УДК 551.5:629.1.04

EFFECT OF CLIMATIC FACTORS ON SERVICE LIFE OF INSULATING MATERIALS OF TRACTION ELECTRIC MACHINES

H. F. Kudina[1], A. S. Zalata[2], V. V. Karpenko[3], I. V. Prihodzko[4], P. A. Kuritsyn[5]

[1] Doctor of Technical Sciences, Professor, Head of the Department of Water Supply, Chemistry and Ecology, Belarusian State University of Transport (BelSUT); Leading Researcher, State Scientific Institution "Institute of Mechanics of Metal-Polymer Systems them. V. A. Bely of the National Academy of Sciences of Belarus (GNU IMMS named after V. A. Bely of the National Academy of Sciences of Belarus), Gomel, Belarus, e-mail: kudina_mpri@tut.by
[2] Chief Designer of JSC "Ukrainian Energy Machines", Kharkiv, Ukraine, e-mail: icteo@spetm.com.ua
[3] Ph.D in Engineering, Member of the Crimean Academy of Sciences, Deputy Chief Designer, Head of the Test Center for Traction Electrical Equipment, Ukrainian Power Machines JSC Kharkiv, Ukraine, e-mail: icteo@spetm.com.ua
[4] Ph.D in Engineering, Associate Professor, Head of the Laboratory "Electrical and Electronic Systems" IC ZhT BelSUT, EE "Belarusian State University of Transport" (BelSUT), Gomel, Belarus, e-mail: iv_prixodko@mail.ru
[5] Master of Technical Sciences, Junior Researcher of the Laboratory "Electrical and Electronic Systems" IC ZhT BelSUT, EE "Belarusian State University of Transport" (BelSUT), Gomel, Belarus, e-mail: pavelkuritsyn97@gmail.com

Abstract

The aspects of operation of electrical equipment under the influence of limit values of a number of climatic parameters, as well as the performance of equipment with a change in altitude, are considered. The results of experimental comparative studies of the electrical insulation resistance of TEM samples based on the insulation temperature resistance class of 220 with serial samples based on class *F* or *H* are presented. Based on the results of comparative tests confirmed the expediency and prospects of application of insulation class 220. The analysis of the results of the impact of climatic factors on the physical and mechanical properties and service life of insulation materials, as well as the safety and quality of electrical equipment.

Keywords: electrical equipment, electrical machines, climatic factors, class of insulation heating resistance, insulation resistance, safety and reliability of equipment.

ВЛИЯНИЕ КЛИМАТИЧЕСКИХ ФАКТОРОВ НА СРОК ЭКСПЛУАТАЦИИ ИЗОЛЯЦИОННЫХ МАТЕРИАЛОВ ТЯГОВЫХ ЭЛЕКТРИЧЕСКИХ МАШИН

Е. Ф. Кудина, А. С. Залата, В. В. Карпенко, И. В. Приходько, П. А. Курицын

Реферат

Рассмотрены аспекты функционирования электрооборудования под воздействием предельных значений ряда климатических параметров, а также характеристики оборудования с изменением высоты над уровнем моря. Представлены результаты экспериментальных сравнительных исследований сопротивления изоляции образцов тяговых электрических машин и агрегатов класса нагревостойсости 220 с серийными образцами с изоляцией классов *F* или *H*. По результатам сравнительных испытаний подтверждена целесообразность и перспективы применения изоляции класса 220. Приведен анализ результатов воздействия климатических факторов на физико-механические свойства и срок службы изоляционных материалов, а также безопасность и качество электрооборудования.

Ключевые слова: электрооборудование, электрические машины, климатические факторы, класс нагревостойкости изоляции, сопротивление изоляции, безопасность и надежность оборудования.

Introduction

Temperature changes significantly affect the properties of materials. As the temperature increases, the resistance of some metals increases, as well as the modulus of elasticity and ultimate strength decreases. A decrease in temperature leads to a change in the inductance of high-frequency coils and throttles, as well as a decrease in ductility and the appearance of brittleness of metals. And most importantly, temperature significantly affects the electrical characteristics of dielectric materials. The increase in temperature leads to a sharp drop in insulation resistance, an increase in dielectric losses, a decrease in dielectric constant, and individual dielectric materials lose strength characteristics.

