International Journal of Electrical and Computer Engineering (IJECE)
Vol. 11, No. 1, February 2021, pp. 155~162
ISSN: 2088-8708, DOI: 10.11591/ijece.v11i1.pp155-162

Computational and experimental study of air-core HTS transformer electrothermal behaviour at current limiting mode

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Article Info

Article history:

Received Sep 16, 2018
Revised Jul 3, 2020
Accepted Jul 31, 2020

Keywords:

Computer simulation
Fault current limiting
High-temperature superconductivity
HTS transformer
Power transformers

ABSTRACT

The paper provides the results of the experimental and computational study of the processes occurring in high temperature superconducting transformer windings while secondary winding is short-circuited. The obtained mathematical simulation matches closely with the experimental results. The temperature variation curves for superconducting windings were analysed, and conclusions were made on the necessity of changes in HTS transformer design, namely the necessity of windings heat-insulation from each other and adding a high-resistance coating material for HTS wire in HTS transformer primary winding.

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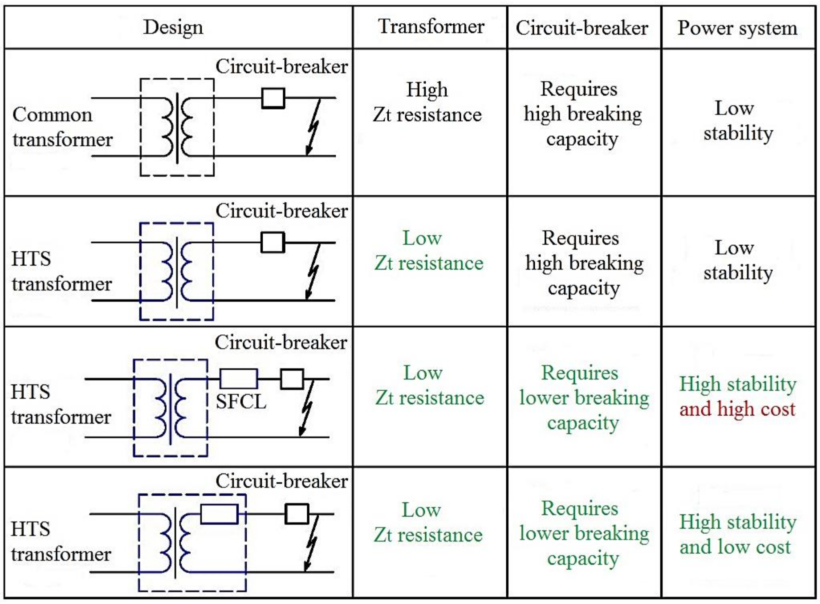
1. INTRODUCTION

The power engineers of tomorrow will inevitably face the problems caused by common increase in power consumption and, consequentially, in power generation [1]. One of the key factors, which occurs even today, is a population mass switching to electric cars. The author of [2] has calculated over 200% load on distribution network power equipment would be expected even at 47% switch from common cars to electric ones should power demand of electric cars charging plants be unregulated. Considering just this one of many factors, conclusion can be made that load density will exceed up-to-date allowable limits in large cities.

Considering this, applying technologies based on high-temperature superconductivity (HTS) becomes a relevant solution to the resulting problems. Namely, they are superconducting cables to increase power line rating without changing its voltage, and current limiters to decrease fault currents, which increase due to increase in supply system power. Currently, there are many types of HTS current limiters [3-12] because the process of current limiting itself occurs due to the unique property of HTS wires, used in these limiters, to lose their superconductivity when current exceeds a certain value. Therefore, attaining current limiting properties doesn't require developing any dedicated devices but integrating this new effect into the known and commonly used ones: transformers, electric machines, cables. The advantages of this integration are illustrated with an example of a transformer in Figure 1 (in order to emphasize inconsistency in Russian terminology, the author uses another term for HTS current limiter: SFCL [superconducting fault current limiter]; the term HTS current limiter is used further in the text).

This paper focuses on the problems encountered in the integration of common transformer characteristics and HTS current limiter into one device. In particular, the problem of transformer windings overheating at current limiting mode is considered. The criteria for selecting of HTS transformer parameters, based on placing restrictions on the state curve, are developed along with justification of some requirements for windings design.



