International Journal of Electrical and Computer Engineering (IJECE)
Vol. 13, No. 1, February 2023, pp. 238~248
ISSN: 2088-8708, DOI: 10.11591/ijece.v13i1.pp238-248

Methodology for determining the parameters of high-temperature superconducting power transformers with current limiting function

Vadim Zinovievich Manusov[1], Dmitriy Mihailovich Ivanov[1], Arseniy Valerievich Semenov[1], Gennady Viktorovich Ivanov[2]
[1]Department of Power Supply Systems, Novosibirsk State Technical University, Novosibirsk, Russian Federation
[2]Department of Radio Electronics and Electrical Engineering, Surgut State University, Surgut, Russian Federation

Article Info

Article history:

Received Sep 9, 2021
Revised Aug 12, 2022
Accepted Sep 3, 2022

Keywords:

Design methodology
Energy efficiency
High-temperature superconductivity
High-temperature superconducting transformers
Liquid nitrogen
Short-circuit current limitation

ABSTRACT

This paper substantiates a new adaptive method for determining parameters of high-temperature superconducting power transformers with current limiting function. The main focus is the design of current-limiting superconducting windings in the light of new restrictions on current density, magnetic induction, critical current and critical temperature. The presented method considers the nature of alternating current (AC) losses in a superconductor under nominal operating conditions, features of the dielectric medium (liquid nitrogen), as well as the reduced values of the short-circuit voltage (0.5 to 1.5%). The main design features of high-temperature superconducting (HTS) transformers are specified, and a prototype of a three-phase HTS transformer of 63 kVA with a short-circuit current limiting function is developed. It is shown that HTS units have some advantages over conventional transformers: a 90 to 95% active losses reduction, short-circuit current limitation function, explosion and fire safety, a 60% reduction in weight and size, and increased efficiency (up to 99.8%). Experimental studies confirm that the short-circuit current limitation function is safe and efficient. It is demonstrated that during the short-circuit current limitation, significant heat flows occur on the windings, which should not exceed the critical value above which the superconductor could not return to the superconducting state by itself.

Corresponding Author:

Dmitriy Mihailovich Ivanov
Department of Power Supply Systems, Novosibirsk State Technical University
20, Karl Marx prospekt, Novosibirsk, 630073, Russian Federation
Email: mrdemasi123@gmail.com

1. INTRODUCTION

High-temperature superconducting (HTS) transformers are the most innovative solution when it comes to electric power systems modernization and improved energy efficiency. The design and research of transformers with high-temperature superconducting windings are of great interest and are described in publications of scientists from leading world institutes [1], [2]. Attempts are made to optimize the design and technical characteristics of HTS transformers from the side of energy efficiency, energy saving and reduction of weight and size [3]. In [4], the results of the work of many design and research teams that developed about 20 HTS transformers in the power range of 25 to 5,000 kVA were collected and analyzed. However, despite the considerable interest of the scientific community in HTS transformers, there are no well-founded methods and principles of designing such electric machines. That is why developing a novel methodology for determining parameters and designing HTS transformers, taking into account the superconductor's particular properties, is an important contemporary challenge.

General research approach of HTS transformers is characterized as systematic due to the wide coverage of various design processes when using HTS technologies for voltage transformation and their interaction with other elements or electric power system objects. This study's main purpose is to determine the basic requirements and conditions for the engineering and design of HTS transformers. Special attention is paid to searching for optimal and economically feasible designs of windings, cryostat and magnetic core of the transformer, exemplified by a three-phase prototype of a 63 kVA HTS transformer with a current limiting function. A case study of voltage transformation and the short-circuit currents limitation, as the two most essential components of the performance of an electric power system, is carried out, based on a single device. Results of computer models as well as experiments are provided and confirmed the benefit of our methodology. Our focus lies on studying the possibility of the HTS transformer to limit the fault current due to a sharp increase in the conductor's resistance when the critical current or temperature is exceeded.

2. PROPOSED METHOD FOR DETERMINING THE ELECTRICAL PARAMETERS OF HTS TRANSFORMERS

Transformers have significant resistances and affect the energy losses in the mains, the voltage deviations at consumer locations, and therefore play a crucial role in the calculations and analysis of the operation of electric power systems. Currently, there is no established methodology for determining parameters of HTS transformers. The analysis of the designed experimental models [5]–[9] allows adapting the classical methods for new method for determining the parameters of transformers to HTS machines with current limiting function. Our study is aimed at developing a HTS transformer for reliable current limitation in the light of new restrictions on current density, magnetic induction, critical current and critical temperature of superconductor.

2.1. Current density and core induction

The main difference between HTS and conventional transformers is the windings. The windings consist of HTS wires made of second-generation superconductors. The thickness of the second-generation HTS wires manufactured by the company "S-Innovations" is only 0.1 to 0.2 mm. However, the average operating current density of such a wire at a temperature of 77 K is 200 to 400 A/mm^2, which is two orders of magnitude higher than in a copper wire. When choosing the values of current density and magnetic induction during the transformer designing, it is necessary to consider the dependence of the critical current density J_c on the magnetic induction B [10]. Figure 1 shows the $J_c(B)$ dependences for Yttrium barium copper oxide (YBCO) superconductors for the temperature range 10 to 77 K [11].

