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Current limiting performance of 9 kVA superconducting transformers

***Abstract**. The second-generation superconducting tapes with high resistivity in the resistive state allow us to build superconducting transformers with the short-circuit limiting feature. A few 9 kVA single-phase transformers with superconducting and conventional copper windings were designed and fabricated for comparison. In this paper, current limiting performance of these transformers in fault conditions was investigated and discussed.*

***Streszczenie.** Taśmy nadprzewodnikowe drugiej generacji o wysokiej rezystywności w stanie rezystywnym pozwalają budować transformatory z funkcją ograniczania prądu. Zaprojektowano i wykonano kilka jednofazowych transformatorów o mocy 9 kVA z uzwojeniami nadprzewodnikowymi i konwencjonalnymi miedzianymi w celu porównania ich właściwości. W tym artykule omówiono skuteczność ograniczania prądu przez te transformatory w warunkach zwarcia. (**Skuteczność ograniczania prądu transformatorów nadprzewodnikowych 9 kVA**).*

Keywords: superconducting transformer, 2G HTS tape, fault current limitation.
Słowa kluczowe: transformator nadprzewodnikowy, taśma nadprzewodnikowa drugiej generacji, ograniczanie prądu zwarciowego.

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Introduction

The second-generation superconducting tapes with a high resistivity in the resistive state allow the construction of a short-circuit resistance transformer because once the critical current density of the HTS tape is exceeded, the total resistance of a superconducting winding increases sharply to a value which may limit a short-circuit current [1]-[4]. The level to which the fault current is limited by a superconducting transformer depends on the operation characteristic of the superconducting windings, their construction and the parameters of the HTS tapes used. This article presents the results of an experimental investigation of a few 1-phase 9 kVA superconducting transformers designed, built and tested.

Design of the transformer

The construction of the transformer on which the tests were performed is presented in Fig. 1. The transformer's specifications are shown in Table 1. The rated primary voltage was 220 V and the voltage ratio was 2:1. This transformer consists of two windings: a primary high voltage winding (HV) and a secondary low voltage winding (LV). During the short-circuit tests, the windings of the transformer were placed inside of a non-metallic cryostat filled with liquid nitrogen (except transformer F, Fig. 4), while the iron core was at a room temperature. A wound and cut core was used for the construction of the transformer's magnetic circuit. The short-circuit tests were performed for 6 transformers with various windings and air gaps (Fig. 2 - 4). Transformers A and B each have one winding made of the superconducting tape and the other one made of a copper wire. Both of the windings were cooled in liquid nitrogen. The HTS transformers C and D have, respectively, a 10 mm air gap and a 1 mm air gap (Fig. 3). Transformers E and F are conventional transformers with copper windings, tested at a room temperature and at the liquid nitrogen temperature.

We have designed and fabricated 5 types of windings which were made of the superconducting tape and a copper wire. The parameters of the windings are listed in Table 2. All windings are wound on separate bobbins of different diameters, which gives the possibility to configure the windings to work with two different air gaps: δ = 10 mm (A, B, C, E, F) and δ = 1 mm (D). In this way, we can determine the impact of the air gap between the HTS transformer windings on short-circuit current limiting performance, as the values of short-circuit reactance X_f depend on the value of air gap δ. Figure 5 presents differences in the air gaps in various transformers.

