Vol. **130** (2016) *ACTA PHYSICA POLONICA A* No. 2

Proceedings of the XVII National Conference on Superconductivity, Karpacz 2015

Fault Current Limitation by 2G HTS Superconducting Transformer — Experimental Investigation

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Transformers represent one of the oldest and most mature elements in a power transmission and distribution network. The new superconducting transformers are smaller and lighter than conventional ones and they have lower power losses, too. Also, the new 2G superconducting tapes with high resistivity in the normal state allow to build transformers with high short-circuit strength. The short-circuit current limiting feature of the superconducting transformer, which is the most important benefit of replacing conventional windings by superconducting ones, provides protection and significantly reduces the wear and tear of circuit breakers and other substation power equipment. This paper describes the design and experimental investigations results of a model of a 1-phase, 8.8 kVA superconducting transformer with windings made of 2G HTS tape. A special regard is given to the ability of the device's superconducting winding to limit the short-circuit current, in particular its equivalent resistance in normal state at a temperature of 77 K (i.e. resistance of the resistive layers of the HTS tape just after transition to the non-superconducting state).

DOI: 10.12693/APhysPolA.130.516
PACS/topics: 74.90.+n, 84.70.+p, 84.71.–b, 85.25.–j, 85.25.Am, 85.25.Qc

1. Introduction

Due to its construction conventional transformers are particularly exposed to the dynamic and thermal effects of short-circuit currents [1]. The first peak of short-circuit current, called surge current (cig. 1), causes the dynamic forces that could destroy the transformer winding during the first 5 ms of short-circuit duration (cig. 2). On the other hand, long-term flow of the steady-state short-circuit current through the winding can cause overheating of the windings (cig. 1). So it is important to limit surge current in less than 5 ms. Against thermal failure protects well know protection equipments. But this is not possible to limit the first peak of surge current with conventional current limiters.

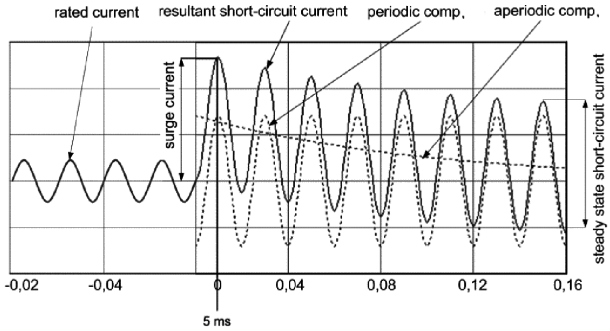

Fig. 1. Wave forms of transformers short-circuit currents.

Fig. 2. Dynamic effects of short-circuit current [1].

2. Superconducting transformers

The resistance of superconducting transformers to short-circuit, which is the result of the fault current self-limitation effect of superconducting windings, is the most important benefit of replacing the conventional windings with the superconducting ones [2–4]. After transition of the superconducting transformer to the resistive state, the increase of the total winding resistance, which depends on the resistivity of the used superconducting tape, causes, compared to its impedance in the superconducting state, a few to several hundred fold increase in the impedance of the transformer (cig. 3). A properly designed and built superconducting transformer reduces first peak of short-circuit current — surge current, in time lower that 5 ms thus secures the transformer from dynamic and thermal failure [3]. Also a low short-circuit voltage causes the voltage fluctuation at changes of power network load to be smaller.

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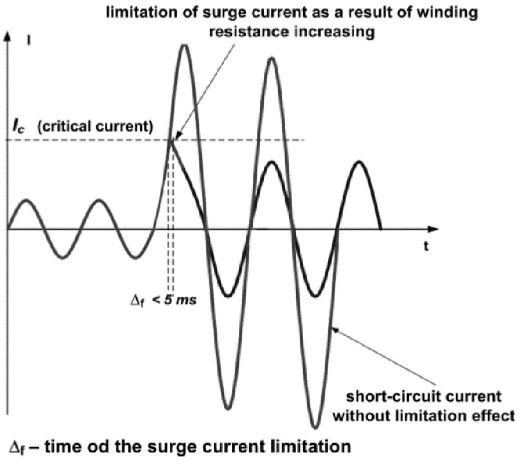

Fig. 3. Limitation of short-circuit current.

