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The influence of the geometry and resistance of the high voltage winding of the HTS transformer on the inrush current parameters

Streszczenie. *W pracy dokonano analizy prądu włączania transformatorów nadprzewodnikowych. Wartość i czas zaniku prądu włączania zależą od wymiarów promieniowych i osiowych uzwojenia górnego napięcia. W przypadku transformatorów nadprzewodnikowych parametry te istotnie zależą też od stanu w jakim znajduje się nadprzewodnik. Analizy dokonano na podstawie pomiarów prądu włączania transformatorów nadprzewodnikowych o mocach 8,5 kVA i 13,8 kVA o różnej geometrii uzwojeń. (**Wpływ geometrii i rezystancji uzwojenia górnego napięcia transformatora HTS na parametry prądu włączania**).*

Abstract. *In this work we have analysed the inrush current of superconducting transformers. The value and time of decay of the inrush current depend on the radial and axial dimensions of the high voltage winding. In the case of superconducting transformers, these parameters also depend on the state of the superconductor. Analysis was made on the basis of measurements of the superconducting transformer inrush current of 8 kVA and 13.8 kVA with different winding geometries.*

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

Introduction

The inrush current of conventional transformers is a relatively well-known phenomenon. As regards superconducting transformers, there is comparatively little information on this subject. It is known that the inrush current of the superconducting transformers achieves higher values and longer decay times compared to the current of the conventional transformers. This is due to the different characteristics of superconducting windings, smaller dimensions of these windings and smaller magnetic cores of superconducting transformers. The study investigates the influence of the geometry and resistance of superconducting transformer windings on the values and decay time of inrush current on the basis of measurements of transformers of the power of 8.5 kVA and 13.8 kVA.

Effect of winding geometry

For the calculation of the maximum value of the first current pulse, the formula given by Specht [1] [2] is used:

$$I_M = \frac{E_m}{\omega L_a}\left(\frac{2B_m + B_r - B_n}{B_m}\right) \tag{1}$$

where L_a is the inductance of the ring coil without iron, given by the relation:

$$L_a = z^2 \mu_0 \frac{A}{l} \tag{2}$$

in which A is the cross-section area of the high voltage winding (HV) (Fig. 1):

$$A = \frac{\pi D^2}{4} \tag{3}$$

where D is the average diameter of the coil of the high voltage winding. The symbol l, occurring in formula (2), is the average length of the magnetic field lines that penetrate the coil. Other designations in the formulas: E_m – maximum voltage of the source, ω – pulsation, α – phase angle of the voltage, A – cross-section area of the winding, z – the number of coils, B_m – the maximum induction in the normal operation of the transformer, B_r – induction of residual magnetism, B_n – induction of core saturation.

From formula (1) it follows that with the increase in mean diameter of the coil of the high voltage winding D, the maximum value of the first switching current pulse decreases. This value also decreases with decreasing mean line lengths of magnetic field force l.

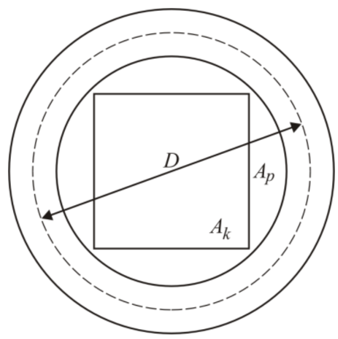

Fig. 1. Cross-section through the column and high voltage winding of the transformer

Dependence (1) leads to large computational errors. It does not take into account the resistance of the high voltage winding responsible for damping the inrush current. In addition, the mean length of the magnetic field line l corresponds to the average flow length in the transformer core, since the dependence (1) is derived assuming that the transformer core is winding its entire length.

