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Impact of critical current values in HTS transformer winding on decay time of inrush current

Abstract. *This paper presents mathematical analysis of the first inrush current pulse for transformers with windings made of superconducting materials. Formulas are derived hereby, allowing for calculation of pulse duration. Moreover, dependences are shown which allow for specifying the time when transformer's primary winding is in the resistive state.*

Streszczenie. *W artykule przedstawiono analizę matematyczną pierwszego impulsu prądu włączania transformatora z uzwojeniami wykonanymi z materiału nadprzewodnikowego. Wyprowadzono wzory umożliwiające wyliczenie czasu trwania impulsu. Podano również zależności umożliwiające określenie czasu przez jaki uzwojenie pierwotne transformatora znajduje się w stanie rezystywnym.* ***(Wpływ wartości prądu krytycznego uzwojenia transformatora HTS na czas zaniku prądu włączania****)*

Keywords: inrush current, transformers, superconductor.
Słowa kluczowe: prąd włączania, transformator, nadprzewodnik.

Introduction

Transformers with windings made of superconducting materials are one of the most promising applications of high-temperature superconductors. The main process- and operations-related problem pertains to the method for maintaining their windings in the superconducting state. The inrush current phenomenon has been identified as an important issue here. On attempt to activate a superconducting transformer, due to the fact that the inrush current exceeds the value of superconductor's critical current I_c, transition of windings from the superconducting to the resistive state takes place. This transition is accompanied by thermal effects in windings, related to the inrush current by means of the Joule's law. They can lead to a thermal damage of the superconducting winding.

The source of the transformer's inrush current is a transient state in the electrical circuit coupled with the magnetic circuit [1]. Under certain conditions this state can result in transformer's core saturation and occurrence of the direct-current component of the magnetising current. Inrush current is composed of the direct component and the disturbance component. The direct component is no-load current that amounts to 1-10% of the rated current value, depending on the transformer's power. The disturbance component is high-value unidirectional current occurring in transformer's core saturation conditions. Due to the fact that the peak value of the unidirectional current can be 20-40 times higher that the rated current, the direct component of the current will not be taken into consideration in this paper.

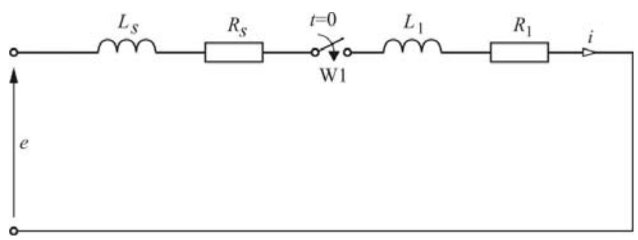

Fig. 1. Equivalent circuit diagram - transformer's core saturation condition

For core saturation conditions the equivalent circuit diagram of a no-load transformer basically becomes the combination of the primary winding resistance R_1 and the primary winding inductance L_1 connected in series, measured in core saturation conditions (Fig. 1). The resistance R_s and inductance L_s of the transformer's power supply circuit are also shown in the circuit diagram. The following equation describes the circuit shown in Figure 1:

$$e = -\sqrt{2}E\sin\omega t = Ri + L\frac{di}{dt} \quad (1)$$

where R is the equivalent circuit resistance, and L is the equivalent circuit inductance. For superconducting transformers the value of the winding resistance depends on the state of the superconductor [2]. In the superconducting state, the superconductor's resistance is less than 10^{-21} Ω·m. It increases rapidly when the current critical value I_c, critical temperature T_c, or the critical magnetic field strength H_c is exceeded. The simplified characteristic of superconductor's transition as a function of current change is shown in Figure 2.

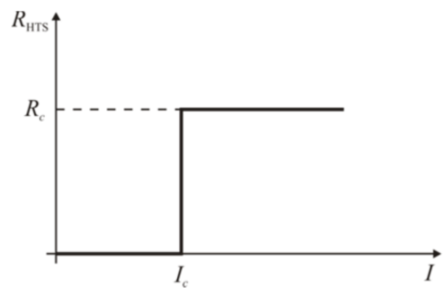

Fig. 2. Simplified characteristic of superconducting tape transition

The resistance of the transformer's primary windings significantly impacts the inrush current peak value and this current wave decay time.