3. 2G HTS tapes for transformers windings

In the layer structure of the 2G tape where the superconductor layer is approximately 1% of the total thickness of the tape, it is possible to modify the tape structure in order to obtain the required technical and operating parameters for the HTS transformer [3]. This ensures a reliable and repeatable reduction of the fault current in the power grid by a 2G HTS transformer. Table I presents a comparison of 2G tapes made by two different manufacturers: American Superconductor and SuperPower Inc.

TABLE I

Parameters of 2G HTS tapes [5].

Parameter	344C	344S	Sc12050	SCS12050	SCS4050
width/thickness (average), [mm]	4.4/0.2	4.33/0.29	12/0.055	12/0.095	4/0.095
critical current I_c (average), [A]	60÷90	70÷90	200÷300	250	90
critical current density J_c, $[\frac{\text{A}}{\text{mm}^2}]$	102	136	454	220	230
tape equivalent resistance R' $[\frac{\Omega}{\text{m}}]$	0.0033	0.255	0.105	0.0036	0.0108

The resistance of 2G HTS tape in the normal state is equal to the equivalent resistance of connected in parallel resistances of the layers (substrate and stabilizers) of the tape, and these depend on the resistivity of the layers materials, their thickness and the percentage in the entire cross-section of the tape [3].

4. Design of the HTS transformer

In Laboratory of Superconducting Technologies in Lublin there was designed and built the single-phase model of a 8.8 kVA HTS transformer [6], presented in cig. 4. This transformer consists of three windings: two

Fig. 4. Model of a single-phase 8.8 kVA HTS transformer.

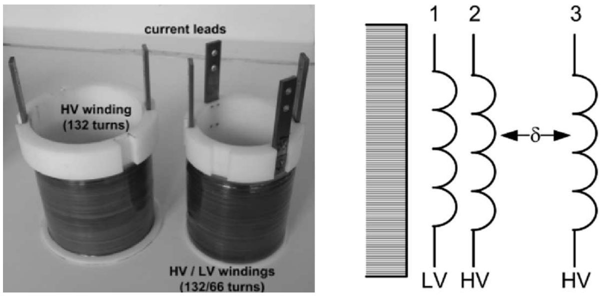

Fig. 5. Windings of the HTS transformer and their configuration.

TABLE II

Specification of the model of HTS transformer

Electrical parameters		
frequency	50 Hz	
voltage: primary/secondary	220/110 V	
rated current of primary/secondary winding	40/80 A	
turn ratio	2	
Magnetic core dimensions		
iron core limb cross section, [m^2]	0.0049	
iron core yoke cross section, [m^2]	0.0049	
height/length of iron core window, [m]	0.23/0.07	
rated magnetic induction B, [T]	1.53	
Windings dimensions [m]		
	$\delta = 0.01$	$\delta = 0.001$
a_1,	0.001	0.001
a_2,	0.001	0.001
b_1,	0.0765	0.0675
b_2,	0.0655	0.0655
r_1,	0.0775	0.0685
r_2,	0.0665	0.0665
L_w,	0.132	0.132
D_{av},	0.142	0.132
layers m_{prim}/m_{sec}	4/2	4/2
length of HTS tapes, HV/LV,	64/27	57/27

HV (high voltage) windings and one LV (low voltage) winding (cig. 5).

One of the HV windings is wound directly on the LV winding while the other one is wound on a separate bobbin. In this way, we can determine the impact of the winding's air gap δ on the performance of the HTS transformer and its short-circuit current limiting features, as the values of short-circuit reactance X_F depend on the value of δ. All the windings are placed in a non-metallic cryostat with liquid nitrogen, while the iron core is situated at a room temperature. Table II presents the specifications of the HTS transformer with two air gap width values.

All the superconducting windings are made of SuperPower SCS4050 tape with critical current $I_c = 115$ A. The rated currents of transformers windings (Table II) are lower that $I_c\ rms = 82$ A. The equivalent resistance of the SCS4050 tape is about 0.0108 Ωm.

The calculated values of the primary and the secondary windings resistance, for $\delta = 0.01$ m, are given in Table III. The values of the short-circuit impedance and the short-circuit voltage for $\delta = 0.01$ m are presented in Table IV.