The above dependence allows determining an optimal range for choosing the transformer core magnetic induction when a sufficient critical current density is maintained. This current ensures a high performance of the HTS wire under the nominal operating conditions without loss of superconductivity. When analyzing the dependences of $j_c(B)$ for different cross-sections of HTS YBCO wires, it is proposed to accept a range of inductances of the magnetic core rod equal to 1.1 to 2 T. This range ensures high values of the critical current density and obtains optimal values of the idle current and magnetic losses in the core. Furthermore, it allows experimentally achieving a wide range of the calculated inductions for magnetic systems of HTS transformers for various grades of hot-rolled, cold-rolled and amorphous steels. If required, the induction can be selected to provide lower critical current values to optimize the transformer for regions with a large number of two-phase and single-phase short circuits. The lower critical current effectively protects the transformer from short circuits. However, it is unnecessary to overestimate the value of induction. The reason is idle losses, since they are prevalent in HTS transformers due to the lack of resistance in the windings under nominal operating conditions.

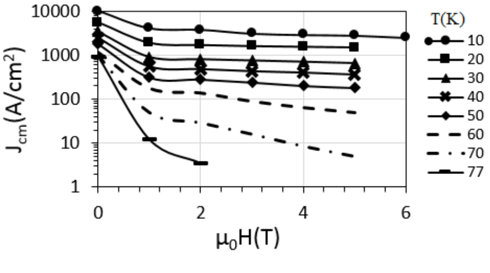


Figure 1. Critical current density J_{cm} as a function of the magnetic induction at different temperatures

2.2. HTS transformers losses

The main losses in transformers are losses in the windings-electrical losses, and losses in the steel core-magnetic losses or core losses. Short-circuit losses (SC) in HTS transformers are in stark contrast to the conventional ones. There are various theories and methods how to characterize alternating current (AC) losses in superconductors [12]–[15]. The authors of such papers specify the dependence of the losses on the value and direction of the alternating magnetic field. Depending on the source of the alternating magnetic field, the losses are split into two components: i) losses from self-induced field-caused by the magnetic field from the flowing current and ii) losses from the external field-are determined by the leakage field of the windings. Losses from self-induced field are determined as [16]:

$$\Delta P_{SF1}(I_T) = \frac{f\mu_0 I_C^{\,2}}{2\pi}\left[\left(2-\frac{I_T}{I_C}\right)\frac{I_T}{I_C}+2\left(1-\frac{I_T}{I_C}\right)\ln\left(1-\frac{I_T}{I_C}\right)\right] \tag{1}$$

where I_C is the critical current, I_T is the transport current (the maximum current in the conductor), μ_0 is the magnetic constant, f is the frequency.

However, expression (1) is valid only for windings made of a single wire. Laying parallel-connected conductors in windings changes the distribution of the magnetic field inside the superimposed wires. The dependence shown in Figure 2 [17] indicates a significant increase in losses, coming from the magnetic self-induced field, with an increase in the number of parallel wires in the windings.

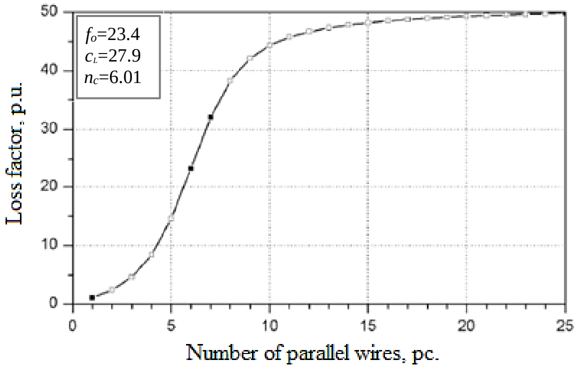


Figure 2. Dependence of the loss factor on the number of parallel wires

The total losses from the self-induced field in the windings are:

$$\Delta P_{SF} = 3(n_{pHV}\cdot k\cdot \Delta P_{SF1}(I_{THV}) + n_{pLW}\cdot k\cdot \Delta P_{SF1}(I_{TLW})) \tag{2}$$

where n_{pHv} and n_{pLW} are the numbers of parallel wires in the high voltage (HV) and low voltage (LV) windings, k is the loss factor, I_{THV} and I_{TLW} are the transport currents in HW and LW windings.

In wire superconductors, an external perpendicular magnetic field leads to higher losses than a field parallel to the plane of the conductor. In general, the losses from the external field can be split into two components. On the one hand, the hysteresis losses in superconductors are determined by (3) [18]:

$$\Delta P_H = I_C a_{HTS} B f \tag{3}$$

where a_{HTS} is the width of the wire superconducting layer.
On the other hand, Eddy current losses induced in non-superconducting layers of the HTS wire are [19]:

$$\Delta P_{Eddy} = \frac{\pi^2 b_{Me} a_{Me}^{\;3}}{6\rho}(Bf)^2 \tag{4}$$

where b_{Me} is the thickness of the metal layers of the superconducting tape, a_{Me} is the width of the wire's metal layer, and ρ is the resistivity.