Inrush current measurements

The inrush current value has been measured for the 10 kVA superconducting transformer (TrHTS). HV and LV windings in the transformer are made of the Super Power SCS4050 (Re)BCO superconducting tape, for which the rms value of the critical current amounts to 115 A in the temperature of 77 K. The magnetic circuit is made of a coiled and cut core RZC-70/230-70, material: sheet metal PN ET52-27, with magnetic flux density B_{max}=1.75 T at H_{max}=10 A/cm and core loss P=0.8 W/kg at B=1 T and f=50 Hz. Transformer windings are cooled with liquid nitrogen to 77 K. The transformer core works at ambient temperature. For comparison purposes a transformer with copper windings (TrCu) has been constructed over the same core type. Table 1 shows electrical parameters of windings in both transformers [3].

Table 1. Parameters of primary windings

Parameter		TrHTS1	TrCu
Primary winding inductance, L_1		1.7 mH	2.0 mH
Primary winding resistance, R_1	(294 K)	6.36 Ω	0.152 Ω
	(77 K) superconducting state	$0.055 \cdot 10^{-18}$ Ω	—
	(77 K) resistive state	0.594 Ω	—

The highest measured peak value of the inrush current for the TrHTS transformer amounts to 178 A (Fig. 3). This pulse exceeds by 63 A the critical current value for the superconducting tape SCS4050 of which windings are made. Maximum inrush current for the transformer with copper windings (TrCu) amounts to 164 A.

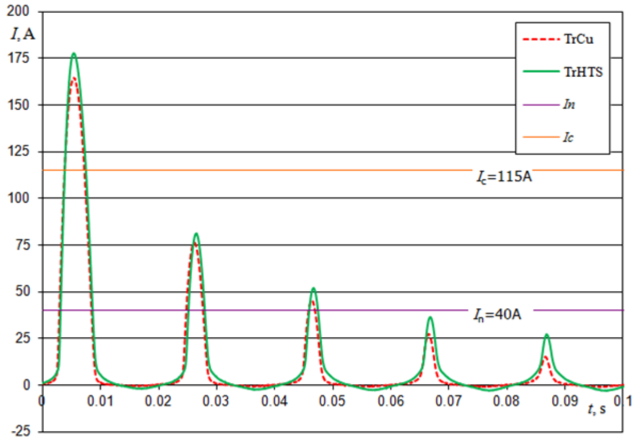

Fig. 3. Pulse waveform after transformer activation

The non-linear resistance of superconducting winding impacts significantly the direct-current component decay time. After 180 ms the inrush current peak value for HTS transformer is damped 14.2 times compared to the first pulse, whereas for transformer with copper windings it is damped 65.6 times (Fig. 4).

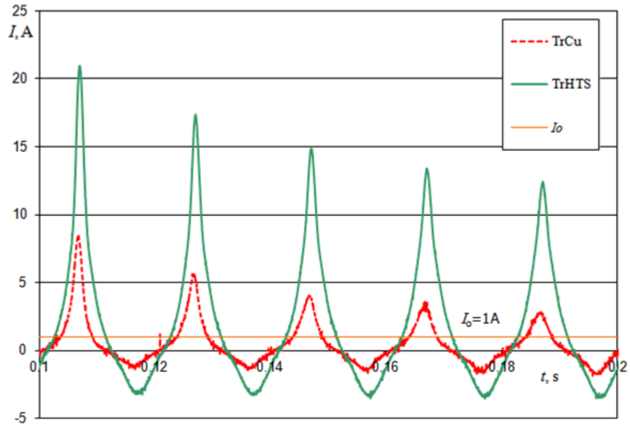

Fig. 4. Pulse waveform after 0.1 s from transformer activation

Table 2. Results of inrush current measurements

Parameter	TrHTS1	TrCu
Inrush current peak value	178 A	164 A
Direct-current component decay time	350 ms	200 ms

Table 2 shows results of measurements. The first inrush current pulse in the superconducting transformer is 14 A higher than the pulse observed for the transformer with copper windings. The inrush current wave decay time in the superconducting transformer is 150 ms longer than in case of conventional transformers.

Theoretical analysis

If, during duration of the unidirectional current pulse, the primary winding had not exited the superconducting state, then only the power mains resistance would be responsible for inrush current damping. In such case the current pulse would be changing according to curve 2, shown in Figure 5.

