**International Journal of Electrical and Computer Engineering (IJECE)**
Vol. 8, No. 1, February 2018, pp. 505~512
ISSN: 2088-8708, DOI: 10.11591/ijece.v8i1.pp505-512

# A Study of Superconducting Transformer with Short-Circuit Current Limitation

**V.Z. Manusov, D.A. Pavlyuchenko, J.S. Ahyoev**
Departement of Power Supply Systems, Novosibirsk State Technical University, Russian Federation

**Article Info**

***Article history:***

Received Aug 2, 2017
Revised Nov 18, 2017
Accepted Dec 2, 2017

***Keyword:***

Energy-efficiency
Power losses
Pre-fault conditions
Short-circuit current limitation
Superconducting winding
Transformer

**ABSTRACT**

The paper presents physico-mathematical models for analyzing transient processes in electrical networks having transformers with a high temperature superconducting winding. One of the main purposes of the study is the investigation of the short circuit current limitation process with the use of a transformer with a high temperature superconducting winding, that allows the combination of two series-connected elements, transformer and reactor, in one device. The efficiency of this method for short circuit current limitation is provided by the fact that the critical value of superconducting winding temperature is exceeded under short circuit current flowing, then it passes into the normal state with a high impedance winding, thus limiting a short circuit current. It is important to know the moment when superconducting material passes into the normal state with the loss of superconductivity. For this purpose, the program for calculating the quantity of heat under short circuit current flowing before its interruption was developed. If a 40 MVA transformer with a high temperature superconducting winding is considered, short circuit should be cleared after 100 ms without transformer disconnection. It is proposed to use a hybrid winding in addition to the main winding for short circuit current limitation. Conducted investigations showed that the return of a winding into the superconducting state depends primarily on the ratio between a short circuit current and a rated load current. This represents the criterion for returning or not returning into the superconducting state for transformer windings.

***Corresponding Author:***

D.A. Pavlyuchenko,
Departement of Power Supply Systems,
Novosibirsk State Technical University,
20, Karl Marx prospekt, Novosibirsk, 630073, Russian Federation.
Email: pavlyuchenko@corp.nstu.ru

## 1. INTRODUCTION

One of the advantages of using high temperature superconducting (HTS) transformers, in addition to high values of permissible current density per winding wire cross-section, is the capability of short circuit current limitation under fault conditions. An additional advantage of HTS transformers is fire and explosion safety. It is determined by the replacement of transformer oil, the main insulating material for windings, for liquid nitrogen. Liquid nitrogen is a dielectric having electric breakdown intensity of 20 kV/mm$^2$ at 77 K that is similar to characteristics of transformer oil under normal conditions.

Physical and mathematical verification of the capability for short circuit current limitation in electrical networks with HTS transformers will be considered in next sections. Superconducting windings have a special property: when current exceeds a specified critical value, it develops a critical value for magnetic field in a superconducting wire, then a wire losses superconducting properties and passes into the resistive state. Such transition is followed by transient processes that features should be considered when designing and operating HTS transformers [1], [2].

When current flowing through a HTS transformer winding exceeds the critical current $I_K(T)$ determined by a wire type, a radial component of an electromagnetic field, a value of flowing current, and temperature, then a HTS wire may pass from the superconducting state into the normal state at the normal temperature. In this case, the resistance of a superconducting layer in a wire increases considerably, then a flowing current is forced into other layers of a HTS wire. As a cross-section of these layers is not sufficient for current flowing, a resistance of this cross-section increases considerably that leads to short circuit current limitation. The main parameters of a current-limiting winding are the following: the value of current to be limited, short circuit duration without winding damages, and permissible temperature rise.

Consider short circuit current limitation with the use of transformers having HTS windings with the following assumptions [2]: a HTS wire passes from the superconducting state into the normal state uniformly along the wire length; all network elements, except a limiting resistance, are linear.

