Grzegorz KOMARZYNIEC[1]

Lublin University of Technology, Institute of Electrical Engineering and Electrotechnologies (1)

Damping of inrush current in superconducting transformer

Streszczenie. *W pracy dokonano analizy zjawisk prądu włączania transformatorów z uzwojeniami wykonanymi z nadprzewodników wysokotemperaturowych. Przeanalizowano zjawisko tłumienia prądu włączania transformatora nadprzewodnikowego. Rezultaty analizy teoretycznej odniesiono do wyników otrzymanych z pomiarów jednofazowego transformatora HTS o mocy 8,5 kVA. Zwrócono uwagę na różnice występujące w przebiegu prądów włączania transformatorów nadprzewodnikowych i transformatorów konwencjonalnych. Wyjaśniono mechanizm tłumienia prądu transformatora HTS gdy jego uzwojenia znajdują się w stanie nadprzewodzenia i w stanie rezystywnym.*
Tłumienie prądu włączania transformatora nadprzewodnikowego.

Abstract*. In present study we analyze the inrush current in transformers with windings made of high-temperature superconducting materials. We analyze the phenomenon of damping the inrush current in superconducting transformers. Theoretical analysis results are compared with results of measurements of one-phase HTS 8,5 kVA transformer. We discuss differences in inrush current waveform in superconducting and conventional transformers. We also explain the damping mechanism of inrush current in HTS transformer when its windings are in superconductive, and in resistive states.*

Słowa kluczowe: transformator, nadprzewodnictwo, transformator HTS, prąd włączania
Keywords: transformer, superconductivity, HTS transformer, inrush current

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Introduction

Transformers with windings made of superconductive materials are one of the most promising applications of high-temperature superconductors (HTS). The basic problem with exploitation of HTS transformers is keeping their windings in superconductive state. Loss of superconducting state can occur as a result of current flow whose magnitude is higher than the critical value of the superconducting material, from which are made the HTS transformer winding. This might happen while transformer is severely overloaded. High current in primary winding can also flow while switching on the unloaded transformer into the power network. This current might be several times higher than the critical current of the superconductor that the winding is made of. Inrush current can make switching HTS transformer on difficult, and even lead to thermal damage in windings.

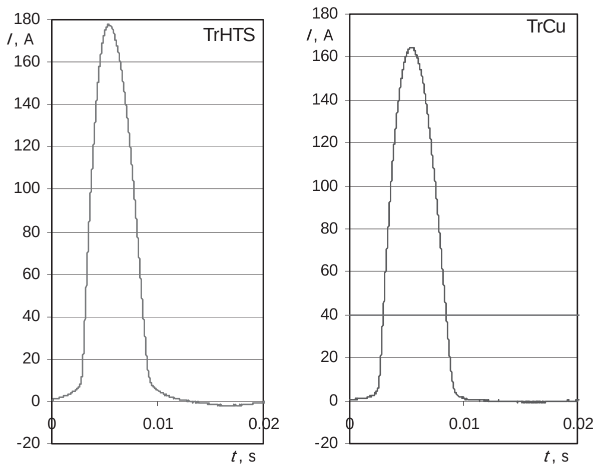

Fig. 1. First inrush current impulse in a superconducting transformer (TrHTS) and a conventional transformer (TrCu).

In articles [1][2] we compared inrush current of a one-phase superconducting transformer (TrHTS) of 8.5 kVA power with a transformer of same power with copper windings (TrCu) [3]. Nominal parameters of both transformers are given in Table 1. Measurements show, that the maximal value of the first inrush current impulse in HTS transformer exceeds a little the maximal value of the first inrush current impulse in a conventional transformer (Fig. 1). The magnitude are: for TrHTS 178A and 164A for TrCu. It was also shown that the damping time of inrush current is longer for HTS transformer (Fig. 2) at 350 ms. This value for a conventional transformer is 200 ms. The flow of inrush current in the power supply circuit of the transformer causes many phenomena that affect the operation of the devices installed in the system.

Inrush current transfers onto secondary side of current transformers and might cause their saturation, causes overvoltages and resonant phenomena, might also cause dysfunction of protection devices, welding of switches contacts, blowing fuses [4]. High value and long duration of inrush current in HTS transformer mean huge side effects.

The primary winding resistance is responsible for inrush current impulses damping. For superconductive material this resistance is a non-linear function of temperature, current density and magnetic field intensity.