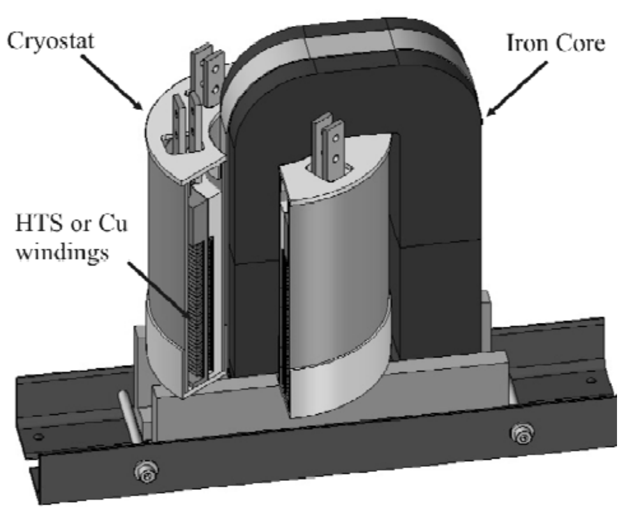

Fig.1. Model of a 9 kVA superconducting transformer

Table 1. Transformers specification

Electrical parameters	
Frequency, Hz	50
Voltage: primary (HV) / secondary (LV)	220 / 110
Rated current of primary / secondary winding, A	40 / 80
Numbers of turns, primary / secondary winding	132 / 66
Turn ratio	2
Magnetic core specification	
Iron core limb cross section, cm^2	49
Iron core yoke cross section, cm^2	49
Height/length of iron core window, cm	23 / 7
Rated magnetic induction B, T	1,53

All superconducting windings were constructed with SuperPower SCS4050 tape (115 A at 77 K) - Table 3. The rated current of transformers I_N = 80 A. The windings were insulated with a polyimide Kapton film. The conventional windings of the transformers were made of a 2 mm x 4 mm copper wire.

Table 2. Windings specification

Winding	prim. Cu	prim. HTS I	prim. HTS II	sec. HTS	sec. Cu
Material	Cu	SuperPower SCS4050			Cu
Int. diam. , mm	154	154	135	131	126
Out. diam., mm	170	156	137	133	134
Height, mm	132				
Number of turns	132	132	132	66	66
I_C, A	-	115	115	115	-
R @ 294 K	152 mΩ	7,24 Ω	6,17 Ω	3,10 Ω	63 mΩ
L, mH	2,05	2,080	1,748	0,39	0,39
Layers	4	4	4	2	2
Length of HTS tape,	-	64 m	56 m	27 m	-

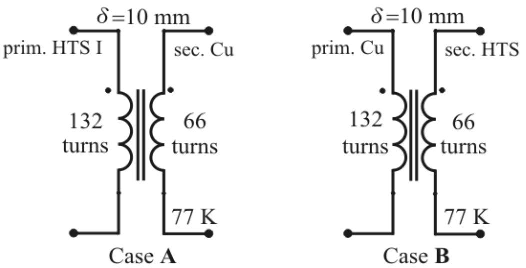

Fig. 2. Diagrams of transformers with windings made of copper wire and SCS4050 tape

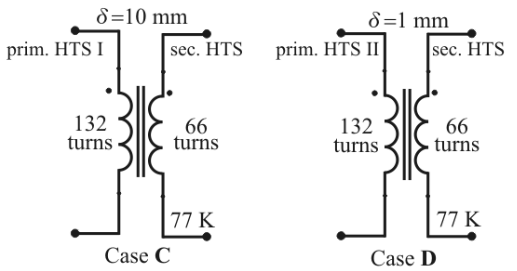

Fig. 3. Diagrams of transformers with windings made of SCS4050 tape

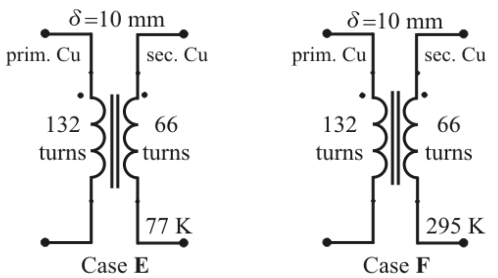

Fig. 4. Diagrams of transformers with windings made of copper wire

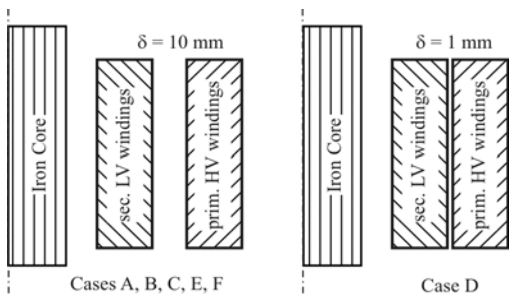

Fig. 5. Air-gap width in the transformers

Table 3. SuperPower SCS 4050 wire specification

SPEC	Value
Width, mm	4
Thickness , mm	0,095
Silver overlayer thickness, μm	2
Copper stabilizer thickness, mm	0,04
Substrate thickness (Hastelloy), mm	0,05