## 2. PROBLEM STATEMENT

High temperature superconducting wires are nonideal superconductors of the second order. It means that the transition from a superconducting state into the normal state takes some time through an intermediate mixed state when a magnetic field does not fully penetrate into a superconductor (*superconductor is a diamagnetic and stops a magnetic field from penetrating*). A mixed state exists in the range from the first critical current $I_{K1}$ to the second critical current $I_{K2}$. Under this state, current flows simultaneously through both a superconducting layer, and nonsuperconducting layers [3-5]. In this case, a resistance of a HTS wire is determined by an equivalent resistance of a superconducting layer and nonsuperconducting layers as parallel elements.

$$R_{Eq}\left(I,T\right)=\frac{R_{NSC}\left(T\right)*R_{SC}\left(I,T\right)}{R_{NSC}\left(T\right)+R_{SC}\left(I,T\right)}, \tag{1}$$

where $R_{NSC}$ – resistance of nonsuperconducting layers of a winding wire; $R_{SC}$ – resistance of a superconducting layer of a winding wire; $I$ – operating current through a wire; $T$ – temperature of a wire.

The resistance of a superconducting layer can be determined from the current-voltage characteristic of a HTS material as shown in Figure 1.

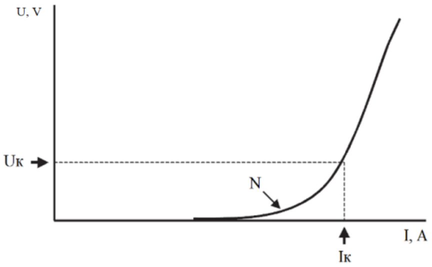

Figure 1. Current-voltage characteristic of a HTS material

$$R_{SC}\left(I,T\right)=10^{-6}\left(\frac{I}{I_K\left(T\right)}\right)^n*\frac{1}{I}, \tag{2}$$

$$I_\kappa(T)=-\frac{I_{\kappa 0}}{0{,}1848}\ln\left(\frac{T}{77}\right), \tag{3}$$

where $n$ – exponent of a current-voltage characteristic for a HTS wire determining the quality of a superconductor; $I_K(T)$ – critical current of a HTS wire at a temperature of T ($I_K(T)$ is equal to zero at temperatures above 90 K); $I_{K0}$ – critical current in a self-field at 77 K.

Resistance of nonsuperconducting layers is determined as an equivalent resistance of all layers connected in parallel in a HTS tape of a transformer winding.

$$R_{NSC} = \frac{1}{1/R_{BL}(T) + 1/R_{Ag}(T) + 1/R_C(T) + 1/R_{Hast}(T)}, \tag{4}$$

where $R_{BL}(T)$ – resistance of buffer layers; $R_{Ag}(T)$ – resistance of the silver layer; $R_C(T)$ – resistance of the copper layer; $R_{Hast}(T)$ – resistance of hastelloy.

Figure 2 presents resistivity of silver, copper, steel and hastelloy versus temperature in Kelvin. At the same time, it is possible to assume a linear part of the characteristic for temperatures below 100 K when calculating a resistivity for a nonsuperconducting layer. In this case, a layer resistivity can be calculated using the following equation:

$$R(T) = \frac{\rho(T)}{ab} \tag{5}$$

where ρ – layer resistivity with consideration of a temperature coefficient of resistance; *a* and *b* – width and thickness of a conductor layer.

To do calculations with HTS transformers, it is very important to know when a superconductor, which is the basis for a superconducting winding, passes into the normal state. It is possible to occur at short circuit currents not interrupted for a long time that results in overheating of HTS winding wires with the loss of superconductivity and all its advantages.

It is considered that a HTS wire passes into the normal state when voltage of one microvolt occurs along a wire of one centimeter length.

