding [kg],
- $c_v(T)$ – specific heat on temperature [$J/(kg \cdot K)$],
- Δt – time step [s],
- T_1 – temperature from previous step [K].

Every turn in our limiter is insulated with kapton tape. Additional all SFCL is wrapped with one layer of this tape. Therefore we assumed that there is no heat transfer from SFCL to liquid nitrogen during short-circuit. And equation (2) takes the following form:

$$T_2 = \frac{RI^2}{mc_v(T)} \Delta t + T_1 \quad (3)$$

As a results of simulations we obtained following results:

Table 3. Comparison of the secondary winding temperature for $t = 5$ ms, $t = 10$ ms, $t = 15$ ms and $t = 20$ ms for three different U_S values
Tabela 3. Porównanie temperatury uzwojenia wtórnego dla $t = 5$ ms, $t = 10$ ms, $t = 15$ ms and $t = 20$ ms dla trzech różnych wartości U_S

U_S, V_{rms}	T, K ($t = 5$ ms)	T, K ($t = 10$ ms)	T, K ($t = 15$ ms)	T, K ($t = 20$ ms)
20	79,73	81,37	86,37	87,39
30	81,9	83,48	87,53	88,36
40	87,34	89,97	91,97	92,66

As can be seen in table 3 and figure 8, during the first 5 milliseconds after the onset of short circuit, secondary winding temperature rise is the largest. The increase in temperature causes

a significant resistance increase. Moreover, with the temperature increasing the critical current value is decreasing. This phenomena is also cause growth of the resistance.

We are not shown primary winding temperature in the figure 8 because it is not necessary to clarify the issues presented in the paper. Moreover, such short-circuit current as we obtained in the experiment causes that winding quench partially, not in all of length. To complete transition to the resistive state, current at least twice of the critical is needed. This issue is described in detail in [5] and [6].

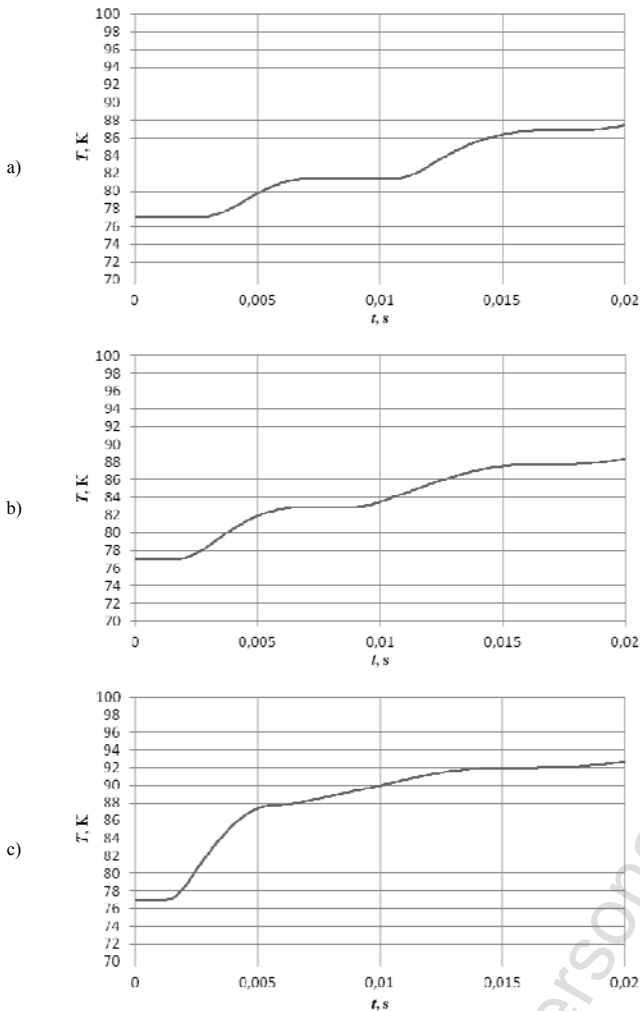


Fig. 8. Temperatures of the SFCL secondary winding during first 20 ms of short-circuit for three power supply voltages: a) 20 V, b) 30 V and c) 40 V
Rys. 8. Temperatura uzwojenia wtórnego nadprzewodnikowego ogranicznika prądu podczas pierwszych 20 ms trwania zwarcia dla trzech napięć zasilania: a) 20 V, b) 30 V and c) 40 V

4. Summary

Inductive superconducting fault current limiter has been tested. Windings of the SFCL was made from second generation superconducting tape. This tape has a high resistance in normal state ($\approx 0,14 \Omega/\text{m}$ at 90 K and $\approx 0,5 \Omega/\text{m}$ at 295K)¹. The short-circuit current flowing through the tape has greater value than critical current. Power dissipated in the winding reaches a kilo or even megawatts. Superconducting tape is quite narrow and has very small cross section so that high power causes a strong and rapid heating. Large and rapid increase in temperature causes rapid increase resistance. Therefore heating of the windings is very important phenomenon because the greater resistance the better current limitation.

In our experiment, the power source allows for the achievement of small currents but can be observed increase of impedance

due to increase in temperature. In real grid short currents reach of tens kiloampers. Power dissipate would be much greater. Temperature and resistance would reach much higher values. In this case the current limit can reach 70%.

Increase temperature of the windings is useful phenomenon, but it also has one big disadvantage. After short-circuit, when temperature of the SFCL is much higher than critical value (Table 1), current in limiter circuit must be switch off for several minutes. This is time necessary to re-cooling limiter. Interval of time dependences on the size and type of limiter construction.

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¹ In comparison tapes of the first generation has resistance $\approx 0,03\Omega/\text{m}$