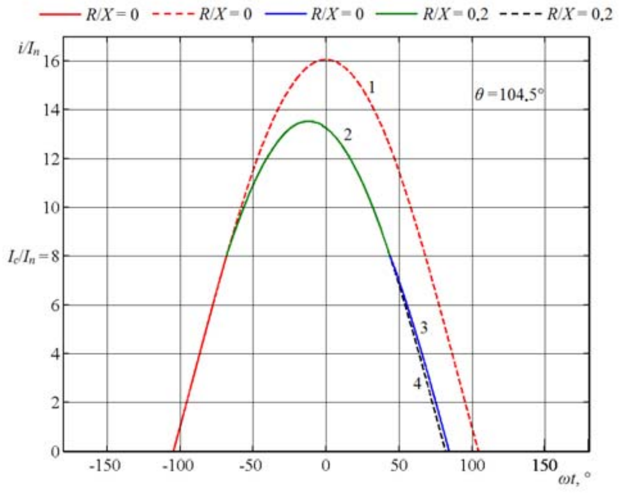

Fig. 5. Current pulse analysis

The winding enters the resistive state when the instantaneous value of the unidirectional current exceeds the superconductor's critical current value I_c. In such case the unidirectional current pulse changes according to curve 1, 3, 4, as shown in Figure 5. During duration of the pulse leading edge the transformer's winding is in the superconducting state till the moment the critical current value I_c is exceeded (curve 1). The winding is in the resistive state when the current pulse changes according to curve 3. When the trailing current pulse value drops below the critical current value I_c, the winding returns to the superconducting state. Curve 5 shows how the current pulse would be decaying if the superconductor had not returned to the superconducting state. Situation like this can happen when temperature of the superconductor, heated by means of the unidirectional current pulse, will not drop below the critical value T_c before pulse decay. For purposes of the figure it has been assumed that the circuit's R/X ratio amounts to zero in the superconducting state, whereas in the resistive state it amounts to 0.2. Unidirectional current is damped by means of the transformer's primary winding resistance when it is changing according to curve 3. The long period of time in which the winding remains in the resistive state translates into shortening of the unidirectional current pulse duration, thus increasing the inrush current decay rate. On the other hand, it can contribute to the increase of winding temperature, causing its thermal damage. It is therefore important to develop a mathematical model of the phenomenon which will allow for determination of the unidirectional current pulse duration and the time during which the winding remains in the resistive state.

Mathematical description

By solving equation (1) for appropriately selected initial conditions, the duration of the unidirectional current pulse and the time during which the transformer's primary winding remains in the resistive state can be determined. Figure 6 shows graphical analysis of the current pulse featuring φ flux waveform, supply voltage u, and changes in the transformer's primary winding resistance R_1. It was assumed that the transformer is activated at $\omega t=-\pi$.

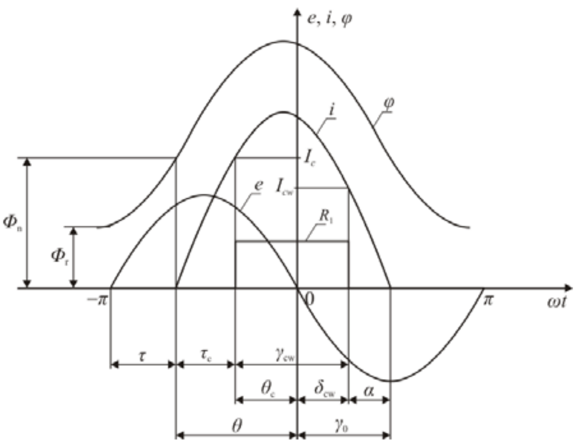

Fig. 6. Graphical analysis of the current pulse

According to Figure 6, the following equation can be used to describe the φ flux:

(2) $$\varphi = \Phi_m + \Phi_m \cos\omega t + \Phi_r$$

By transforming the equation (2) so that it includes $\omega t=-\theta$ and $\varphi=\Phi_n$, we obtain a formula for the θ angle, at which the core saturation occurs and the unidirectional current pulse emerges:

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

The unidirectional current pulse emerges after time:

(4) $$t_\tau = (\pi - \theta)\frac{\pi}{180\omega}$$

since activation of the transformer.