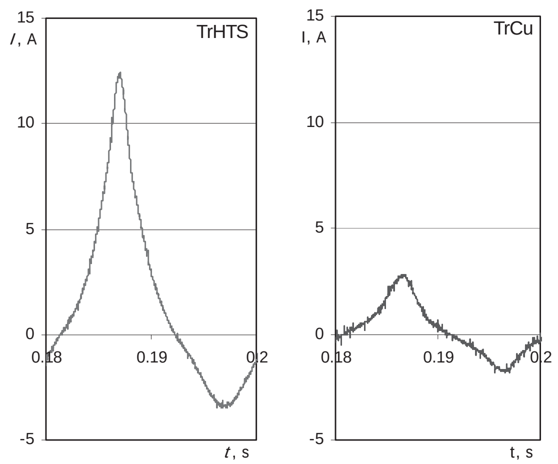

Fig. 2. Current impulses 180 ms after switching transformers on.

Table 1. HTS transformer's parameters.

	TrHTS	TrCu
Power	8.5 kVA	8.5 kVA
Frequency	50 Hz	50 Hz
Voltage HV/LV	220 V/110 V	220 V/110 V
Current HV/LV	40 A/80 A	40 A/80 A
Induction	1.6 T	1.6 T
Percent short-circuit voltage	0.9%	8.5%

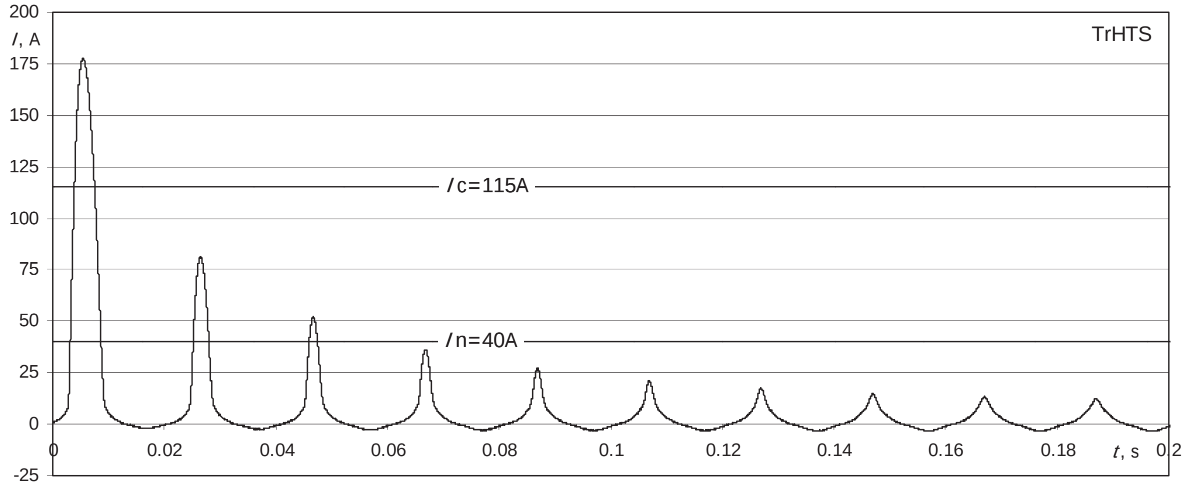

Fig. 3. Waveform of inrush current of a HTS transformer.

HTS transformer's inrush current

First we analyze switching an unloaded HTS transformer to an ideal power source. Circuit scheme is shown in Fig. 4.

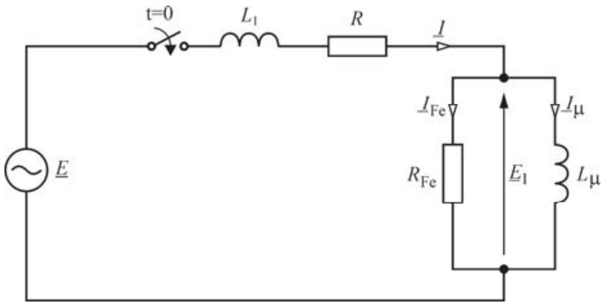

Fig. 4. Circuit into which the HTS transformer is switched.