TABLE III

Calculated total windings resistance [Ω] (77 K, $\delta = 0.01$ m)

HV winding	0.702
LV winding	0.300

TABLE IV

Short-circuit impedance and short-circuit voltage of the transformer model ($\delta = 0.01$ m).

HV winding	X_f [Ω]	R_f [Ω]	Z_f [Ω]	u [%]
I	0.250	0.00	0.250	4.54
II	0.250	1.90	1.910	34.8

TABLE V

Surge current and steady-state short-circuit current ($\delta = 0.01$ m).

HV winding	u [%]	I_{fmax} [A]	I_f, [A]	I_f/I_{1n}
I	4.54	1246	881	22
II	34.8	163	115	2.9

cor the superconducting transformers, these values are given in the superconducting (I) and the normal (II) state. In the superconducting state the short-circuit impedance, and thus the short-circuit voltage, depends only on the value of the short-circuit reactance. Table V presents the values of the limited surge current and steady-state short-circuit current for the transformer windings with $\delta = 0.01$ m.

When the fault current exceeds the value of the critical current of the tape and there is no transition to the normal state, the short-circuit currents would reach the value limited only by the short-circuit impedance of the superconducting windings in the superconducting state — I.

In fact, the transition of the superconducting windings to the normal state increases their resistance which limits the short-circuit currents to the value resulting from the short-circuit impedance of the superconducting windings in the normal state — II.

5. Experimental examination

Experimental studies included the determination of short-circuit characteristics and short-circuit tests, using the parameters of the HTS tape, in order to verify the ability of the superconducting winding to limit the short-circuit current [6, 7]. The examinations were carried out for a HTS transformer with two values of air gap width, compared with a conventional (copper) transformer of the same nominal power. The core dimension, air gap width δ, winding height L_w, as well as the number of turns of HV and LV windings are the same in both transformers. The values of short-circuit reactance, X_f, short-circuit voltage, $u_{\%}$, and steady-state fault current I_f of the Cu transformer are: 0.45 Ω, 8.5% and 833 A, respectively. Short-circuit characteristics and short circuit tests were carried out in an experimental setup presented in cig. 6.

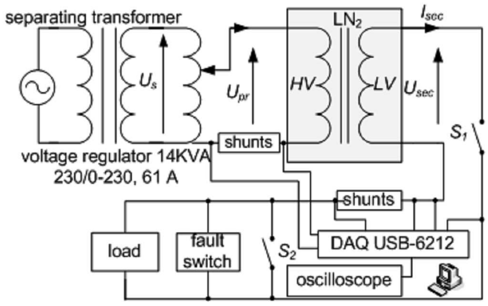

Fig. 6. Experimental setup for the transformer short-circuit tests.

The primary winding is supplied with a voltage regulator coupled with the power source via a separating transformer. Loaded secondary winding is shorted by a short-circuit system. The shunt resistor is 1 mV/1 A. All the measurements are realized with a PC DAQ Card and the LabView Software. The short-circuit characteristic presented in cig. 7 was determined for a current range up to the rated current of the primary winding, for shorted secondary winding (S_1 and S_2 closed).

cor the rated current of 40 A, the values of the short-circuit voltage $u_{\%}$ of HTS transformer, with two values of δ, as well as Cu transformer correspond very well to the values provided by theoretical calculations using the winding dimensions. Values of short-circuit reactance $X_f$corresponding to the measured values of $u_{\%}$ are: 0.28, 0.06, and 0.47 Ω, respectively.

At the same heights of the windings and the same widths of the air gap, both short-circuit impedance and

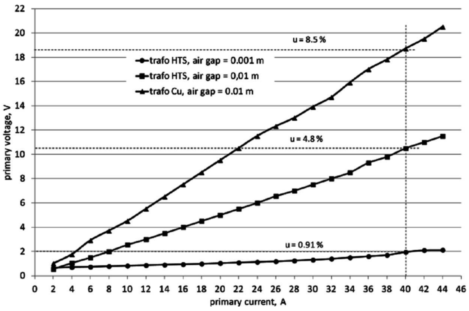

Fig. 7. Short-circuit characteristic (primary winding supplied).