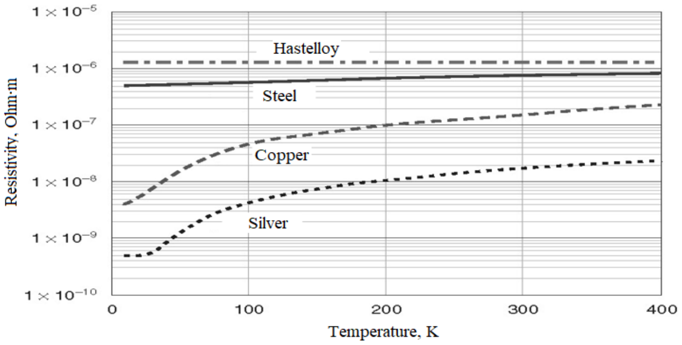

Figure 2. Resistivity of metals versus temperature

## 3. PROPOSED METHOD AND ANALYSES

To facilitate conditions for returning a conductor into the superconducting state under no-current conditions or load conditions, it is necessary to determine the quantity of heat which is released during short circuit current flowing before interruption. For this purpose, the program was developed in MATLAB with the following assumption: short circuit occurs at the outgoing feeder of the 40 MVA HTS transformer with short circuit clearing after 0.1 s without transformer disconnection.

This paper proposes the use of a hybrid winding for short circuit current limitation where only a part of turns is used for limitation. It can be achieved by the use of various wires with different parameters. In this case, a non-current-limiting part has a low resistance in the normal state, while a current-limiting part has a high resistance for short circuit current limitation.

Such construction of the HTS transformer winding allows the combination of two elements of electrical networks, transformer and reactor, connected in series in one device having functions of both voltage transformation and short circuit current limitation.

With known $R_{Eq}(I, T)$, a wire length in a current-limiting part of the winding can be found.

$$L_W = \frac{R_{\lim} n_h n_w}{R_{Eq}(I,T)}, \tag{6}$$

where $R_{lim}$ – required resistance for short circuit current limitation; $n_h$ and $n_w$ – the number of layers in height and in width respectively.

Figure 3 shows the cross-sectional view of the HTS transformer.

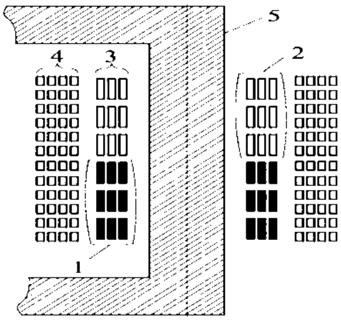

Figure 3. Cross-sectional view of the HTS transformer, 1) current-limiting part of the winding, 2) transformer part of the winding, 3) low-voltage winding, 4) high-voltage winding, 5) magnetic core

The number of winding turns used for short circuit current limitation is given by:

$$w = \frac{L_W}{2\pi r_T}, \quad (7)$$

where $r_T$ – average turn radius.

To simulate a transient process under short circuit conditions with the HTS transformer, the equivalent circuit shown in Figure 4 was used.

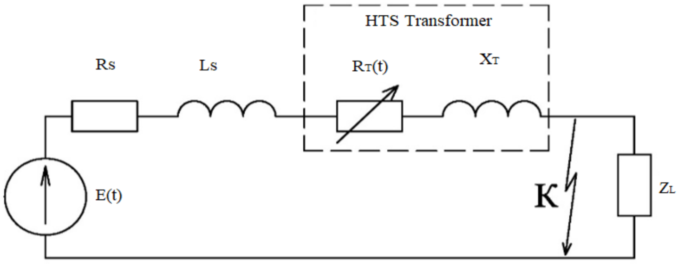

Figure 4. Equivalent circuit for transient process simulation

A transient process at the occurrence of short circuit can be described by the following differential Equation [6]:

$$U_m \sin(\omega t + \alpha) = (L_S + L_T)\frac{di(t)}{dt} + i(t)(R_S + R_T(T)), \quad (8)$$

where $R_S$ and $L_S$ – resistance and inductance of the system; $R_T$ and $L_T$ – resistance and inductance of the transformer.