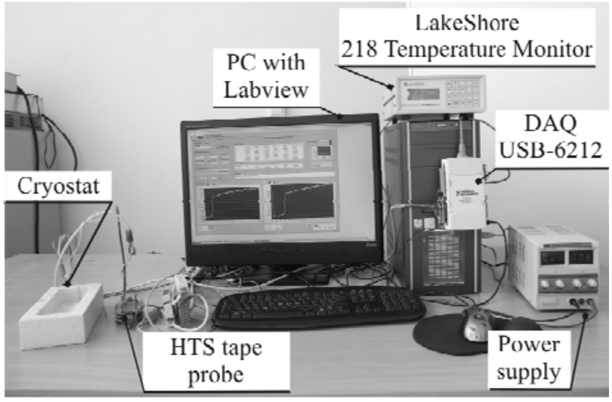

Fig. 6. Experimental setup for measurement the resistance of HTS tape

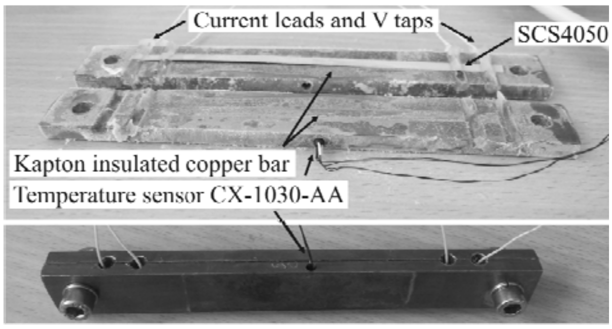

Fig. 7. Experimental setup – HTS tape probe

Characteristics of SCS4050 tape

During a fault, the current in the circuit exceeds the critical current of the HTS tape and then the HTS tape becomes resistive. Because of the ohmic heating, the resistance and the temperature of the HTS tape rise during a short-circuit [5]-[10].

An experimental setup to measure the temperature-dependent resistance of the superconducting tape is presented in Fig. 6. The SCS4050 tape is placed between two copper bars and equipped with current leads and voltage taps (Fig. 7). The length of the HTS tape between the voltage taps was 10 cm. In order to obtain electrical insulation and allow heat transfer, the wire was insulated from the copper bars with a thin polyimide Kapton film. The copper bars provide homogeneous distribution of temperature over the entire piece of wire. They also assure that temperature changes are slower. The temperature was measured with a CX-1030-AA temperature sensor, placed inside of one of the copper bars and connected to a LakeShore 218 Temperature Monitor. A NI USB 6212 DAQ device and software elaborated in NI LabView software (Fig. 6) were used to record the temperature, current and voltage values during the experiment. Also the current source and DAQ device for voltage and current reading were controlled by the same software.

A copper mounting with a piece of SCS4050 tape was placed in a liquid nitrogen bath. Cooled down to 77 K, the copper mounting was placed at a room temperature and gradually heated up to 300 K. The measured temperature-dependent resistance of the 4 mm wide SCS4050 tape is presented in Fig. 8. The measured critical temperature value is about 88 K.

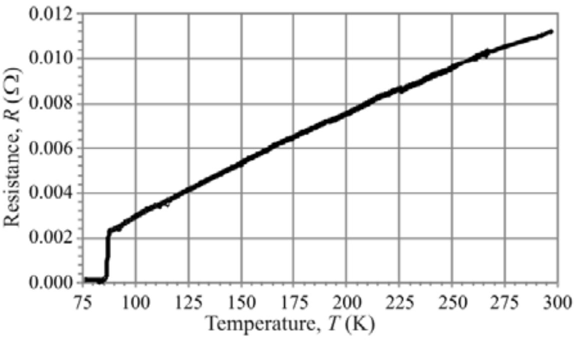

Fig. 8. Measured temperature-dependent resistance of the 4-mm-wide SCS4050 tape (length of tape: 10 cm)

Experimental setup for short-circuit tests of the transformer

The experimental setup consists of a voltage source $U_S = 220\ V_{rms}$, resistive load $R_{load} = 8{,}33\ \Omega$, a switch SW, two thyristors and a NI USB 6212 DAQ device (Fig. 9 - 10). Voltage values were measured with the use of differential probes. The currents in the windings were recorded indirectly, by measuring voltage drops at shunts. The data acquisition, the fault synchronization with the U_S and fault duration are controlled by software elaborated in NI LabView. At the beginning of the measurements, the switch is closed and the thyristors are turned off. The load current flows through the transformer's HTS windings which are in the superconducting state. After 20 ms, the thyristors are turned on. The fault is effected by SCR controller at the moment when voltage is crossing zero. The short-circuit current flows through the transformer. After a 50 ms fault duration, the thyristors are turned off and the load current flows through the transformer.