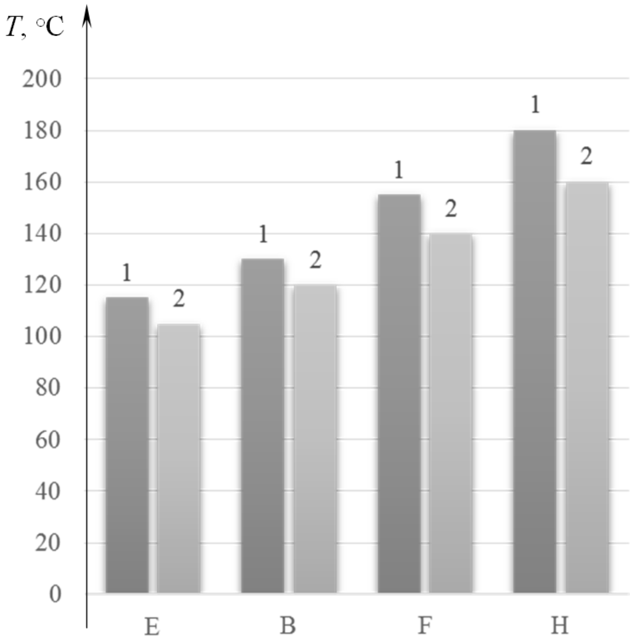
The electrical strength of most dielectrics (polyethylene, epoxy resin, etc.) when exposed to heat first increases, and the mechanical strength decreases due to removal of moisture. Then, a significant decrease in electrical strength is observed, and the end result is mechanical breakdown of the dielectric. Insulation materials are subjected to intense aging under the action of cyclic exposure to heat and cold, accompanied by changes in electrical characteristics and physicochemical properties. Organic insulation materials are most susceptible to aging. Prolonged exposure to high temperature reduces the mechanical strength of organic materials, thereby making them more brittle and may eventually be destroyed by slight impact or vibration [1]. Thermal aging of elements is considered one of the factors increasing the percentage of equipment failures, as their service life is significantly reduced [2].

Checking the electrical strength and insulation resistance of materials is one of the stages of analysis that determine the possibility of further operation not only of dielectric materials, but also of equipment as a whole. This is especially important when it comes to high voltage. On railway rolling stock, a number of equipment (high-voltage inter-car connections, main switches, overvoltage limiters, etc.) are operated under a voltage of up to 30 kV, and a decrease in insulation resistance due to an increase in temperature, and, as a result, electrical strength, can cause breakdown of insulation or overlap on the surface, which can lead to irreparable consequences.

The negative influence of climatic factors may increase if high air humidity is added to the effects of temperature. In real-world settings, these factors are often concomitant. The influence of climatic parameters must be taken into account when designing not only control elements and control objects, but also traction equipment and, in particular, electrical machines. In addition, the analysis of the impact of these factors is an important task.

Influence of climatic parameters on operation of electric machines. Some equipment (electric motors, generators, etc.) during operation is able to release heat into the environment and thereby change climatic parameters. This applies primarily to equipment operating in a confined space. Heating of the electric machine as a whole and its individual parts, for example, winding and steel of the stator, rotor, bearings, is due to heat generation in these and other parts [3]. Determining the heating temperature of individual parts of the electric machine by calculation is a rather complex process. The heating temperature of electrical machines may depend on various factors. The value of the steady state temperature of the engine depends on the load on its shaft. The application of a significant load leads to the release of a large amount of heat per unit time. The allowable heating of electrical machines depends on the insulation class of windings, manifold, contact rings, etc.

One of the main properties of insulation of windings of electrical machines is heating resistance of insulation material. In accordance with GOST 8865, this is the ability of electrical insulation materials, impregnating compositions and insulation of wires without damage and without significant deterioration of practically important properties to withstand the effects of increased temperature for a long time [4]. Increasing the temperature of the windings of electrical machines above permissible values leads to a reduction in the service life of the insulation. Thus, insulation heating resistance is one of the main parameters that determines the reliability of operation and the life of electrical machines. The most common insulation classes are *E*, *B*, *F* and *H*. Due to low operating temperatures, class E finds limited use in low-power machines. Insulation of classes *B* and *F* was most widespread, and in specialized electric machines operating in heavy load conditions, class *H* insulation is used (Figure 1) [4]. At the same time, a large reserve for improving technical characteristics, including the resource characteristics of traction electric machines (TEM), is the transition to an insulation class of 200 and 220. Such design of isolation finds more and more broad application in TEM of foreign manufacturers, including "Alstom transport" (France), General Electric (USA), Traktionssysteme Austria GmbH (Austria), etc.