Short circuit was simulated by closing the switch which shunts the load. Solution of equation (8) is

$$i(t) = \frac{U_m}{Z_K}\sin(\omega t + \alpha - \phi_K) + [\frac{U_m}{Z_K}\sin(\alpha - \phi_H) - \frac{U_m}{Z_K}\sin(\alpha - \phi_K)] \cdot e^{-\frac{t}{T_a}}, \quad (9)$$

where $Z_K$ – impedance of the short-circuited part.

Curves of the short circuit current without and with limitation are shown in Figure 5.

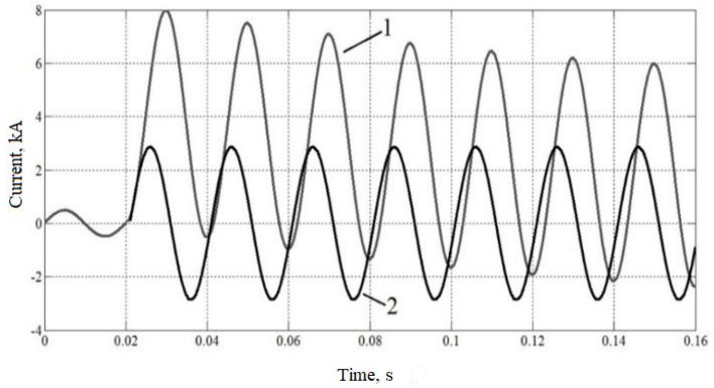

Figure 5. Curves of the short circuit current without (1) and with (2) limitation

The most significant aspect with short circuit current limitation is the determination of time for return of a HTS transformer winding into the initial superconducting state. To find this time, it is necessary to calculate the quantity of heat released in a wire during dead-time of automatic reclosing. Released heat during the short circuit is equal to the Joule losses in a time interval of *dt*.

$$Q(I,T)=\int_0^{t_1} I^2R(T)dt \tag{10}$$

Temperature rise for a HTS transformer winding wire with consideration of released heat can be determined using the following equation [2, 7, 8]

$$C\frac{dT(I,T)}{dt}=Q(I,T)-Aq(T)\,, \tag{11}$$

where $C$ – heat capacity of the wire; $A$ – the area of cooling determining by the surface of the winding; $q$ – density of heat flow passing into liquid nitrogen from the winding surface.

$$C=V_{HTS}c_{HTS}(T)+V_{Hast}c_{Hast}(T)+V_{BL}c_{BL}(T)+V_{Ag}c_{Ag}(T)+V_Cc_C(T)\,, \tag{12}$$

where $V_{HTS}$ and $C_{HTS}$ – volume and specific heat capacity of the HTS layer; $V_{Hast}$ and $C_{Hast}$ – volume and specific heat capacity of the hastelloy layer; $V_{BL}$ and $C_{BL}$ – volume and specific heat capacity of the buffer layer; $V_{Ag}$ and $C_{Ag}$ – volume and specific heat capacity of the silver layer; $V_C$ and $C_C$ – volume and specific heat capacity of the copper layer.

Equations (10) – (12) should be solved as a consistent system. As a result, the nonsteady-state equation of thermal conductivity was obtained that describes the temperature change of the current-limiting part of the winding depending on the short circuit current flowing through the winding and time before short circuit clearing by relay protection in the power system:

$$T(t)=T_0+\Delta T(t)=T_0+\frac{Q(I,T)-W}{C(T)}\,, \tag{13}$$

where $T_0$ – initial temperature of liquid nitrogen (77 K).