Design	Transformer	Circuit-breaker	Power system
Common transformer — Circuit-breaker	High Zt resistance	Requires high breaking capacity	Low stability
HTS transformer — Circuit-breaker	Low Zt resistance	Requires high breaking capacity	Low stability
HTS transformer — SFCL — Circuit-breaker	Low Zt resistance	Requires lower breaking capacity	High stability and high cost
HTS transformer — Circuit-breaker	Low Zt resistance	Requires lower breaking capacity	High stability and low cost

Figure 1. Design versions of a power grid with and without HTS current limiters (in the figure, SFCL means "superconducting current limiter")

2. PROBLEM DESCRIPTION

A profound understanding of a problem, encountered in the attempt of designing an HTS device, requires considering the processes of various scales and physical nature. To begin with, the design of HTS wire should be examined. HTS wire is a composite tape see in Figure 2 which has a finest ceramic layer with superconducting properties: yttrium barium copper oxide (YBCO); all the other layers ensure protection from stress and chemical exposure. It should be noted that the described superconducting properties appear only when HTS wires are cooled to sufficiently low temperatures [13]. For example, YBCO has a critical temperature of 93 K at which superconducting properties appear. To achieve efficiency in performance, superconductors are commonly immersed in a low-temperature medium such as liquid nitrogen with a boiling point at 77 K.

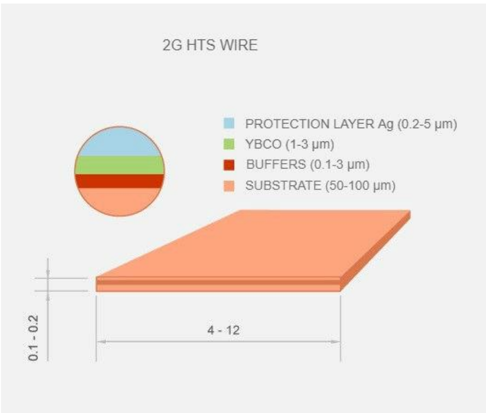


Figure 2. Second generation HTS wire (measurements are shown in mm)

However, the external layer of material, which provides protection, usually is also the main circuit for current to flow in for the case of superconducting properties loss. Moreover, at present, a technology for manufacturing superconducting wires enables a wide variety of metals to be used as a protection layer: stainless steel, bronze, etc. This enables to select a superconducting wire with the desirable properties.

It is obvious from the foregoing that current limiting occurs due to HTS wire superconducting properties loss. Thus, in terms of electronics, any HTS device should be considered a component with non-linear current-voltage characteristic (I-V curve). The non-linear segment gradually changes into the linear one as current increase on account of current mainly flowing in a relatively linear part of HTS wire non-superconducting layers, which is due to increase of superconducting layer resistance [14]. However, any current flowing in non-superconducting layers results in Joule losses in non-superconducting material bulk. This results in wire temperature excursion, which may cause its self-destruction. Thus, when designing HTS devices for power industry needs, potential consequences of emergency states should be considered. This problem becomes particularly difficult when designing HTS current-limiting transformers.

3. HTS TRANSFORMER: EXPERIMENTAL SETUP DESCRIPTION

Further correct mathematical descriptions of HTS transformer electrothermal behaviour require obtaining the oscilloscope graphs for current and voltage in HTS transformer windings at the known parameters of the experiment. For this purpose, an experimental setup was built: a transformer with HTS windings and open magnetic structure. The transformer scheme is shown in Figure 3 and the photo is in Figure 4. Table 1 provides the main parameters of the item. The built transformer is of the warm iron type, i. e. operating at the near-room temperature.

Figure 4 illustrates the scheme of the performed experiment. The primary winding of the HTS transformer was directly connected to 220 V mains. The secondary winding was examined in two states: open-circuited and short-circuited ones. The interest in these two states of the secondary winding will be explained further on when developing a mathematical simulation. Currents in primary and secondary windings along with their voltage drop were measured via FLUKE 435-II register. The results of the experiment together with the simulation results are provided in Chapter 5 of the paper.