1 – field winding, 2 – armature windings

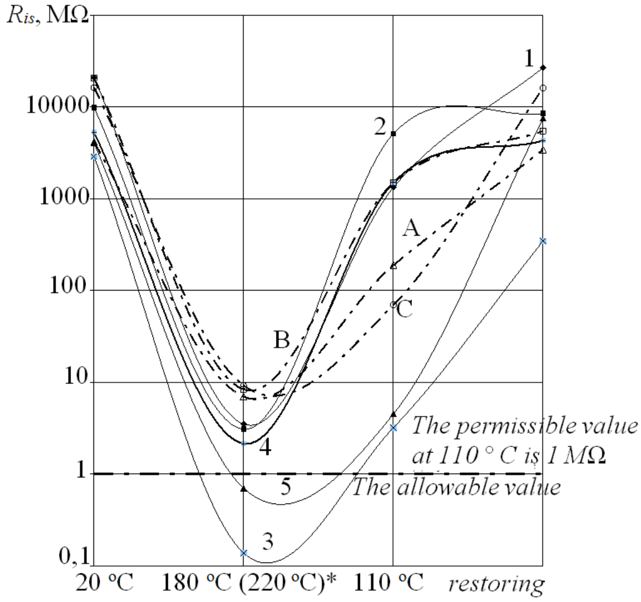
Figure 1 – Limit permissible exceeding winding temperature of electrical machines (at temperature environment from 10 °C to 40 °C)

As a result of research conducted at the test center of traction electrical equipment SE "Plant "Electrotyazhmash" it was found, that samples of TEM with a class of 220 have a significantly higher insulation heating resistance compared to samples of TEM with a class of H, as well as not inferior in resistance to low temperatures and show the ability to operate under conditions of high humidity for a longer period than most samples with a class of heating resistance *H* [5]. The quality assessment of insulation properties and their comparative analysis were carried out on the change of electrical resistance of insulation at various types of climatic effects.

Effect of elevated ambient temperature [6]. The samples were subjected to medium temperature (180 ± 3) °C for class *H* and (220 ± 3) °C for the 220 class in the test chamber, maintained until heated throughout the volume, then cooled to a temperature corresponding to normal climatic conditions tests (hereinafter referred to as n.c.c.t.).

Figure 2 presents the results of the studies in the form of temperature dependences $R_{is} = f\,(\mathrm{T})$.

All the presented samples showed high values of insulation resistance (the permissible value at a temperature of 110 °C is not less than 1 MΩ). Samples with an insulation class of 220 (Figure 2, and at a temperature of 220 °C had significantly higher insulation resistance values than samples with class *H* at a temperature of 180 ° C (from 2 to 40 times), and also not inferior to class *H* according to the insulation resistance at a temperature of 110 °C.



* 180 ° C heating temperature for insulation class *H*, 220 ° C - heating temperature for insulation class 220

1-5 – insulation class *H*;
A, B, C – insulation class 220

Figure 2 – Dependence of TEM insulation resistance values on the environment temperature effect (high temperature effect)

The effect of low ambient temperature [7]. The samples were exposed to a medium temperature of (minus 50 ± 3) °C in the test chamber, held until cooled throughout the volume, then heated to a temperature of (40 ± 3) °C. Figure 3 presents the results of the study of the samples in the form of temperature dependences $R_{is} = f\,(\mathrm{T})$. It can be seen from the figure that all the samples presented had high values of the insulation resistance over the entire range of ambient temperatures and restored them after the test to high values (the allowable value after the recovery in the n.c.c.t. is not less than 20 MΩ).

Samples with an insulation class of 220 showed insulation resistance values during the action of a reduced temperature minus 50 °C higher than samples with class *H*, and also did not yield to class *H* according to the insulation resistance with an increase in the temperature of the medium to 40 °C and recovery in n.c.c.t. [5].