In order to avoid failures of the superconducting transformer it is essential to determine the time during which the primary winding is in the resistive state. The moment in time when the unidirectional current i reaches the critical value I_c corresponds to the θ_c angle, as shown in Figure 6. By assuming, according to Figure 6, that boundary conditions amount to $i=I_c$ and $\omega t=-\theta_c$ and introducing them into equation (1), after transformation the following formula for θ_c angle can be obtained:

(5) $$tg\theta_c = I_c \frac{Z^2}{\sqrt{2}EX} A + B$$

where parameters A and B are as follows:

(6) $$A = \frac{e^{\frac{R}{X}\tau_c}}{\left(\sin\tau_c - \frac{R}{X}\cos\tau_c + \frac{R}{X}e^{\frac{R}{X}\tau_c}\right)\cos(\theta - \tau_c)}$$

(7) $$B = \frac{\frac{R}{X}\sin\tau_c + \cos\tau_c - e^{\frac{R}{X}\tau_c}}{\sin\tau_c - \frac{R}{X}\cos\tau_c + \frac{R}{X}e^{\frac{R}{X}\tau_c}}$$

Dependence (5) shows that the value of the θ_c angle is correlated to the critical current value I_c and the circuit's R/X ratio value. Figures 7 and 8 show sample θ_c angle variation characteristics as a function of the current I_c, for selected θ angle values and R/X ratio.

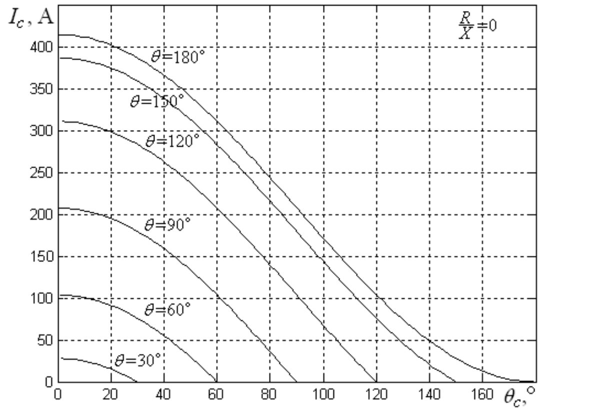

Fig. 7. θ_c angle variation as a function of the current I_c for selected θ angles

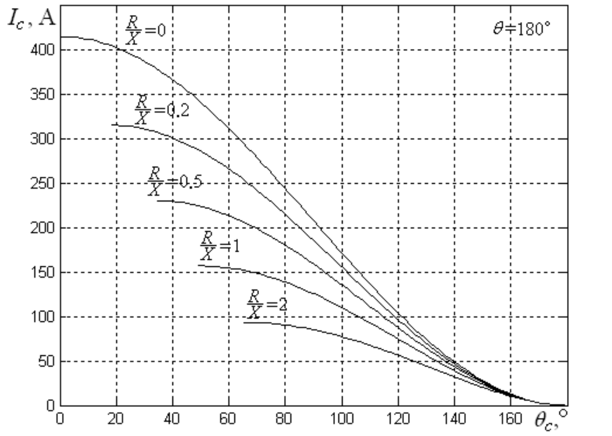

Fig. 8. θ_C angle variation as a function of the current I_c for selected R/X ratio values

By knowing angles θ and θ_c, we can determine the time after which the winding enters into the resistive state:

(8) $$t_{\theta c} = (\tau + \tau_c)\frac{\pi}{180\omega}$$

where:

(9) $$\tau = \pi - \theta$$

(10) $$\tau_c = \theta - \theta_c$$

Assuming that the winding returns to the superconducting state for the instantaneous current value amounting to I_{cw} (Fig. 6), the δ_{cw} angle can be determined, at which the winding returns to the superconducting state. The angle can be determined by introducing $i=I_{cw}$ and $\omega t=\delta_{cw}$ into equation (1). After transformations the following formula is obtained:

(11) $$tg\delta_{cw} = \left(I_c - I_{cw}e^{\frac{R}{X}\gamma_{cw}}\right)\frac{Z^2}{\sqrt{2}EX}G + H$$

where parameters G and H are as follows:

(12) $$G = \frac{1}{\left(\frac{R}{X}e^{\frac{R}{X}\gamma_{cw}} - \frac{R}{X}\cos\gamma_{cw} + \sin\gamma_{cw}\right)\cos(\gamma_{cw} - \theta_c)}$$

(13) $$H = \frac{e^{\frac{R}{X}\gamma_{cw}} - \frac{R}{X}\sin\gamma_{cw} - \cos\gamma_{cw}}{\frac{R}{X}e^{\frac{R}{X}\gamma_{cw}} - \frac{R}{X}\cos\gamma_{cw} + \sin\gamma_{cw}}$$

Dependence (11) shows that the value of the δ_{cw} angle depends on the value of the critical current I_c, at which the transformer's primary winding exits the superconducting state and the current I_{cw}, at which it returns to the superconducting state. Figure 9 show the δ_{cw} angle variation characteristics as a function of the current I_{cw} for selected values of I_{cw}.