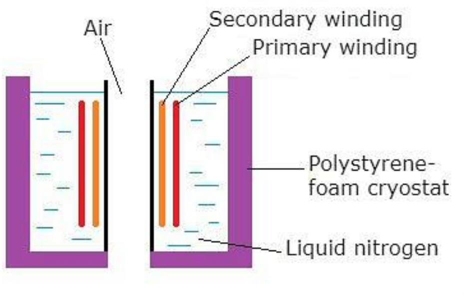


Figure 3. Experimental setup scheme

Figure 4. HTS transformer appearance, spools with windings (on the left), windings immersed in cryostat (on the right)

Table 1. Design parameters of the HTS transformer

Parameter	Primary winding	Secondary winding
Cross-section area of the HTS tape, manufactured by SuperOx, mm^2	0.4	
Critical current of the tape, A	80	160
Voltage, V	220	110
Rated current, A	50	100
Number of turns	47	23
Windings hight, mm	210	215
Windings diameter, mm	130	110
Inductance, mH	~0.16	~0.4
Insulation	Kapton	
Cooling medium	Liquid nitrogen	
Core	Air	

4. HTS TRANSFORMER: SIMULATION OF ELECTROTHERMAL BEHAVIOUR AT CURRENT LIMITING MODE

Consistent with the scheme in Figure 5, we developed electrics of the mathematical simulation, which includes transformer differential equations for describing the transient processes occurring in it [15]. The assumption here is that the transformer magnetic structure has zero losses and does not reach saturation.

$$L_1 \frac{di_1}{dt} + i_1(R_{sc1}(i,T) + R_1) + M \frac{di_2}{dt} = Usin(\omega t) \quad (1)$$

$$L_2 \frac{di_2}{dt} + i_2(R_{sc2}(i,T) + R_2(t)) + M \frac{di_1}{dt} = 0 \quad (2)$$

Here L1 and L2 are the inductances of the transformer primary and secondary windings, correspondingly, H; M is the transformer windings mutual inductance, H. R1 and R2 are the resistances of the primary and secondary windings circuits, Ohm, due to non-superconducting wires and terminals resistance along with supply system resistance for R1, and load resistance for R2; R2 dependence on time represents the resistance change in case of short circuit. i1 and i2 are the currents in the primary and secondary windings, A; U is the magnitude of a supply (power system) voltage, V; ω is the angular frequency, rad/s. Rsc1 and Rsc2 are the non-linear resistances of the HTS transformer windings, which are dependant on their current i and temperature T, Ohm.

The following expression is commonly used to describe a non-linear I-V curve of an HTS wire on the assumption that HTS wire has equal properties lengthwise:

$$R_{sc}(I,T) = \left(\frac{1}{\frac{E_0}{i}\left(\frac{i}{I_c(T)}\right)^n} + \frac{1}{R_{layers}(T)} \right)^{-1} \quad (3)$$

Here $I_c(T)$ is the current which, by convention, is set to be conductor critical current, A; it is taken to be equal to 80A for this wire at liquid nitrogen temperature (77K). The current at which electric strength of the field inside the superconductor equals 1 μV/cm is commonly called critical current (the criterion was suggested by an HTS tape manufacturer); E_0 is the winding voltage at critical current, V; n is the power index for I-V curve of a superconducting tape, which is taken to be equal to 15 and temperature-independent. R_{layers} is the HTS tape non-superconducting layers resistance, which is temperature-dependent, Ohm. For information on specific resistance and heat capacity refer to the support literature, in this paper information from [16-18] was used. Whereas in expression 3, critical current I_c behaves according to the following law [18]:

$$I_к(T) = -\frac{I_{c0}}{0{,}1848} \ln\left(\frac{T}{93}\right) \quad (4)$$

Note that critical current may be considered equal to zero when the temperature rises above 90 K.

The winding heating process should be taken into consideration to develop an adequate simulation. Heat balance equation is developed to consider superconducting coil heating. This is on the assumption that temperature distribution is uniform through HTS coil bulk, we also neglect coil insulation material effect on temperature variation and hysteresis occurrence at liquid nitrogen boiling:

$$\frac{dT}{dt} = \frac{Q(I,R_{sc}) - Aq(\Delta T)}{C_\Sigma(T)} \quad (5)$$

where Q is the amount of heat in the coil bulk, which loses superconductivity at current flowing in it per unit time, W; A is the area of the coil surface, m^2; q is the specific heat flow from unit area of the coil surface to liquid nitrogen per unit time see in Figure 5, W/m^2; C_Σ is the HTS coil total heat capacity, which is temperature-dependent, J/K [16, 17].

The amount of heat, created by the current flowing in HTS winding, may be found as shown below:

$$Q(I,R_{sc}) = i(R_{sc})^2 R_{sc}(T) \quad (6)$$

Specific heat flow q is a complicated function of the temperature difference between a surface being cooled and liquid nitrogen, this function is shown in Figure 6. As is obvious, when superconducting coil is significantly overheated, heat withdrawal won't be effective, which causes further overheat until HTS wire heat breakdown occurs.