Besides the losses due to the magnetic field, explained above, resistive losses in transformer current leads are also present. They are determined according to the equation given in (5) [16]:

$$\Delta P_{C.L.} = \frac{I^2}{A_{C.L.}}\int_0^l \rho_{C.L.}(x)dx + A_{C.L.}\lambda_{C.L.}(T)\frac{dT}{dx} \qquad (5)$$

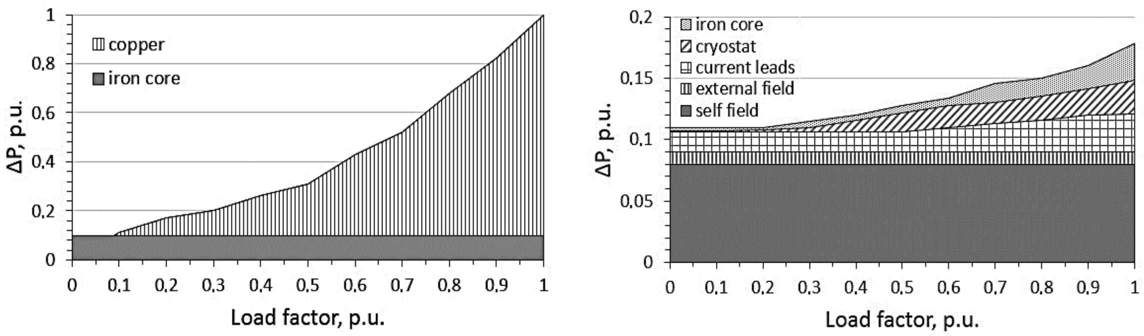
where I is the current flowing in the current lead, $A_{C.L}$ is the cross-sectional area of the lead, l is the length of the lead, $\rho_{C.L}$ is the resistivity of the lead, $\lambda_{C.L}$ is the coefficient of thermal conductivity of the lead, T is the temperature.

It is worth noting that also heat losses ΔP_{cryo} pass through the surface of the cryostat. Depending on the cryostat material, the heat leakage should not exceed 2.5 W/m^2 [6], [16]. Adding up all losses, the total losses in the windings of the HTS transformer become (6).

$$\Delta P_{SC} = \Delta P_{SF} + \Delta P_H + \Delta P_{Eddy} + \Delta P_{C.L.} + \Delta P_{cryo} \qquad (6)$$

Core losses ΔP_{core}, depending on the square of the magnetic induction B, are similar for HTS transformers as well as for conventional ones. Figure 3 shows a general comparison of all the losses in conventional Figure 3(a) and HTS Figure 3(b) transformers [16], [20]. The total loss of a superconducting transformer is ultra-low compared to conventional transformers. In the idle state, the losses of a superconducting transformer are 50%, and in the full load state, only 10% of the losses of conventional transformers.

Most of the losses (about 75%) of conventional transformers are caused by resistive losses in the windings, whereas about 25% are the result of the iron core work. The main portion of the losses of a superconducting transformer are the core losses (~67.2%). Because the losses in the HTS transformer windings do not depend on the current density, it can be concluded that the transformers can operate with nearly highest efficiency at any load factor. Figure 4 shows the dependence of the efficiency on the load factor for conventional and HTS transformers. When fully loaded, the efficiency of the HTS device can reach 99.9%, exceeding the efficiency of the conventional one by 0.3 to 0.4%.



(a) (b)

Figure 3. Dependence of losses on the load factor for (a) conventional transformers and (b) HTS transformers

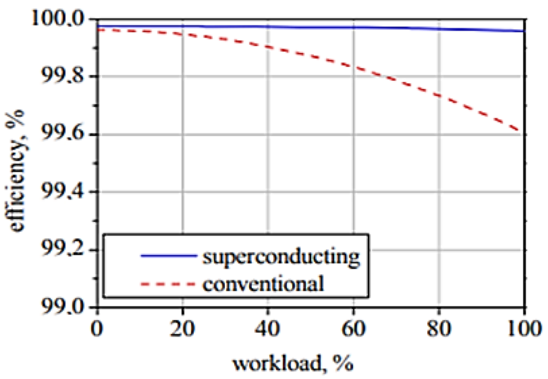


Figure 4. Dependence of the efficiency on the load for HTS and conventional transformers

The obtained results of the study of the types and magnitudes of losses in the transformers windings make it possible to establish the optimal range of U_{sc}. The superconducting transformers can raise the efficiency of power transformers from 99.6 to 99.9%. Due to the zero active losses in the windings and the ability of the HTS transformers to operate with high efficiency regardless of the load, it becomes possible to reduce the U_{sc} to values of 0.5 to 2%, depending on the rated power and the selected parameters of the superconducting windings of the transformer.