Therefore, the general mathematical model can be developed that allows determining the quantity of heat and winding heating to establish requirements to short circuit current limitation with the use of a transformer with HTS windings. As a desired criterion, solution of the nonsteady-state equation of thermal conductivity (13) and the differential equation of short circuit current changing (8) can be considered:

$$\begin{cases} R_T = 0, & \text{at } I < I_{K1} \\ R_T = \dfrac{R_{NSC}(T)\cdot R_{SC}(I,T)}{R_{NSC}(T)+R_{SC}(I,T)}, & \text{at } I_{K1} < I < I_{K2} \\ R_T = R_{NSC}(T), & \text{at } I > I_{K2} \\ R_T = f(T), \text{ after short-circuit clearing, at } I = 0 \end{cases} \quad (14)$$

The power released in the resistance of the HTS transformer is illustrated in Figure 6.

The maximum of power is observed at the initial moment of the short circuit (in the first half-cycle) and depends on the influence of the initial short circuit current. The dependence of the maximum power (at the initial moment of the short circuit) on the value of resistance for different time constants of resistance rise is given in Figure 7.

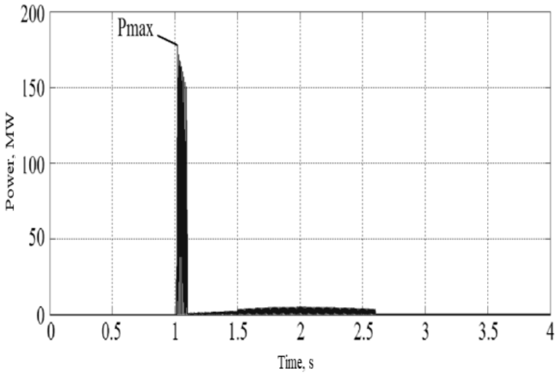

Figure 6. Power released in the resistance of the HTS transformer

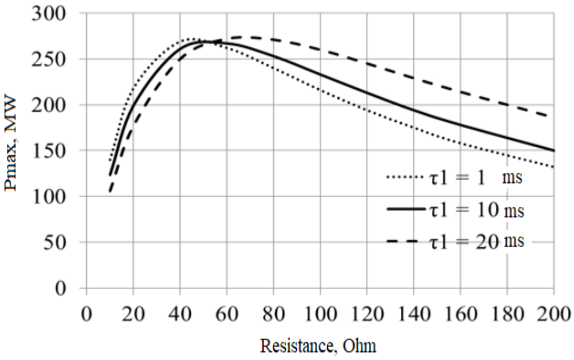

Figure 7. Dependence of the maximum power on the value of resistance for different time constants of resistance rise

Figures 6 and Figure 7 show that the maximum power depends on both the value of resistance and the rate of rise of resistance.

Conducted investigations showed that the return of a winding into the superconducting state after short circuit clearing depends primarily on the ratio between the short circuit current and the rated load current [9-14]. In other words, the ratio between the short circuit current and the load current should be a such value that the quantity of heat does not exceed the critical value during a short circuit. Other approaches are also possible. When the ratio is exceeded, a transformer should be disconnected to return the winding into the superconducting state.

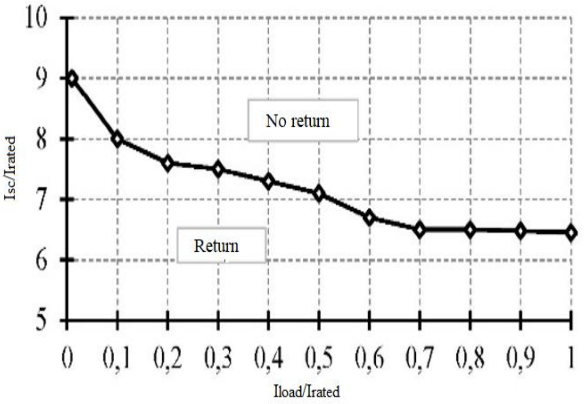

Figure 8. Criterion for winding return into the HTS state after short circuit clearing

Detailed mathematical models of HTS transformers for analyzing transients in electrical networks are given in [15-18], including models demonstrating a superconducting limiting device of the inductive type and models investigating the influence of HTS transformers on power system stability (Figure 8).