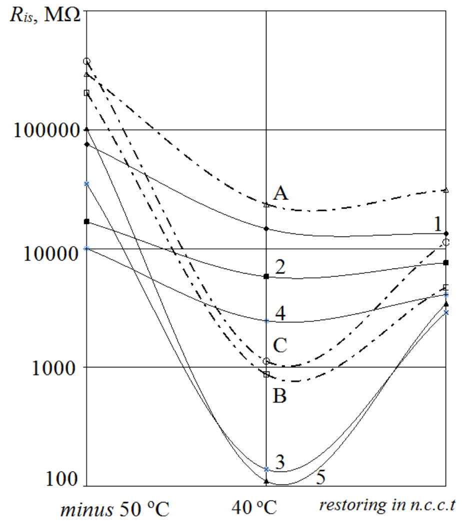
The effect of high humidity of air [7]. The samples were subjected to six consecutive cycles (cycle time 24 hours), each of the first five cycles consisted of two steps: 16 hours at a temperature of 40 ± 2 °C and a relative humidity of 95 ± 3% and 8 hours at a temperature of 35 ± 2 °C and a relative humidity of 95-100%. In the last sixth cycle: 16 hours at a temperature of (40 ± 2) °C and relative humidity (95 ± 3)% and 8 hours at a temperature of (25 ± 2) ° C and relative humidity (95-100)%.

Figure 4 shows the results of measurements of the insulation resistance of the samples in the form of time dependences $R_{is} = f\,(\mathrm{t})$.

where t is the duration of the test in hours, and Ris is the average values of insulation resistance of the samples in the *n*-th cycle, corresponding to each stage. $R_{is} = \Sigma R_{isi} \,/\, i$, where *i* is the number of measured insulation resistance values in each cycle (in stages of 16 hours $i = 4$, in stages of 8 hours $i = 2$).

All the samples presented during the exposure to high humidity showed high values of insulation resistance.

doi.org/10.36773/1818-1112-2022-128-2-83-86

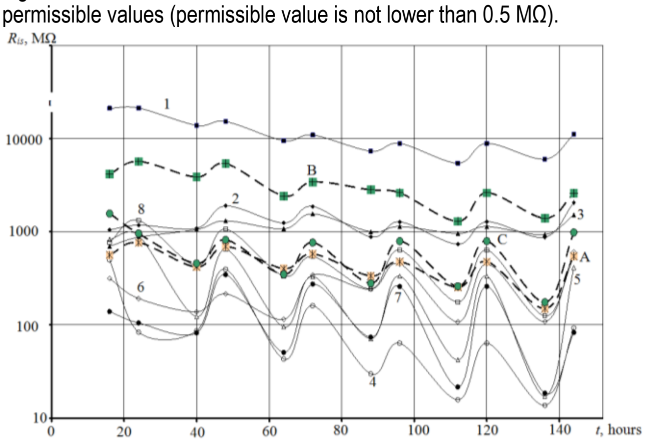


The allowable value after the recovery in ncct and 40 MΩ

1-5 – insulation class *H*;
A, B, C – insulation class 220

Figure 3 – Dependence of TEM insulation resistance values on the environment temperature effect (low temperature effect)

It can be seen from Fig. 4 that samples with an insulation class of 220 were not inferior to most samples with class *H* in the process of testing for insulation resistance values, and these values were not lower than permissible values (permissible value is not lower than 0.5 MΩ).



1-8 – insulation class *H*; A, B, C – insulation class 220

Figure 4 – Dependences of the insulation resistance to the housing against the time of exposure to high humidity

When exposed to high humidity, the dependence of insulation resistance on the time of exposure has the following dependence

$$R_{из} = R_0 \cdot e^{\gamma} t$$

where t – time, hour;

R_0 – characterizes initial insulation resistance before tests, MOhm;

γ – coefficient, which depends on physical properties of insulation, characterizes the rate of insulation resistance reduction when exposed to wet air.

In real-world operation, the TEM may be exposed to soil humidity much longer than the time the images were tested. Based on the obtained dependencies, it is possible to predict the value of *R* from after any period of operation and calculate for what time *R* from will reach the permissible value. To do this, you must express the time value from the above formula:

$$t = \frac{1}{\gamma} \cdot \ln \frac{R_{из}}{R_0}$$

By approximating the experimental data given in Figure 4, mathematical models of the dependence of insulation resistance on the exposure time of high humidity can be obtained.

As can be seen from Figure 5, in two out of eight TEM samples with insulation class *H*, insulation resistance for the presented period according to the forecast will decrease to values below the permissible 0.5 MOhm.