2.3. Critical parameters of a superconductor and the current limiting function

The most important parameters for the normal operation of HTS transformers with a current limiting function are the superconductor's critical parameters: critical current, critical temperature, and critical field. Since it is impossible to increase the magnetic fields close to the critical value in the transformer, only temperature and current will affect the transformer engineering and design. The critical current $I_c(t)$ determines the maximum allowable current that can flow through a superconductor without switching to a resistive state. When choosing the rated current I_{Rated} of the superconducting winding, let us assume a current margin factor of C_M, which will provide the necessary protection of the superconductor from quench (unexpected failure in the resistive state).

$$I_{Rated} = \frac{I_c(T)}{C_M} \tag{7}$$

The value of the margin factor will be determined based on the operation conditions of the transformer under the overload mode set for the design. The existing superconducting wires, with high values of critical currents up to 439 A [21] at an operating temperature of 77 K, allow setting the safety factor in the range of 1.25 to 2. This allows operating the HTS transformer in the overload mode, in excess of the rated current up to 90% without loss of superconductivity.

The use of second generation HTS wires as transformer windings, in the superconducting state at a temperature of 77 K, has a significant effect on electromagnetic transients due to the "switching effect" (mode of transition from the superconducting state to the resistive state). This property of a superconductor allows to instantly limit the most dangerous surge current. At the initial moment of the transition to the resistive state, the current is pushed into the non-superconducting layers of the wire, thereby causing significant heat release. After the short circuit is eliminated due to the increased resistivity, the superconducting wire begins to cool. Assume the temperature difference between the winding and the cryomedium is large (about 30 K). In that case, liquid nitrogen can transfer to the film boiling mode, which results in minimal heat removal from the winding Figure 5 [22]. This mode of nitrogen boiling is unacceptable since it can lead to a thermal failure of the winding, which can only be prevented by a forced transformer shutdown.

The return of the superconductor to the superconducting state after the failure elimination depends on the correlation between the ratio of the short-circuit current to the rated current, I_{SC}/I_{Rated}, and the ratio of the operating current to the rated current, I_{oper}/I_{Rated}, Figure 6 [23], [24]. In generally, the ratio of the operating current to the limited short-circuit current must be such that the heat released on the windings in the current-limiting mode does not exceed the critical value Q_{Cr}, above which the superconductor could not return to the superconducting state by itself.

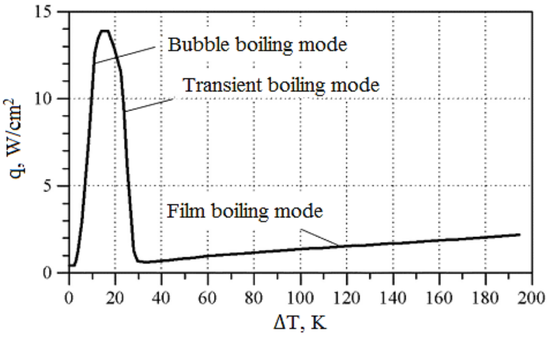


Figure 5. Dependence of the heat flux density on the temperature difference between the cooled surface and the cooling liquid

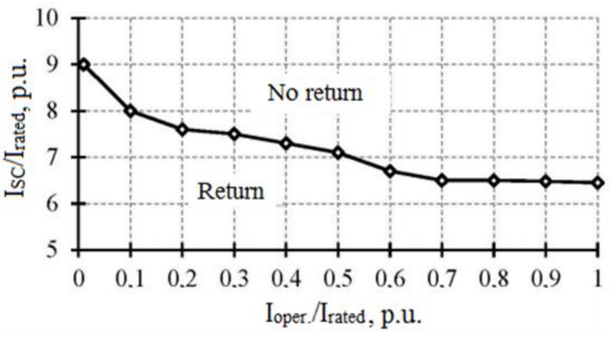


Figure 6. Criterion for the winding to return to the superconducting state

3. DESIGN OF AN EXPERIMENTAL THREE-PHASE HTS TRANSFORMER

The theory presented in section 2 allow create the novel method for determining the parameters of HTS transformers. Our method allows to design HTS transformers with high stability to winding overheating and the "quench" phenomenon. Below, the process of designing and assembling the main parts of a HTS transformer is explained: windings, magnetic circuit, cryostat. Concrete design decisions and values are provided for an experimental transformer. Experimental results obtained with this transformer are discussed in section 4.

3.1. Windings

The layered cylindrical winding design is optimal for transformers with a power of less than 1 MVA. The advantages of this type include minimal AC losses; reduces deviation of the leakage magnetic field, which improves the characteristics of HTS wires. In addition, this type of windings is ideal for the design of a transformer with a current limiting function [4], [25]. The windings of our experimental transformer are made of a 2G HTS tapes. The conductor is a thin multi-layer wire with a non-magnetic metal substrate and a layer of superconducting material-yttrium-barium-copper oxide $Y_1Ba_2Cu_3O_{7-X}$ (YBCO-123), which is covered with a protective layer of silver, as well as other auxiliary layers. Since the desired transformation ratio is equal to three, HTS wires of 4 mm width for the high voltage side and 12 mm width for the low voltage side are selected for the windings. The use of a larger wire cross-section on the LV side is due to the need for a current margin for the safe operation of a transformer with a high current density under the overload mode. The parameters of the designed windings are shown in Table 1.