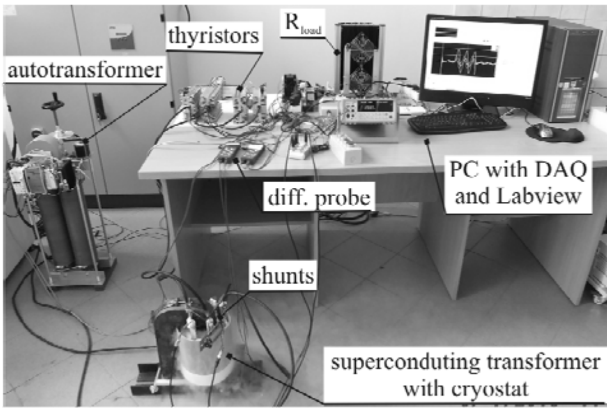

Fig. 9. Experimental setup for short-circuit tests of the transformer

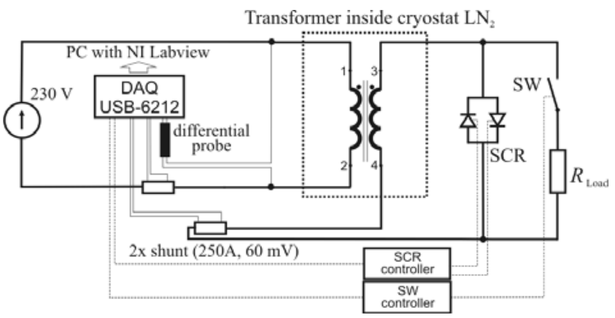

Fig. 10. Diagram of the experimental setup

Test results and discussion

During all short-circuit tests, the iron core of transformers was at a room temperature, but when the windings of the transformers were cooled down the temperature of the iron cores in cases A - E was lower than in case F because the iron core was cooled down by the vaporized nitrogen. The magnetic permeability of the iron core was the highest in case F.

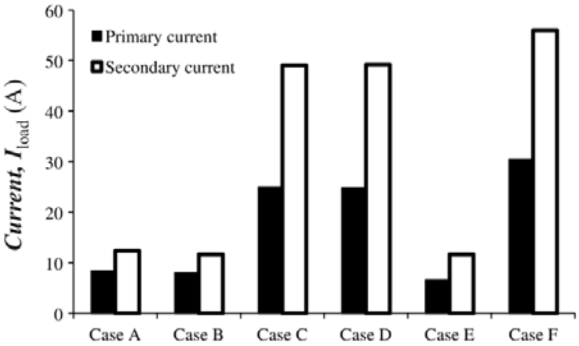

Fig. 11. Comparison of the load current in the transformer windings at $R_{load} = 8{,}33\ \Omega$

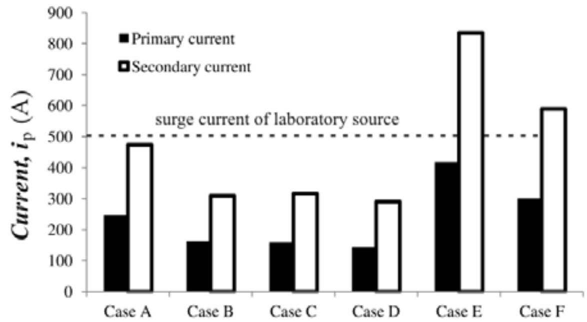

Fig. 12. Comparison of the current's first peak after short in the transformers windings