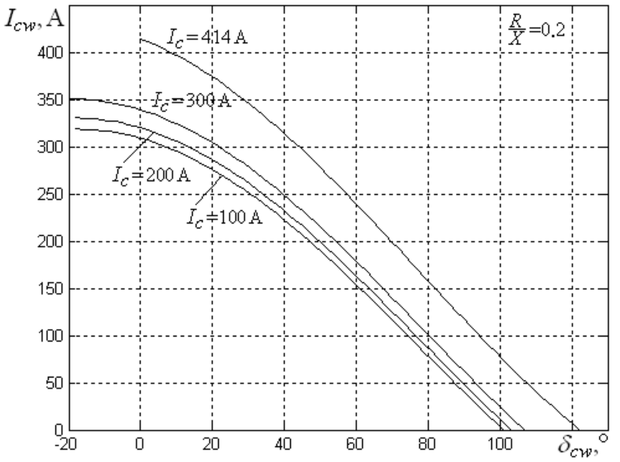

Fig. 9. δ_{cw} angle variation as a function of the current I_{cw} for selected values of I_c

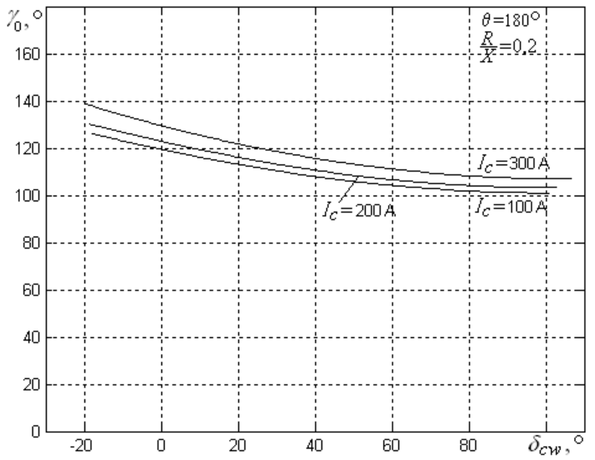

Fig. 10. γ_0 angle variation as a function of the δ_{cw} angle for selected values of I_c

By knowing the value of the γ_0 angle, duration of the unidirectional current pulse can be determined:

(18) $$t = (\theta + \gamma_0)\frac{\pi}{180\omega}$$

Summary

Dependences presented in this paper allow for estimations of duration of the first inrush current pulse for transformers with windings made of superconducting materials. They can be used to determine if the transformer's primary winding exited the superconducting state and to calculate the time during which it remained in the resistive state. The specified dependences can be easily used for calculation of parameters of subsequent unidirectional current pulses. In the first step, the residual magnetic flux density B_r shall be calculated before the next pulse occurs. By determining its value using equation (3), the θ angle can be calculated at which this pulse occurs. Further calculation procedure is the same as for the first pulse.

Based on the listed dependences, it is possible to determine the time when transformer's primary winding remained in the resistive state:

(14) $$t_{cw} = (\theta_c + \delta_{cw})\frac{\pi}{180\omega}$$

As shown in Figure 6, the unidirectional current pulse decays for the γ_0 angle. The γ_0 angle is determined by introducing $i=0$ and $\omega t=\gamma_0$ into formula (1). The following equation describes this angle:

(15) $$tg\gamma_0 = I_{cw}\frac{Z^2}{\sqrt{2}EX}K + M$$

where parameters K and M are as follows:

(16) $$K = \frac{1}{\left(\frac{R}{X}e^{\frac{R}{X}\alpha} - \frac{R}{X}\cos\alpha + \sin\alpha\right)\cos(\alpha + \delta_{cw})}$$ (17)

$$M = \frac{e^{\frac{R}{X}\alpha} - \frac{R}{X}\sin\alpha - \cos\alpha}{\frac{R}{X}e^{\frac{R}{X}\alpha} - \frac{R}{X}\cos\alpha + \sin\alpha}$$

Dependence (15) shows that the value of the γ_0 angle depends on the circuit's R/X ratio and the critical current value I_{cw} along with its correlated δ_{cw} angle (Fig. 10).

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