Effect of superconductor resistance

According to dependence (4), the value of the unidirectional inrush current component depends on the resistance of the transformer's high voltage winding [3].

$$i = -\frac{\sqrt{2}EX}{Z^2}\left(\begin{array}{l}\dfrac{R}{X}\sin\omega t - \cos\omega t \\ +\left(\dfrac{R}{X}\sin\theta + \cos\theta\right)e^{-\frac{R}{X}(\omega t+\theta)}\end{array}\right) \tag{4}$$

In the case of superconducting transformers, the resistance of the high voltage winding depends on the state in which the superconductor is located. When the transformer is operating under nominal conditions, the windings are in the superconducting state and their resistance is zero. Thus the damping of the inrush current does not occur. The resistance of the high voltage winding increases rapidly when the inrush current pulse exceeds the value of the critical current I_c of the superconductor. The return to the superconducting state occurs when the instantaneous value of the inrush current pulse i decreases below the critical current I_c, while the winding temperature falls below the critical value T_c and the magnetic field strength falls below the critical value H_c. Such superconducting windings cause that the switching current of the superconducting transformer reaches higher values and longer decay times compared to conventional transformers.

Table. 1. Rated parameters [4][5]

Parameter	TrCu 8.5 kVA	TrHTS1 8.5 kVA	TrHTS2 8.5 kVA	TrHTS3 13.8 kVA
Power	8.5 kVA	8.5 kVA	8.5 kVA	13.8 kVA
Frequency	50 Hz	50 Hz	50 Hz	50 Hz
HV/LV voltage	220 V/110 V	220 V/110 V	220 V/110 V	230 V/60 V
HV/LV current	40 A/80 A	40 A/80 A	40 A/80 A	60 A/230 A
I_c/I_n HV/LV ratio	–	2.18/1.1	2.18/1.1	1.44/1.44
Magnetic induction	1.6 T	1.6 T	1.6 T	1.6 T
Neutral current	1.0 A	3.1 A	3.3 A	0.7 A
Short circuit voltage	8.5%	0.9%	4.8%	3.2%

Table. 2. Dimensions of windings [4][5]

Parameter		TrCu 8.5 kVA	TrHTS1 8.5 kVA	TrHTS2 8.5 kVA	TrHTS3 13.8 kVA
Internal radius of LV winding	r_{D1}	65.6	65.6	65.6	70
External radius of LV winding	r_{D2}	69.6	65.9	65.9	70.3
Average radius of LV winding	r_{DS}	67.5	65.75	65.75	70.15
Internal radius of HV winding	r_{G1}	77.9	67.9	77.9	88
External radius of HV windings	r_{G2}	85.9	68.6	78.6	88.4
Average radius of HV windings	r_{GS}	81.9	68.25	78.25	88.2
Thickness of LV winding	k_{DN}	4	0.3	0.3	0.3
Thickness of HV winding	k_{GN}	8	0.7	0.7	0.4
Height of the winding	h	140	140	140	130
Lower winding distance from the core	h_{P1}	45	45	45	60
Upper winding distance from the core	h_{P2}	45	45	45	60
Width of air gap	δ	8.3	2	12	17.7
Average radius of air gap	r_δ	73.75	66.9	71.9	79.15

Table. 3. Winding parameters [4][5]

Parameter	TrCu 8.5 kVA	TrHTS1 8.5 kVA	TrHTS2 8.5 kVA	TrHTS3 13.8 kVA
Number of HV/LV coils	132/66	132/66	132/66	84/22
Material of HV and LV windings	Cu	Super Power SCS4050 (Re)BCO	Super Power SCS4050 (Re)BCO	Super Power (Re)BCO SCS4050-AP /SCS12050-AP
Critical current	-	115 A	115 A	87 A/333 A
Dimensions of HV and LV windings	2.0×4.0 mm	0.1×4.0 mm	0.1×4.0 mm	0.1×4.0 mm /0.1×12.0 mm
Length of HV/LV winding wires	68 m/28 m	55 m/27 m	65 m/27 m	46.6 m/9.7 m
Resistance of HV/LV windings (294K)	Ω/63 mΩ	6.36 Ω/3.1 Ω	7.24 Ω/3.1 Ω	2.9 Ω/0.57 Ω
Resistance of HV/LV winding (77K)	-	$0.055 \cdot 10^{-18}$ Ω /$0.027 \cdot 10^{-18}$ Ω	$0.065 \cdot 10^{-18}$ Ω /$0.027 \cdot 10^{-18}$ Ω	$0.0466 \cdot 10^{-18}$ Ω /$0.0097 \cdot 10^{-18}$ Ω
Resistance of HV/LV winding after switching to resistive state (77K)	-	27 μΩ/13 μΩ	32 μΩ/13 μΩ	23 μΩ/5 μΩ
Inductance of HV/LV windings	2.0 mH/0.4 mH	1.7 mH/0.4 mH	2.0 mH/0.4 mH	290 μH/18 μH
Sectional area of HV winding	0.0211 m^2	0.0138 m^2	0.0192 m^2	0.0244 m^2