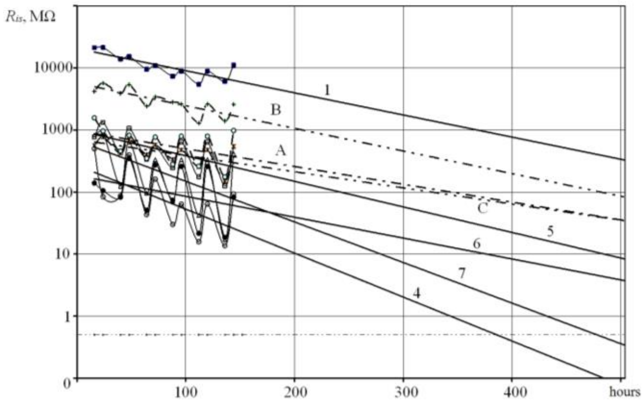


Figure 5 – Predicted dependence of insulation resistance relative to the housing on the time of exposure to high humidity

The time t at which the insulation of a TEM operated under increased moisture conditions retains the insulation resistance above the permissible value can either be considered analytically by the formula, or determined using the graphs shown in Figure 5, which is actually a continuation of Figure 4, where the time axis is extended by another 350 hours to more clearly show the change in the value of the insulation co-resistance of the samples. From the above results, it can be seen that under the same conditions of humidity testing, the insulation of class 220 compared to *H* has much better performance and therefore is more effective as an insulating coating of the current-carrying parts of electrical machines.

Insulating materials with prolonged exposure to elevated temperatures are subject to thermal aging, as a result of which physical and chemical changes occur in them. Prolonged exposure to elevated air temperature and oxygen can lead to thermal shrinkage of the insulation and, as a result, the formation of cracks. As a result of thermal oxidative degradation in the insulating material, polymer molecules cross-link, thereby increasing crispness and brittleness. And given that electric machines are sources of vibration during operation, this can intensify the process of their failure. Increasing the insulation temperature above the permissible level by 10 °C reduces its service life by half. This phenomenon is based on the general law of the dependence of the rate of chemical reactions on temperature, described by the Vant-Goff and Arrhenius equation [8]. In addition to temperature, changes in air pressure, the presence of ozone, which is a stronger oxidizing agent than oxygen, and other chemicals capable of intensifying this process, have a significant effect on the aging rate of the material.

The set of climatic factors acting on electrical equipment elements and their characteristics are determined by the climatic zone in which they are operated. Of considerable interest is the operation of electric machines in conditions other than normal. The permissible power of electrical machines, according to GOST 183, is determined by the permissible temperature of the stator winding at an ambient temperature of + 40 °C and operation at an altitude of not more than 1000 m above sea level. The actual ambient temperature and height above sea level significantly affect the output power of electrical machines, and if this is not taken into account, they can work for a long time at an ambient temperature exceeding the maximum working temperature. To avoid unacceptable excess of winding temperature, output power must be reduced (Figure 6) [9].

With an increase in the operating height of electric machines (more than 1000 m above sea level), it is also necessary to reduce the load on the shaft (Figure 7) [10]. This is due to a change in a number of operating parameters. In addition to changing the ambient temperature, the atmospheric pressure decreases and, as a result, the air density decreases. Thus, the properties of the cooling medium (refrigerant) change, and electric machines, operating in the same conditions as at altitudes up to 1000 m, will undergo significant overheating, which will result in a reduction in its life.

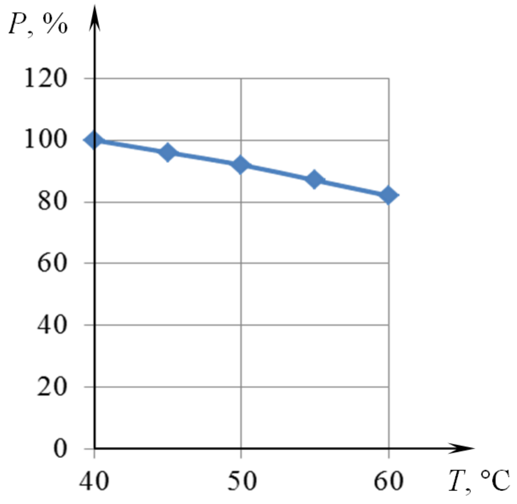


Figure 6 – Dependence of output power *P* of electric machines on temperature *T*