The circuit from Fig. 4 is described by the formula:

(1) $$e = Ri + L\frac{d}{dt}i + e_1$$

Assuming sinusoidal power voltage, ignoring the active current component for covering the iron losses ($R_{Fe}=\infty$), and granting $L=L_1+L_{\mu 0}$, a relation for current can be derived from formula (1) [5] [6]:

(2) $$i = -\frac{\sqrt{2}EX}{Z^2}\left(\frac{R}{X}\sin\omega t - \cos\omega t + \left(\frac{R}{X}\sin\theta + \cos\theta\right)e^{-\frac{R}{X}(\omega t+\theta)}\right)$$

where E – effective voltage value, ω – pulsation, t – time, R – transformer's primary winding resistance, X – winding reactance, Z – winding impedance. The Θ angle appearing in formula (2) is derived from relation [2]:

(3) $$\cos\theta = \frac{B_n - B_m - B_o}{B_m}$$

where B_n – is transformer's core saturation induction, B_m – rated induction, B_o – residual magnetism induction.

The inrush current waveform has two components: (1) fixed component representing transformer's no-load current and (2) unidirectional component. Unidirectional component appears with saturation of transformer's core. It is unidirectional current which might be several times greater than the transformer's rated current.

Set current is only a small percentage of inrush current and can be ignored in calculations. It can be concluded from the HTS 8,5 kVA transformer inrush current flow (Fig. 3), that only first inrush current impulse exceeds the superconductor's critical current. Following impulses are greater than transformer's rated current, but their value is smaller than superconductor's critical current and do not present risk of loss in windings superconductive state. In Figure 5 we show theoretical analysis of unidirectional current first impulse.

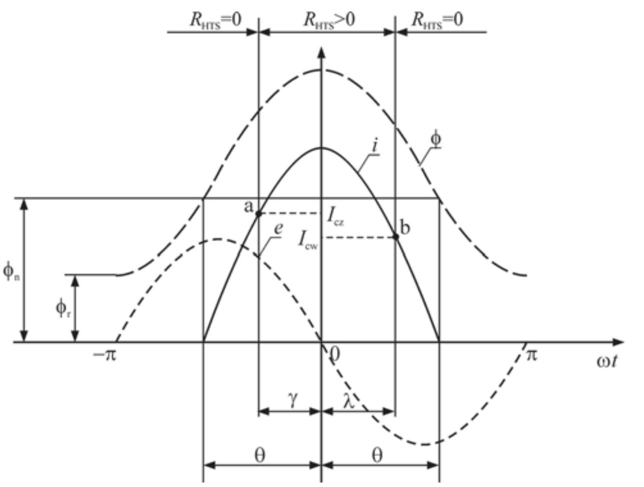

Fig. 5. First pulse of inrush current [5] [6].

Unidirectional current appears when transformer's core is saturated, i.e. at angle $-\Theta$. Momentary value reaches the critical current I_{cz} of superconductor for angle $-\gamma$. In angle range between $-\Theta$ and $-\gamma$ transformer's winding is in superconductive state ($R_{HTS}=0$). When exceeding critical current the transformer's winding gets into resistive state ($R_{HTS}>0$) [7]. It stays in this state in angles range between $-\gamma$ and λ. Width of the λ range depends on the temperature that the winding reaches in resistive state, heat capacity of the winding and cooling system efficiency. In order for the transformer's winding to get into superconductive state, instantaneous value of unidirectional current must be lower than critical current and superconductor's temperature must be lower than the critical temperature. With effective cooling $\lambda=\gamma$, and with great thermal inertia of windings the λ angle can be equal to the Θ angle. In range of angles between λ and Θ winding is in superconductive state ($R_{HTS}=0$).

During one inrush current impulse superconducting winding changes the working mode twice. At point "a" (Fig. 6.) winding goes from superconductive to resistive state. The transition is quick, but not discrete and its course is characteristic of the certain superconductive material. At point "b" winding gets back into superconductive state. In resistive state, according to Joule's law, process of heating the winding due to unidirectional current flow occurs. Along with heating the winding, the superconductor's resistance grows. The superconductive tape's resistance in normal state is approximately a linear function of temperature and can be described by the following formula:

(4) $$R_T = R_0\left(1+\alpha\left(T-T_0\right)\right)$$

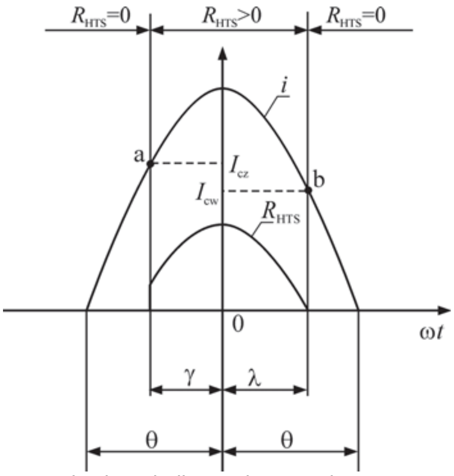

Fig. 6. Superconductive winding resistance change.