Table 1. Parameters of HTS windings of experimental transformer

Parameter	HV Winding	LV winding
Material	$Y_1Ba_2Cu_3O_7$	
Tensile strength, MPa	500	
Critical temperature, K	93	
HTS wire width, mm	4	12
Minimum critical current, A	131	439
Voltage, V	380	127
Rated current, A	95.7	287.2
Number of turns, pc	33	11
Length of one winding phase, m	28.1	8.4
Length of three winding phases, m	84.3	25.2
Winding height, mm	198	154
Winding diameter, mm	271	243
Insulation	Polyimide	

3.2. Magnetic core

For the magnetic core design, the Unicore technology was chosen. The magnetic core is assembled from laminated plates of electrical steel, located parallel to the magnetic core. It provides an easy way of assembly and disassembly, which is important for the prototype since it is planned to optimize the design of the windings.

Figure 7 shows the assembly process and the final version of the laminated magnetic core. To provide insulation, varnish was applied to the plates. In our calculations, the value of the induction is assumed to be 1.65 T. The space factor is 0.883. The weight of the magnetic core is 430 kg, including fasteners.

Figure 7. Assembly process of the magnetic core of experimental three-phase HTS transformer

3.3. Cryostat

A key feature of HTS transformers is the need to design a cryostat-a container for liquid nitrogen in direct contact with the HTS wires. It is possible to distinguish two options of the cryostat design relative to the magnetic system-HTS transformer with a “cold” and “warm” magnetic core [4], [26], [27]. The *“Cold” magnetic core* is in direct contact with liquid nitrogen, and the cryostat covers the entire transformer. The advantages are the simplicity of the cryostat, as well as a lower magnetic leak. The disadvantages include additional heat losses for cooling the entire system. The *“Warm” magnetic core* is not in direct contact with liquid nitrogen and only the windings are immersed in the cryostat. Its operating temperature is approximately equal to room temperature. The advantages and disadvantages are the opposite of the “cold” magnetic core. Practical experience from around the world shows that the “warm” magnetic core design is superior [1]–[9], [28], [29]. The cryostat of our experimental transformer was made out of carbon fiber with an intermediate filling of the wall cavity with aerogel. Carbon fiber is a composite material and is carbon fiber with a binder-polyester resin. This material provides strength and non-shrinkage over a wide temperature range, which is critical for a cryostat. The developed cryostat is shown in Figure 8.

Figure 8. Cryostat of experimental 63 kVA HTS transformer

Tests confirmed that the cryostat meets the requirements for the strength of the material and does not affect the electromagnetic field induced by the transformer windings. The thermal insulation allows conducting physical experiments of up to 1.5 hours duration, which is sufficient for the purposes of the experiments. When further designing the prototype for pilot operation, a thermal insulation margin should be provided, since pilot operation involves a longer (continuous) mode of operation of the transformer, in contrast to experiments (one-time short-term operation).

3.4. Physical model of experimental three-phase HTS transformer

The designed prototype of a three-phase HTS transformer of 63 kVA as shown in Figure 9 allows for experimental studies, analysis of the transients during current limitation and of the influence of the HTS device on improving the energy efficiency of mains. One of the most important problems is to investigate the influence of HTS transformers on the dynamic and static stability of electric power systems. To the best of our knowledge, such studies have not been carried out yet. The basic parameters of the developed HTS transformer of 63 kVA, with a voltage ratio of 380/127, are shown in Table 2.

Figure 9. Three-phase prototype of HTS transformer

Table 2. Key electrical parameters of experimental HTS transformer

Parameter	Value
Power, kVA	63
Number of phases	3
Frequency, Hz	50
Voltage ratio	380/127
Operating temperature, K	77
Winding arrangement	Y-Y
Rated current of the HV winding, A	95.7
Rated current of the LV winding, A	287.2
Idle current, %	6%
Core induction, B	1.65
Operating current density, A/mm^2	239
U_{SC}, %	1

4. EXPERIMENTAL VERIFICATION OF THE POSSIBILITY OF SHORT-CIRCUIT CURRENT LIMITATION

The short-circuit current is limited due to the transition of the HTS winding from the superconducting state. This, in turn, occurs when the short-circuit current exceeds the value of the critical current of the HTS conductor. In addition, the failure of superconductivity may occur due to the excess of the critical temperature. The short-circuit current is limited in the first half-wave of the sinusoidal current wave-so during the first 0.01 s (that is faster than relay protection devices in mains can react) [28]–[31]. The limiting function allows preventing the negative consequences of short circuits-damage to equipment, disconnection of consumers. Our experimental studies include determining the characteristics of short-circuit transients to test the ability of the HTS windings to limit the short-circuit current. The equivalent-circuit of the experimental studies is shown in Figure 10.