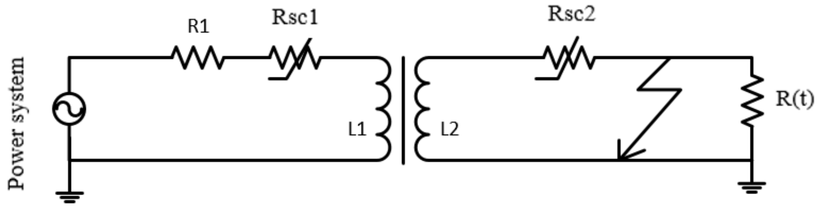


Figure 5. Scheme of the experiment

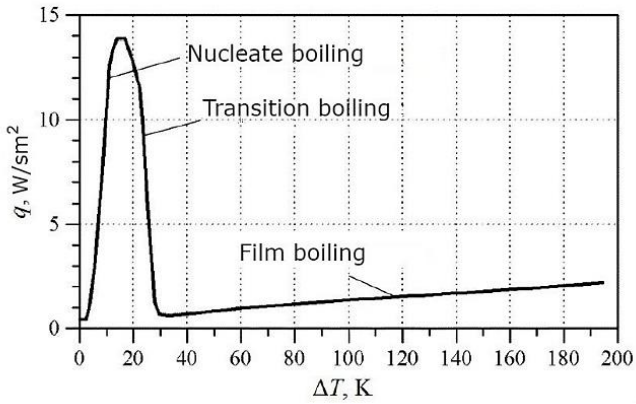


Figure 6. Specific heat flow as a function of the temperature difference between a surface being cooled and a liquid coolant [19]

5. THE RESULTS OF CURRENT LIMITING STUDY AND OPTIMISATION OF THE TRANSFORMER HTS WINDINGS

A simultaneous computational solving of the (1-6) for the known parameters from Table 1 allows obtaining an approximate simulation of HTS transformer electrothermal behaviour as shown in Figures 7-9. Figure 7 shows a comparison between the results of the experiment and computer simulation of current limiting in HTS transformer windings. The fact that experimental current-limiting curves and ones of simulation match closely allows rather accurately extrapolating the experimental results to more prolonged short-circuit, which commonly can't be observed through the experiment due to the threat of equipment damage or mains circuit-breaker tripping.

As mentioned above, the experiment was carried out at directly applying 220 V to the HTS transformer primary winding. The extrapolated current curves at 220 V are shown in Figure 8. The curves of temperature variation in the windings according to the (5 and 6) are also shown here. Because a direct measurement of the windings temperature is rather difficult, the temperature curves based only on the simulation results are provided. Note that the results of current and temperature simulation for the transformer match closely with the corresponding electrothermal behaviour curves for a current limiter [20-25]. Let us focus on two observations resulting from the obtained results.

– First, limiting of the primary winding current results in deterioration of the conditions for current transformation to the secondary winding and, therefore, its reduction. This means that current in the secondary winding can't cause superconductor resistance increase in the secondary winding just as efficiently. Hence, there is little point in coating the secondary winding HTS wire with a metal of high ohmic resistance.
– Second, note that the primary winding temperature appeared to be higher due to its higher damping resistance. However, when applying 220 V to the primary winding thermal stabilization, which is potentially indefinite, is observed. However, all other conditions being equal, a higher voltage of 380 V is applied to the primary winding (Fig. 9), we will observe a quench in the primary winding, i.e. the winding temperature increased to the point of liquid nitrogen film boiling, and heat withdrawal from the windings can't be efficient anymore, which soon results in an intolerable temperature rise. Note that, as mentioned above, due to deterioration of the conditions for transformation, the current in secondary winding is unable to cause any significant overheat of the winding.

– Unfortunately, in a real HTS transformer convection heat transfer from primary winding to secondary one inevitably results in secondary winding resistance increase. Eventually, the secondary winding current will cause even more heat release, which in turn will result in even more overheat of both windings. It offers to require of HTS transformer design that its windings have maximum heat-insulation from each other to avoid the effect described above.