The above shows, that at transformer's winding superconductive state formula (2) can be reduced to the following:

(5) $$i = \frac{\sqrt{2}E}{X}\left(\cos\omega t - \cos\theta\right)$$

Relation (5) shows, that there is no suppression of unidirectional constituent in superconductive state. Unidirectional current has a set value, dependant on winding's reactance and voltage value.
In transformer's windings superconductive state only power network's resistance needs to be taken into account as the chief parameter deciding for the speed of unidirectional current damping.

Influence of network parameters

Electric scheme of the circuit where inrush current was measured is shown in Figure 7. R_z and L_z are respectively resistance and induction of autotransformer's secondary side, R_l and L_l are parameters of examined transformer's power line, R_B is shunt's resistance. R_1, R_{Fe}, L_1 and L_μ are parameters of equivalent circuit of unloaded transformer (Table 2). Parameters of the power circuit were given in Table 3.

Resistance of the circuit in Figure 7 depends on state of HTS transformer's windings work. In superconductive state at R_1=0 it equals the sum of power network resistance and internal source resistance. In winding's normal state, it changes along with changes in unidirectional current momentary values (Fig. 8). The changes dynamics depend on temperature that winding reaches in resistive state, winding's resistance temperature factor, thermal capacity of the winding and cooling efficiency.

Table 2. Parameters of transformer's vicarious scheme.

Parameter	TrHTS
R_1	6.36 Ω (294K)
	0.594 Ω (77K resistive state)
	$0.055\cdot10^{-18}$ Ω (77K superconducting state)
R_{Fe}	958.4 Ω
X_1	0.534 Ω
X_μ	71.2 Ω

Table 3. Parameters of power circuit.

R_z	L_z	L_L	R_L	R_b
1.5 Ω	128 mH	0	11 mΩ	1 mΩ

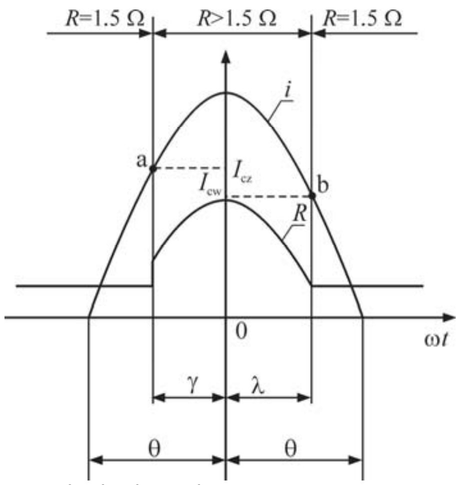

Fig. 8. Changes in circuit's resistance.

In Figure 9 we presented resistive characteristics of a 55 meters piece of SCS4050 tape, made by SuperPower company, used to make the 8.5 kVA transformer's winding. In superconductive state, the tape's resistance is close to zero. After exceeding the critical current I_c=115 A a sudden rise in resistance up to 0.59 Ω occurs. Due to current flow through the resistive material, according to Joule's law, process of heating the tape begins accompanied by further growth in its resistance. At 293 K the SCS4050 tape resistance is 6.36 Ω.