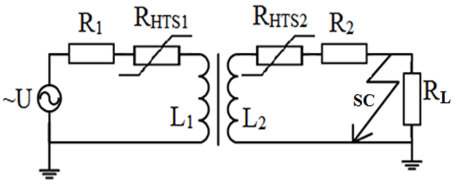


Figure 10. Experiment equivalent-circuit model

In the equivalent-circuit model, R1 and R2 reflect the resistances of the external circuits and current leads of the primary and secondary windings, L1, L2 are the self-inductances of the primary and secondary windings, R_{HTS1}, R_{HTS2} are the nonlinear resistances of the HTS windings of the transformer, U is the voltage amplitude of the supply source, R_L is the load. A series of experiments with line voltage supplied to the HTS transformer with short-circuited terminals of the LV windings was performed. Using the FLUKE 435-II recorder, current waveforms on the HV windings of phase A were obtained in Figure 11. They correlate with the high-accuracy results of computer modelling.

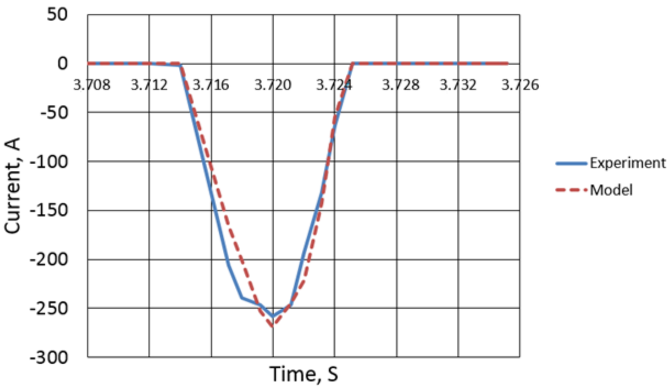
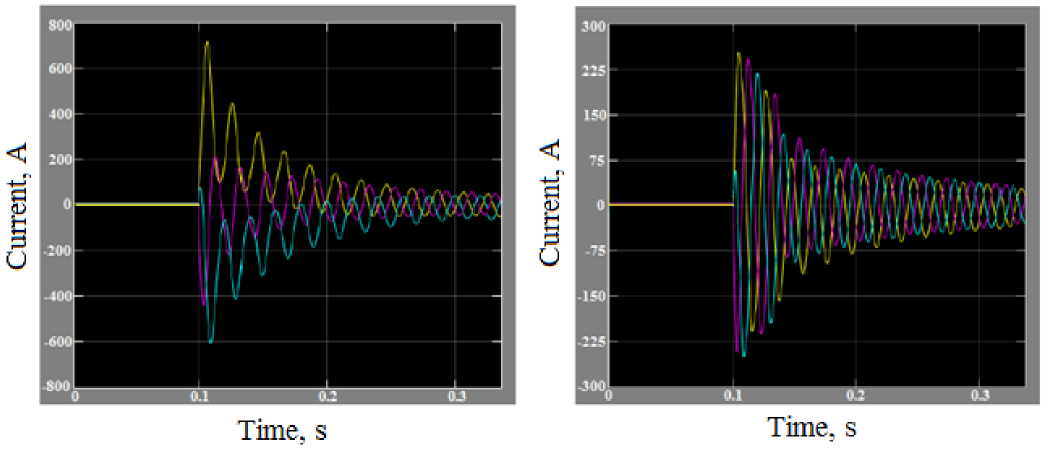


Figure 11. Current in the primary winding phase A of the HTS transformer

The simulation was performed on a previously developed mathematical model verified on a single-phase prototype of an HTS transformer [23], [27]. The waveforms obtained as a result of modeling a three-phase short circuit in the HV windings, check Figure 12, indicate a 2.53-fold decrease in the short-circuit shock current. In this case, the temperature of the superconductor does not exceed the critical temperature (it is only 80.9 K), which contributes to its fast return to the superconducting state and further normal operation of the HTS transformer and the entire mains.



(a) (b)

Figure 12. Current waveforms in the windings during the short circuit (a) in mains without HTS transformer, and (b) in mains with HTS transformer

5. CONCLUSION

The developed methodology for designing HTS transformers can be adopted as a new, adaptive solution in the design of HTS devices. Our method allows to design HTS transformers with high stability to winding overheating and the "quench" phenomenon. Our scientific results include the adoption of new regulatory requirements for the current density (200 to 400 A/mm^2), short-circuit voltage (0.5 to 1.5%), magnetic induction of the rod, the nature of losses in superconducting windings, as well as critical parameters of the superconductor (critical current and temperature). The absence of active losses in the windings under the nominal operating conditions allows increasing the efficiency by an average of 0.3%.

A physical prototype of a three-phase HTS transformer of 63 kVA was constructed for the study of the current limiting processes, based on YBCO second-generation HTS wire. The results of theoretical and experimental studies presented in this work indicate the effectiveness of using an HTS transformer for the purpose of current limitation. The designed and constructed superconducting transformer reduces the first peak of the short-circuit current by 2.53 times, thus protecting the transformer and the entire supply mains from thermal and electrodynamic damage. During the transient process, the heat flow in the winding did not exceed the critical value and the superconductor returned to the superconducting state, which indicates the correct design of the transformer with the current limiting function.