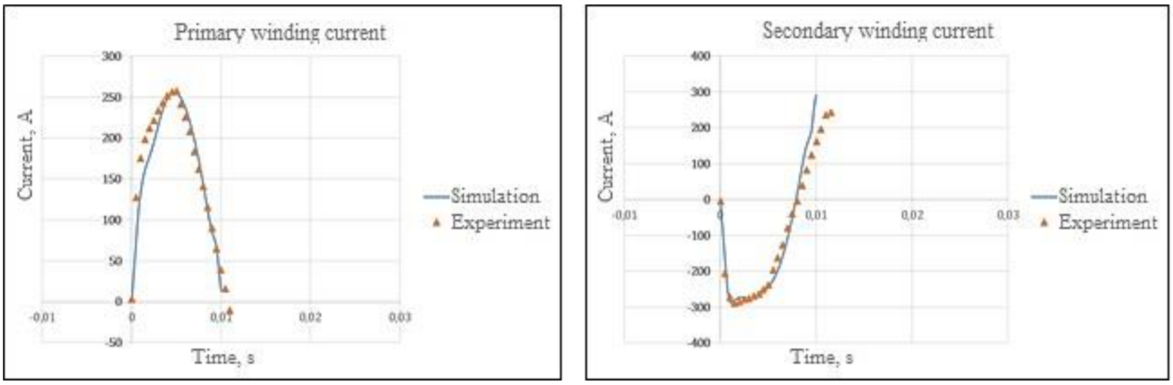


Figure 7. The results of the experiment, performed consistent with the scheme in Figure 5, and computer simulation of winding currents according to the expressions (1-6)

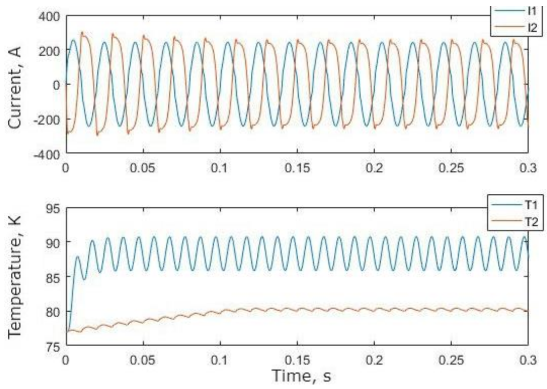


Figure 8. The results of HTS transformer windings electrothermal behaviour simulation at applying mains voltage of 220 V, thermal stabilization is observed (the subscript 1 indicates the processes in the primary winding; the subscript 2, in the secondary one)

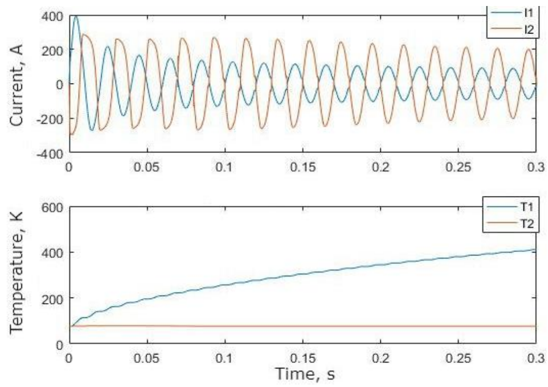


Figure 9. The results of HTS transformer windings electrothermal behaviour simulation at applying mains voltage of 380 V, quench is observed (the subscript 1 indicates the processes in the primary winding; the subscript 2, in the secondary one)

6. CONCLUSION

The physical model of HTS transformer was built to study the processes of current limiting on the basis of YBCO HTS tape with a copper coating. Based on the obtained experimental results: applying mains voltage (220 V) to the primary winding of the transformer while the secondary one is short-circuited, the current-limiting curves were obtained and the process mathematical simulation, which describing the experimental results acceptably, was developed. The pattern of the device thermal behaviour is obtained on the basis of this simulation under the assumption that the device windings are lumped components with isotropic properties of HTS tape and surrounding coolant. Two important conclusions, which determine the further efficiency of HTS transformer design, were made from the results of its electrothermal behaviour analysis: a) The HTS transformer windings should be heat-insulated from each other to prevent heat transfer by convection between them and the resulting cascade overheat. b) Only primary winding HTS wire should be coated with a damping resistance material, because secondary winding damping resistance efficiency decreases measurably due to deterioration of the conditions for current transformation at current limiting. The temperature curves presented above require experimental verification, which is projected for the future. The mathematical simulation requires considering distributed parameters of HTS tape material and specifics of windings convection.

ACKNOWLEDGEMENTS

The research was carried out under the State Assignment of the Ministry of Education and Science of the Russian Federation, Project 8.6809.2017/8.9.

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