## 4. ADVANTAGES OF HTS TRANSFORMERS

Summing up the above-mentioned aspects of the construction and regimes of HTS transformers, it is possible to estimate some technological and ecological advantages of these transformers in comparison with traditional high-voltage oil transformers. The advantages are the following:

a. decrease of load (dynamic) losses of active power in HTS transformer windings by more than 90% at the rated load current that increases transformer efficiency up to 99% and significantly enhances its energy efficiency;
b. decrease of overall dimensions and weight of a HTS transformer by up to 40%. Consequently, it is possible to use these transformers at existing substations without structural changes and widening the area of installation, but with significant increase of a transformer power;
c. short circuit current limitation due to transition of a winding, or windings, depending on a short circuit type, into the normal state that facilitates electromagnetic processes for switching equipment in electrical networks;
d. high overload capability of HTS transformers allows withstanding double overloads in 48 hours without insulation damages and deterioration that does not reduce transformer lifetime [19];
e. fire and explosion safety of HTS transformers due to the lack of oil insulation that enhances ecological compatibility;
f. reduction of noise that increases convenience of HTS transformer arrangement and maintenance;
g. extremely low no-load losses and short circuit losses that significantly depends on allocation and construction of a HTS transformer magnetic core: “warm” (outside a cryostat) and “cold” (inside a cryostat). In this case, a “warm” magnetic core allows using relatively cheap thin-sheet electrical steel with a magnetic induction of up to 1.6 T. A “cold” magnetic core makes a cryostat construction simpler with considerable reduction of core dimensions, however increasing energy consumption for cooling a little. If using amorphous steels or alloys, a released heat equals up to 0.35 W/kg at 1.7T and 50 Hz instead of 0.8 W/kg;
h. maintenance costs of HTS transformers during a lifetime period are lower by one half in comparison with traditional oil transformers (according to some data, lower by 70%).

## 5. CONCLUSION

It is shown that there is a possibility of short circuit current limitation with the help of a transformer with HTS windings in electrical networks, including a case of using a possible additional winding for this aim. At the same time, short circuit current limitation is not so considerable in the initial half-cycle as in the following half-cycles. It is caused by faster damping of the aperiodic component of short circuit current than in traditional transformers with copper windings, and by the temperature rise of a HTS transformer winding.

The return into the superconducting state of a HTS transformer winding considerably depends on the ratio between a short circuit current and a rated load current, and on a stabilizer layer thickness in a HTS wire.

Limitation of various short circuit currents using a HTS transformer due to considerable increase of winding resistances with the loss of the superconducting state allows replacing series reactors having high inductances and resistances. At the same time, active losses in the electrical network are reduced with the increase of reliability, while technical and economic performance of power supply systems are improved in comparison with individual series reactors used for short circuit current limitation.

In the authors’ opinion, application and development of HTS-technologies in power engineering allows increasing current carrying capacity (i.e. thermal limits) in the power system and transmitting more power with the same ratings.

## 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.

## REFERENCES

[1] Sh.I. Lutidze, E.A. Dzhafarov, "Superconducting transformers," *Moscow, Nauchtehlitizdat Publ.*, 206 p., 2002.