In an electrical grid with an HTS transformer operating under an active load, in case of a three-phase short-circuit, there is an instantaneous limitation of the short-circuit surge current. The use of electrical equipment based on the phenomenon of high-temperature superconductivity should be considered as a new innovative solution to the issue of improving the reliability, energy efficiency and stability of electrical grids.

ACKNOWLEDGEMENTS

This research was carried out under the Novosibirsk State Technical University development program, scientific project NoC21-24.

REFERENCES

[1] S. Hellmann, M. Abplanalp, L. Hofstetter, and M. Noe, "Manufacturing of a 1-MVA-class superconducting fault current limiting transformer with recovery-under-load capabilities," *IEEE Transactions on Applied Superconductivity*, vol. 27, no. 4, pp. 1–5, Jun. 2017, doi: 10.1109/TASC.2017.2652493.

[2] E. M. Ali, “The application of superconducting technologies in future electrical power systems,” Durham theses, Durham University, 2013.

[3] A. Moradnouri, M. Vakilian, A. Hekmati, and M. Fardmanesh, “HTS transformer windings design using distributive ratios for minimization of short circuit forces,” *Journal of Superconductivity and Novel Magnetism*, vol. 32, no. 2, pp. 151–158, Feb. 2019, doi: 10.1007/s10948-018-4925-z.

[4] V. Z. Manusov and D. O. Kriukov, “Review of superconducting transformers design,” *Elektrichestvo*, no. 8, pp. 4–16, 2019.

[5] V. S. Vysotsky *et al.*, “Development and test results of HTS windings for superconducting transformer with 1 MVA rated power,” *IEEE Transactions on Applied Superconductivity*, vol. 27, no. 4, pp. 1–5, Jun. 2017, doi: 10.1109/TASC.2016.2639011.

[6] S. Dai, T. Ma, Q. Qiu, Z. Zhu, Y. Teng, and L. Hu, “Development of a 1250-kVA superconducting transformer and its demonstration at the superconducting substation,” *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 1, pp. 1–7, Jan. 2016, doi: 10.1109/TASC.2015.2501105.

[7] D. Hu, Z. Li, Z. Hong, and Z. Jin, “Development of a single-phase 330kVA HTS transformer using GdBCO tapes,” *Physica C: Superconductivity and its Applications*, vol. 539, pp. 8–12, Aug. 2017, doi: 10.1016/j.physc.2017.06.002.

[8] G. Komarzyniec, “14 kVA superconducting transformer with (RE)BCO windings,” in *2017 International Conference on Electromagnetic Devices and Processes in Environment Protection with Seminar Applications of Superconductors (ELMECO & AoS)*, Dec. 2017, pp. 1–4, doi: 10.1109/ELMECO.2017.8267753.

[9] A. Berger, M. Noe, and A. Kudymow, “Test results of 60 kVA current limiting transformer with full recovery under load,” *IEEE Transactions on Applied Superconductivity*, vol. 21, no. 3, pp. 1384–1387, Jun. 2011, doi: 10.1109/TASC.2010.2088098.

[10] M. Xu, D. Shi, and R. F. Fox, “Generalized critical-state model for hard superconductors,” *Physical Review B*, vol. 42, no. 16, pp. 10773–10776, Dec. 1990, doi: 10.1103/PhysRevB.42.10773.

[11] R. Algarni, M. A. Almessiere, Y. Slimani, E. Hannachi, and F. Ben Azzouz, “Enhanced critical current density and flux pinning traits with Dy2O3 nanoparticles added to YBa2Cu3O7-d superconductor,” *Journal of Alloys and Compounds*, vol. 852, Jan. 2021, doi: 10.1016/j.jallcom.2020.157019.

[12] W. Song *et al.*, “AC loss simulation in a HTS 3-Phase 1 MVA transformer using H formulation,” *Cryogenics*, vol. 94, pp. 14–21, Sep. 2018, doi: 10.1016/j.cryogenics.2018.07.003.

[13] A. Ghabeli, M. Yazdani-Asrami, M. R. Besmi, and S. A. Gholamian, “Optimization of distributive ratios of apportioned winding configuration in HTS power transformers for hysteresis loss and leakage flux reduction,” *Journal of Superconductivity and Novel Magnetism*, vol. 28, no. 12, pp. 3463–3479, Dec. 2015, doi: 10.1007/s10948-015-3165-8.

[14] V. V Zubko, S. S. Fetisov, and V. S. Vysotsky, “Hysteresis losses analysis in 2G HTS cables,” *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 3, pp. 1–5, Apr. 2016, doi: 10.1109/TASC.2016.2535151.

[15] B. Shen, F. Grilli, and T. Coombs, “Review of the AC loss computation for HTS using H formulation,” *Superconductor Science and Technology*, vol. 33, no. 3, 2020.

[16] A. Berger, S. Cherevatskiy, M. Noe, and T. Leibfried, “Comparison of the efficiency of superconducting and conventional transformers,” *Journal of Physics: Conference Series*, vol. 234, 2010.

[17] F. Grilli and S. P. Ashworth, “Measuring transport AC losses in YBCO-coated conductor coils,” *Superconductor Science and Technology*, vol. 20, no. 8, 2007.