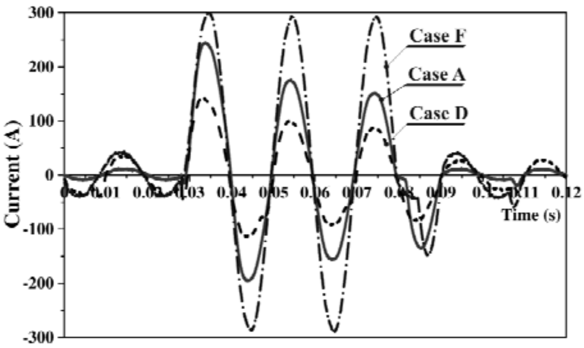

Fig. 13. Time dependent current during current limitation in the primary winding of transformers

Before the fault, the load current flows through the transformer windings. All tests were carried out at the same resistive load $R_{load} = 8{,}33\ \Omega$. The comparison of the load current in the transformer windings (Fig. 11) shows that a higher load current was in the conventional transformer (case F) at a room temperature and in the HTS transformers with both superconducting windings (cases C and D) in a liquid nitrogen bath. In these cases, the impedance of the transformer is smaller because both windings were in the superconducting state. A small, in comparison with the other cases, impedance of the transformer in case F is a result of a different magnetic permeability of the iron core.

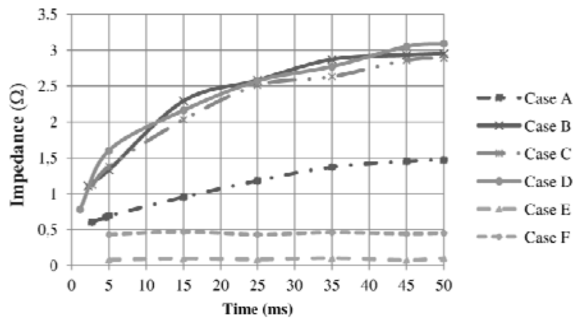

Fig. 14. Comparison of the transformer impedance during the 50 ms fault

The comparison of the current's first peak after a short (Fig. 12-13) shows the capability of the transformer in the test circuit, where the surge current of laboratory source (for each case - 500 A) was significantly limited.

During a fault, the impedance of the transformers with HTS windings (cases A, B, C and D) increases very fast (Fig. 14). The time-dependent impedance of the transformer was calculated from the voltage drop in the primary windings and the current i. When the short-circuit current is higher than the critical current of the HTS tape, the superconducting windings become resistive. Because of the ohmic heating, the resistance of the HTS windings and the transformer impedance rise. The first most dangerous current peak was limited to about 150 A in cases B, C and D, i.e. where the secondary HTS winding was present. The visible decrease of the limited current during a fault (Fig. 13) is caused by the ohmic heating of the coated conductor. In case A, where the secondary winding was made of copper, the current peak was limited to 245 A, the visible growth of the transformer impedance (Fig. 14) being caused by an increase of the resistance of the primary HTS winding.

Comparing the current's first peak in the transformers with HTS windings with the first peak in the transformers with copper windings after a short, we see that the short-circuit current limited with the HTS transformers is about twice lower than the current of the conventional transformer (Fig. 12). The impedance of the transformers with only copper windings (cases E and F) has constant value during a fault (Fig. 14). The cooled transformer (case E) marginally limits the short-circuit current.

The aim of the comparison of cases C and D was to observe the difference in transformers' performance for two values of the air gap between transformer windings. The value of the load current and the current first peak after fault for both transformers are nearly the same. Transformer C has a larger air gap and a higher leakage reactance than transformer D, but the impedance growth during a short is nearly the same because the fault current limitation is a result of an increase of the HTS windings resistance, which is significantly larger than the leakage reactance of transformers (Fig. 14).

Conclusion

We have successfully tested a few solutions of HTS transformers. The analysis of the test results shows that the limitation effect is considerable and the first peak is limited very quickly. The transformers with a single HTS winding limit the short-circuit current significantly better than the conventional transformers with copper windings. The transformers with both HTS windings limit the first peak after a short only slightly better than transformers with only one HTS winding, but there are smaller ohmic losses and lower leakage reactance. The most promising solution of a fault current-limiting transformer is a superconducting transformer with both HTS windings, without an air gap and with an iron core placed outside the cryostat at a room temperature.

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