[2] V.Z. Manusov, N.V. Aleksandrov, "The limiting of short-circuit currents using transformers with high temperature superconducting windings," *Izvestiia Tomskogo politekhnicheskogo universiteta – Bulletin of the Tomsk Polytechnic University*, vol. 323, no. 4, pp. 100-105, 2013.
[3] A. Kozulin, A. Vinogradov, "The high temperature superconducting transformers – a new generation of substation equipment," *Electrical equipment: operation and repair*, no. 12, pp. 7-9, 2008/
[4] Iu.M. Annenkov, A.S. Ivashutenko, "The perspective materials and technologies in electrical insulation and cable technology," *Tomsk, TPU Publ*., 212 p., 2011.
[5] S.S. Kalsi, "Applications of high temperature superconductors to electric power equipment," *New Jersey, John Wiley & Sons Inc.*, 312 p., 2011.
[6] S.A. Ul'ianov, "The electromagnetic transients in electrical systems, "*Moscow, Energiia Publ.*, 520 p., 1970.
[7] H. Merte, J.A. Clark, "Boiling heat transfer data for liquid nitrogen at standard and near-zero gravity," *Advanced Cryogenic Engineering*, vol. 7, pp. 546-550, 1962.
[8] Super Power Inc. Available at: http://www.superpower-inc.com/content/wire-specification (accessed 01.04.2017).
[9] A. Berger, *et al.*, "Comparison of the efficiency of superconducting and conventional transformers," *Journal of Physics: Conference Series,* 234 (2010).
[10] F. Grilli, S. Ashworth, "Measuring transport AC losses in YBCO-coated conductor coils," *Superconductor Science and Technology,* no.20, pp. 794-799, 2007.
[11] E. Brand, M. Indenbom, "Type-II-superconductor strip with current in a perpendicular magnetic field," *Physical Review B*., vol. 48, no. 17, pp. 12893-12906, 1993.
[12] N. Magnusson, A. Wolfbdrandt, "AC losses in high-temperature superconducting tapes exposed to longitudinal magnetic fields," *Cryogenics*, no. 41, pp. 721-724, 2001.
[13] K. Namjoshi, P. Biringer, "Low-Frequency Eddy-Current Loss Estimation in Long Conductors by Using the Moment of Inertia of Cross Sections," *IEEE Transactions on Magnetics*, vol. 24, no. 5, pp. 2181-2185, 1988.
[14] J.K. Sykulski, R.L. Stoll, "The design, construction and operation of high temperature superconducting transformers practical considerations," *CIGRE 2000*, 12-203.
[15] V.Z. Manusov, P.A. Miheev, "Mathematical model of electromagnetic transient process in the electrical network with a superconducting current limiting device of the inductive type," *Moscow: Electrical Engineering*, vol. 7, pp. 50-56, 2008.
[16] V.Z. Manusov, N.V. Aleksandrov, "Influence of superconducting transformers on power system stability," *Novosibirsk: Science Bulletin of Novosibirsk State Technical University*, vol. 3, pp. 160-165, 2013.
[17] T. Ishigohka, *et al.*, "Experimental study on effect of in-rush current of superconducting transformer," *IEEE transaction on applied superconductivity*, vol. 16, no. 2, pp. 1473-1476, June 2006.
[18] V.Z. Manusov, P.A. Miheev, "Influence of superconducting current limiting devices on electromechanical transients in power systems," *Novosibirsk: Science Bulletin of Novosibirsk State Technical University,* vol. 4 (29), pp. 143-156, 2007.
[19] C.S. Weber, *et al.*, "Design and Operational Testing of a 5/10-MVA HTS Utility Power Transformer," *IEEE Transaction on applied superconductivity*, vol 15, no 2, pp. 2210-2213, June 2005.

## BIOGRAPHIES OF AUTHORS

**Vadim Z. Manusov**. Novosibirsk State Technical University, Department of Power Supply Systems, D. Eng, Professor. Main directions of investigations: methods of artificial intelligence for planning and optimization of operating regimes of power systems. E-mail: manusov@corp.nstu.ru

**Dmitry A. Pavlyuchenko**. Novosibirsk State Technical University, Department of Power Supply Systems, Ph.D., Associate Professor, Head of Department. Main directions of investigations: enhancement of energy efficiency, operating performance and development of power supply systems.
E-mail: pavlyuchenko@copr.nstu.ru

**Javod S. Ahyoev**. Novosibirsk State Technical University, Department of Power Supply Systems, postgraduate student. Main directions of investigations: monitoring and diagnostics of current technical condition of high voltage electrical equipment on the basis of the theory of fuzzy sets and fuzzy logic. E-mail: javod_66@mail.ru