[18] G. A. Levin, J. Murphy, T. J. Haugan, J. Scouc, J. Kovac, and P. Kovac, “AC losses of copper stabilized multifilament YBCO coated conductors,” *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, Jun. 2013, doi: 10.1109/TASC.2012.2232337.

[19] D. N. Nguyen, P. V. P. S. S. Sastry, and J. Schwartz, “Numerical calculations of the total ac loss of Cu-stabilized $YBa_2Cu_3O_7-\delta$ coated conductor with a ferromagnetic substrate,” *Journal of Applied Physics*, vol. 101, no. 5, Mar. 2007, doi: 10.1063/1.2712180.

[20] T. Janowski *et al.*, “Superconducting devices for power engineering,” *Acta Physica Polonica A*, vol. 130, no. 2, pp. 537–544, Aug. 2016, doi: 10.12693/APhysPolA.130.537.

[21] S. Samoilenkov *et al.*, “Customised 2G HTS wire for applications,” *Superconductor Science and Technology*, vol. 29, no. 2, 2016.

[22] V. Z. Manusov, D. O. Kriukov, and A. V Semenov, “Computational and experimental study of air-core HTS transformer electrothermal behaviour at current limiting mode,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 1, pp. 155–162, Feb. 2021, doi: 10.11591/ijece.v11i1.pp155-162.

[23] D. M. Ivanov, V. Z. Manusov, and A. V Semenov, “Experimental studies of a high-temperature superconducting prototype transformer with current limiting function,” in *2020 International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE)*, Mar. 2020, pp. 1–5, doi: 10.1109/REEPE49198.2020.9059233.

[24] V. Z. Manusov, D. A. Pavlyuchenko, and J. S. Ahyoev, “A study of superconducting transformer with short-circuit current limitation,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, no. 1, pp. 505–512, Feb. 2018, doi: 10.11591/ijece.v8i1.pp505-512.

[25] A. Moradnouri, A. Ardeshiri, M. Vakilian, A. Hekmati, and M. Fardmanesh, “Survey on high-temperature superconducting transformer windings design,” *Journal of Superconductivity and Novel Magnetism*, vol. 33, no. 9, pp. 2581–2599, Sep. 2020, doi: 10.1007/s10948-020-05539-6.

[26] K. L. K., “Foreign and Russian developments in the field of creation of superconducting electrical machines and devices,” (in Russian), *Izvestiya akademii nauk. Energetika*, vol. 6, pp. 3–26, 2012.

[27] V. Z. Manusov, M. K. Nazarov, and D. M. Ivanov, “Analyses of electrical parameters of power transformers with superconducting windings,” in *2019 20th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices (EDM)*, Jun. 2019, pp. 547–551, doi: 10.1109/EDM.2019.8823091.

[28] J. Ma, J. Geng, J. Gawith, and T. Coombs, “High-temperature superconducting (HTS) transformer-rectifier flux pump for powering no-insulation superconducting magnet with low characteristic resistance,” *Physica C: Superconductivity and its Applications*, vol. 560, pp. 1–6, May 2019, doi: 10.1016/j.physc.2019.01.013.

[29] B. Kondratowicz-Kucewicz and G. Wojtasiewicz, “The proposal of a transformer model with winding made of parallel 2G HTS tapes with transpositioners and its contact cooling system,” *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1–5, Jun. 2018, doi: 10.1109/TASC.2018.2807585.

[30] G. Wojtasiewicz, “Fault current limitation by 2G HTS superconducting transformer - experimental investigation,” *Acta Physica Polonica A*, vol. 130, no. 2, pp. 516–520, Aug. 2016, doi: 10.12693/APhysPolA.130.516.

[31] G. Liu, G. Zhang, G. Liu, H. Wang, and L. Jing, “Experimental and numerical study of high frequency superconducting air-core transformer,” *Superconductor Science and Technology*, vol. 34, no. 8, 2021.

BIOGRAPHIES OF AUTHORS

Vadim Zinovievich Manusov Novosibirsk State Technical University, Department of Power Supply Systems, doctor of technical science, professor. Main direction of research: application of artificial intelligence methods for planning and optimizing modes of electric power systems. He can be contacted at email: manusov36@mail.ru.

Dmitriy Mihailovich Ivanov Novosibirsk State Technical University, Department of Power Supply Systems, PhD student. The main direction of research: Optimization of processes in HTS transformers using artificial intelligence techniques. He can be contacted at email: mrdemasi123@gmail.com.

Arseniy Valerievich Semenov Department of Power Supply Systems, PhD student. The main direction of research: optimization of power system operation modes, study of power system stability with HTS transformers. He can be contacted at email: ars100500@ya.ru.

Gennady Viktorovich Ivanov Surgut State University, Department of Radio Electronics and Electrical Engineering, PhD in Technical Science, Associate Professor. The main direction of research: investigation of modes and characteristics of power grid equipment with a cryogenic dielectric medium. He can be contacted at email: gennad-ivanov@yandex.ru.