Superconducting transformers

Four transformers were tested: three 8.5 kVA ones [4] and one 13.8 kVA one [5]. The 8.5 kVA transformers had the same coil core RZC-70/230-70. Made of electrical sheet PN PN52-27 with a thickness of 0.27 mm and silicon content of 3%, minimum magnetic induction B_m=1.7 T corresponding to field strength H_m=1000 A/m and loss P=0.8 W/kg at B=1 T and f=50 Hz. However, their material and geometry of the windings differed. The TrCu transformer had windings made of copper, while the TrHTS1 and TrHTS2 ones had their windings of superconducting tape. The TrHTS3 transformer had a power of 13.8 kVA and the windings were wound with a superconducting tape. It was made on the bevelled and stepped core, in the sheet metal cutting of 4, 3, 1. The core material was sheet M150-30S. The sheet thickness was 0.3 mm, the silicon content 3%, the maximum total loss 0.97 W/kg at 50 Hz and 1.5 T and 1.5 W/kg at 1.7 T, the minimum magnetic induction 1.75 T at H=800 A/m. The ratings and parameters of the coils are given in Tables 1, 2 and 3. Figure 1 shows the dimensions of the windings in the tables.

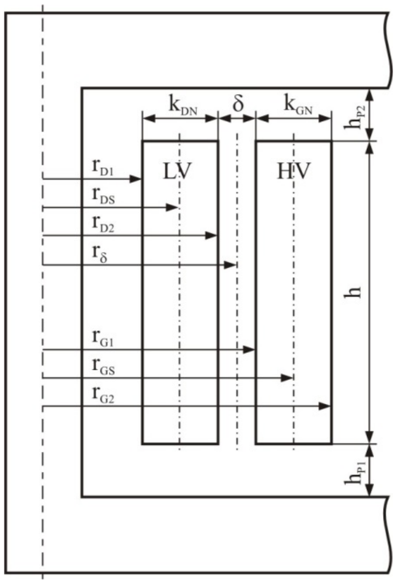

Fig. 2. Basic dimensions of windings

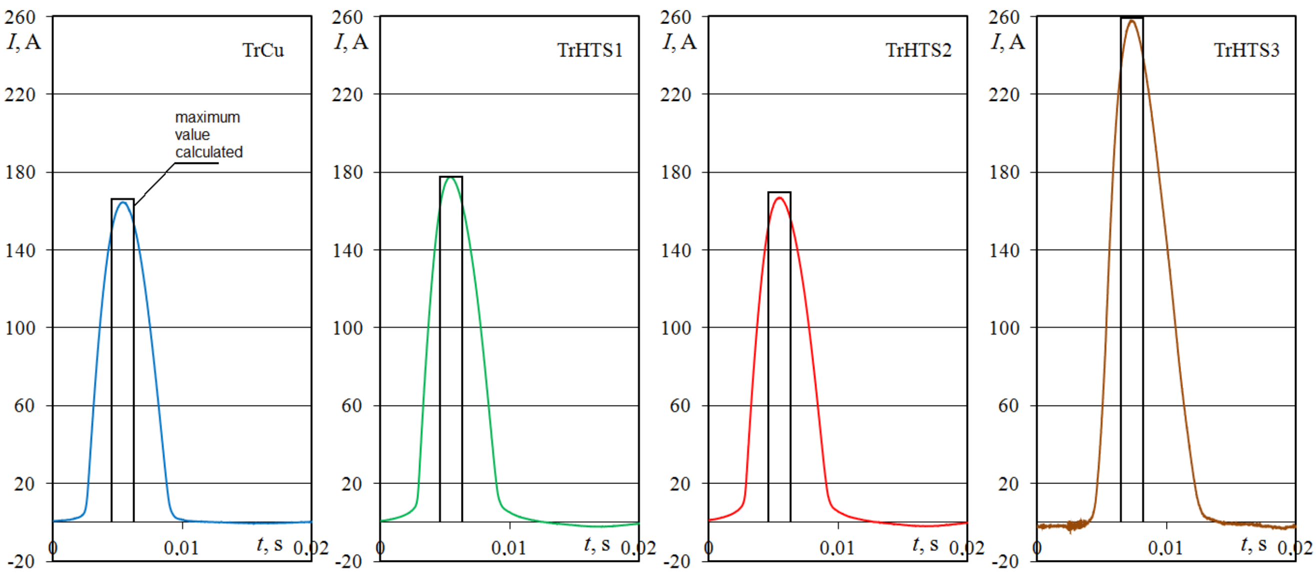

Fig. 3. First impulses of the inrush current of transformers TrCu, TrHTS1, TrHTS2, TrHTS3

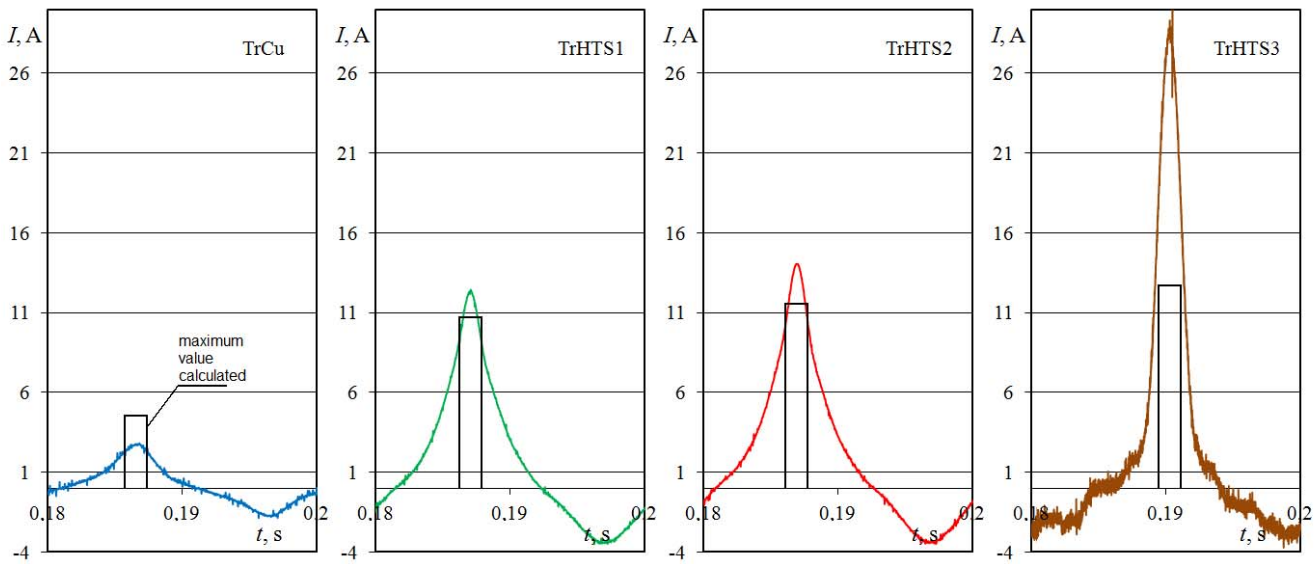

Fig. 4. Impulses of the inrush current of transformers TrCu, TrHTS1, TrHTS2, TrHTS3 after 180 ms

Computational algorithm

The maximum value of the first and next inrush current pulses of HTS transformers can be calculated from:

(5) $$I_m = \frac{\sqrt{2}E}{R}\sin\beta_c$$

where angle β_c is given by the equation:

(6) $$\tan\beta_c = \frac{R}{X}\left(I_c\frac{R^2+X^2}{\sqrt{2}EX}C+D\right)$$

(7) $$C = \frac{1}{\left(e^{\frac{R}{X}\lambda_c}-\frac{R}{X}\sin\lambda_c+\frac{R^2}{X^2}\cos\lambda_c\right)\cos(\theta_c-\lambda_c)}$$