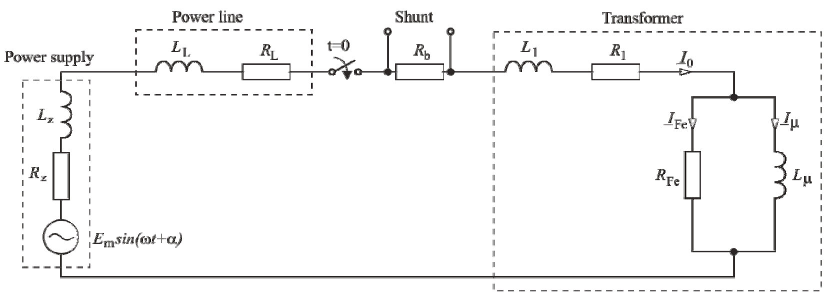

Fig. 7. Electrical circuit

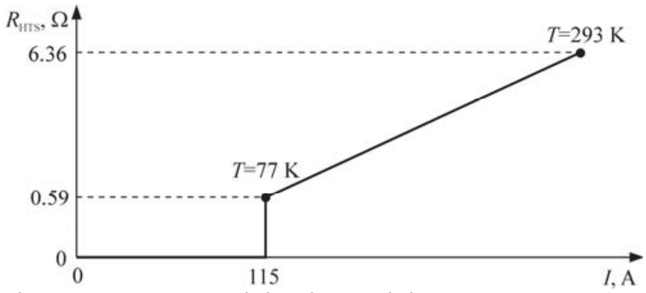

Fig. 9. SCS4050 tape resistive characteristics.

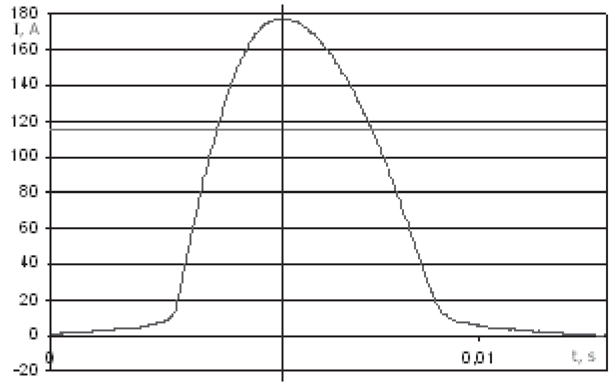

Fig. 10. Inrush current first impulse in HTS.

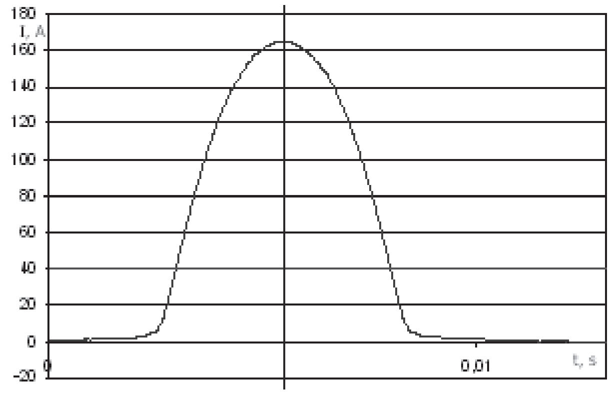

Fig. 11. Inrush current first impulse in conventional transformer.

Table 4. Circuit resistance for TrHTS and TrCu.

TrHTS		TrCu
superconducting state	resistive state	
1.512 Ω	2.102 Ω (77K) ÷ 7.872 Ω (293K)	1.664 Ω

Derived for the SCS4050 tape resistive state from relation (4) temperature resistance factor α is $45.3 \cdot 10^{-3}$.

State of the HTS transformer's winding influences unidirectional current impulses flow. In Figure 10 the first impulse was shown. Different course of rising edge and falling edge is associated with a non-linear circuit resistance. Current value grows quickly because between 0 and 115 A the HTS transformer's winding is in superconductive state. Suppression of the current happens only due to the power network's resistance. Only after the current exceeds the critical value the transformer's windings resistance takes a part in current suppression. In transformer with copper windings both courses are similar (Fig. 11). In Table 4 circuit resistances for both transformers were compared.

Conclusion

Examination of superconducting transformer of 8.5 kVA power shows that unidirectional current accompanying the inrush current is higher in value and has longer fading time than in a conventional transformer. Phenomenon of superconducting transformer's inrush current suppression is much more complex than in a conventional transformer. Value and fading time of unidirectional current is influenced by non-linear resistive characteristics of superconductive material used for making the primary winding. In superconductive state of windings suppression of current is due to the power network resistance. In winding's normal state, suppression depends on winding's resistance value, which is a function of temperature. Getting the windings out of superconductive state accelerates fading of unidirectional current. However this presents a threat for the superconductive tape of it being thermally damaged.

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***Autorzy**:*
dr inż. Grzegorz Komarzyniec,
Politechnika Lubelska,
Instytut Podstaw Elektrotechniki i Elektrotechnologii,
ul. Nadbystrzycka 38a,
20-618 Lublin,
E-mail: g.komarzyniec@pollub.pl