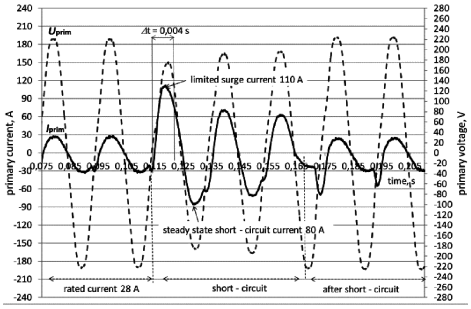

Fig. 8. Wave forms of primary voltage and current — $\delta = 0.01$ m.

short-circuit voltage are higher in the Cu transformer than in the HTS transformer during the superconducting state. In this case, this difference is approximately 56% and it is caused only by the difference in the thickness of Cu and HTS windings because the impact of the Cu transformer windings resistance on the value of short-circuit impedance is small and in the case of the HTS transformer windings it does not occur.

The difference in short-circuit voltage between the HTS transformers with two values of δ arises from fact that the leakage inductance of the windings with $\delta = 0.001$ m is much lower than that inductance of winding with $\delta = 0.01$ m.

Short-circuit tests were carried out in an experimental setup loaded and shorted by a short-circuit system (S_1 — closed, S_2 — open). The short-circuit test results are represented by the wave forms in fig. 8 for the windings with $\delta = 0.01$ m. The short-circuit duration was 0.05 s. Since the HTS transformer limits the fault current as a result of an increase of the HTS windings resistance, the short-circuit reactance of the transformer can be small. However, it is impossible to completely eliminate the short circuit reactance because there will always be an air-gap between the windings, so there will be a leakage inductance. Still, the contribution of short-circuit reactance to the limitation of the fault current, especially of its first peak, is significant because the steepness of the fault current ramp in the first quarter of its period is much greater than that resulting from the sinusoidal wave of the rated current. Fault current limitation (increase of short-circuit reactance) occurs even before the fault current reaches the critical current of HTS winding, thus the limitation is more effective.

Figure 9 shows the increase in resistance of the primary and the secondary windings after a short-circuit. The values of the resistances at the first peak of the short-circuit current reached the values given in Table III. During the short-circuit duration, the resistance of the secondary (LV) winding reaches a value of 0.41 Ω, while the resistance of the primary winding (HV) sharply decreases. This indicates that the primary external winding will return to the superconductive state faster since it is cooled more effectively than the secondary internal winding, as evidenced from the temperature distribution in both windings shown in fig. 10.

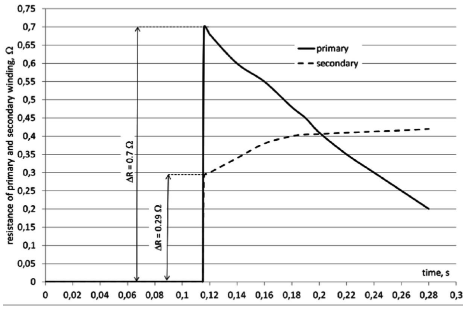

Fig. 9. Resistance of HTS transformer windings during short-circuit duration.

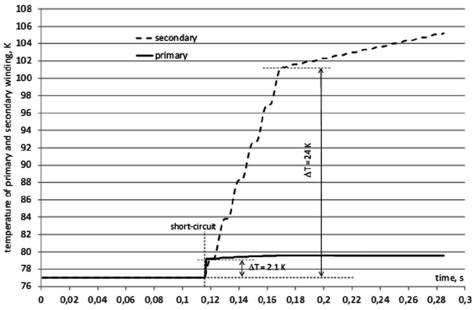

Fig. 10. Temperature distribution of HTS transformer windings during the short-circuit duration.

6. Conclusions

Using the new 2G HTS tapes with proper values of resistivity in the resistive state at a temperature of 77 K, it is possible to build short-circuit resistance HTS transformers with small value of short-circuit voltage $u_{\%}$ since the increase of short-circuit impedance Z_f in the resistive state is sufficient to limit the fault current. After the transition of the superconducting windings to the resistive state, the occurrence of the windings resistance causes a significant increase in the impedance of the transformer compared to its impedance in the superconducting state. The SCS4050 2G tape is suitable for this task. The contribution of short-circuit reactance to the limitation of the fault current, especially of its first peak, is significant because the steepness of the fault current ramp in the first quarter of its period is much greater than that resulting from the sinusoidal wave of the rated current.

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