(8) $$D = \frac{e^{\frac{R}{X}\lambda_c}-\frac{R}{X}\sin\lambda_c-\cos\lambda_c}{e^{\frac{R}{X}\lambda_c}-\frac{R}{X}\sin\lambda_c+\frac{R^2}{X^2}\cos\lambda_c}$$

The angle λ_c from equations (7) and (8) is given by:

(9) $$\lambda_c = \theta_c - \beta_c$$

where angle θ_c describes the equation:

(10) $$tg\theta_c = I_c\frac{R^2+X^2}{\sqrt{2}EX}A+B$$

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

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

The angle τ_c in equations (11) and (12) is given by:

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

where angle θ is:

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

The angles in equations (5) to (14) are related to the course of the one-way inrush current pulse, as shown in Figure 3. It was assumed that the transformer had been switched on for angle $-\pi$.

Summary

The measurements show that between transformers TrHTS1 and TrHTS2 there is a difference in the maximum values of the impulses of the inrush current. The windings of these transformers are made of the same superconducting tape. The difference is due to the different sizes of the primary windings of the two transformers. The axial dimensions of the two windings are the same, while the TrHTS2 transformer windings have larger radial dimensions.

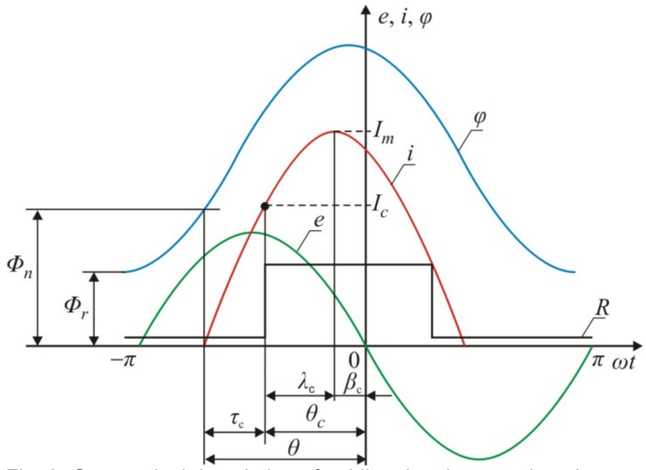

Fig. 3. Geometrical description of unidirectional current impulse

By comparing the results of the inrush current measurement with the results of calculations of the maximum value of impulses of this current, it is clear that for the first impulses of the inrush current good convergence is obtained for all transformers. The relative error between the measured and calculated value does not exceed 1%. This error grows for the tenth pulse. For transformers TrHTS1 and TrHTS2 the calculation error is up to 18%. The biggest error was 70% for the TrCu transformer. A slightly smaller error of 58% was reported for the TrHTS3 transformer.

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BIBLIOGRPHY

[1] Z. Spoljaric, V. Jerkovic, M. Stojkov, Measurement system for transformer inrush current higher harmonics determination, Annals of DAAAM for 2012 & Proceedings of the 23rd International DAAAM Symposium, vol. 23, no.1, 2012,

[2] N. Chiesa, B. A. Mork, H. K. Høidalen, Transformer model for inrush current calculations: simulations, measurements and sensitivity analysis, IEEE Transactions on Power Delivery, vol. 25, no. 4, pp. 2599-2608, 2011,

[3] G. Komarzyniec, J. Kozieł, P. Surdacki, The calculation of the inrush current peak value of superconducting transformers, Selected Problems of Electrical Engineering and Electronics (WZEE), Kielce, 2015,

[4] G. Wojtasiewicz, T. Janowski, S. Kozak, J. Kozak, M. Majka, B. Kondratowicz-Kucewicz, Tests and Performance Analysis of 2G HTS Transformer, IEEE Transactions on Applied Superconductivity, vol. 23, no. 3, June 2013,

[5] G. Komarzyniec, M. Majka, 13,8 kVA transformer with windings made of YBCO HTS tapes, Przegląd Elektrotechniczny, nr 12/2016, s. 69-72,