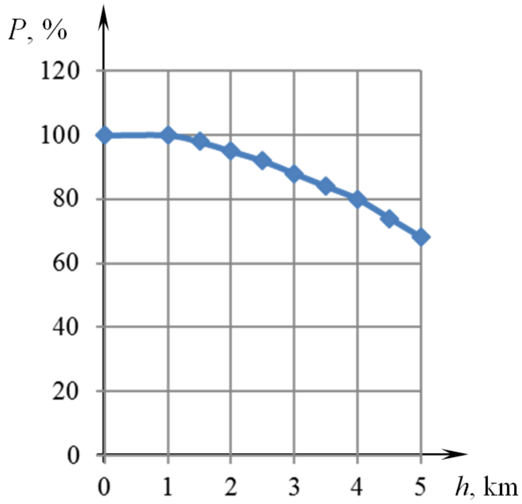


Figure 7 – Dependence of output power *P* of electric machines on height *h*

As the height increases due to the decrease in air density, the actual excess temperature of equipment that generates heat during operation and is completely or partially cooled by free or forced air convection increases. When using such articles at altitudes of more than 1000 m, the allowable temperature excess must be reduced by a value corresponding to the height correction. The standards or specifications for such products shall specify corrections for the amount of reduction of the nominal load of the product (if it is possible) or for the amount of reduction of the maximum permissible temperature exceedances exceeding normal. According to GOST 15150 for products designed for operation at a height of 1000 m to 4300 m, the upper temperature values can be calculated by reducing the maximum value by 0.6 °C for every 100 m for heights more than 1000 m.

Conclusion

Taking into account the influence of climatic factors at the stage of development and design of traction electrical equipment is an important condition that determines the duration and reliability of its operation. The results of climatic tests and mathematical modelling showed the feasibility of using the insulation of the heating resistance class 220 in the production of TEM. This is especially important for equipment that operates in difficult climatic conditions, and the choice of insulating materials largely depends on the life of the equipment.

References

1. Mitreikin, N. A. Reliability and testing of radio parts and radio components / N. A. Mitreikin, A. I. Ozersky. – M. : Radio and communications, 1981. – 272 p.
2. Bondarenko, I. B. Electrical radio elements: in 2 parts / I. B. Bondarenko. – SPb.: SPb. NIU ITMO, 2015. – Part 1: Resistors. – 2012. – 108 p.
3. Borisenko, A. I. Cooling of industrial electric machines / A. I. Borisenko, O. N. Kostikov, A. I. Yakovlev. – M. : Energoatomizdat, 1983. – 296 p.
4. Electric rotating traction machines. General specifications: GOST 2582-2013. – Vved. 01.04.2020. – M. : Interstate Council for Standardization, Metrology and Certification: Standardinform, 2014. – 52 p.
5. Karpenko, V. V. Studies of insulation systems of the 220 °C class of traction electric machines for resistance to external climatic factors / V. V. Karpenko, D. Yu. Vasilenko, S. I. Yatsko // Fundamental and applied problems of technology and technology. – 2015. – № 5 (313). – P. 152–159.
6. Electrotechnical products. Test methods for resistance to climatic external factors: GOST 16962.1-89. – Vved. 01.02.2020. – Minsk : Gosstandard, 2011. – 44 p.
7. Integrated quality control system. Products of electronic engineering, quantum electronics and electrotechnical. Test methods: GOST 20.57.406-81. – Vved. 01.01.81 – M. : Interstate Council for Standardization, Metrology and Certification : Standardinform, 2005. – 132 p.
8. Fundamentals of physical chemistry. Theory and problems: text. manual for universities / V. V. Eremin [et al.]. – M. : Publishing house "Exam," 2005. – 480 p.
9. Technical catalog of electric motors of the Vladimir Electric Motor Plant VEMZ (RUSELPROM). – Vladimir : Vladimir Electric Motor Plant OJSC, 2007. – 108 p.
10. Yuldashev, A. A. The influence of altitude and ambient temperature on the output power of the asynchronous motor / A. A. Yuldashev, Z. Sh. Yuldashev // Bulletin of the Student Scientific Society. – 2014. – № 3. – P. 105–106.

Spisok citirovannyh istochnikov

1. Mitrejkin, N. A. Nadezhnost' i ispytaniya radiodetalej i radiokomponentov / N. A. Mitrejkin, A. I. Ozerskij. – M. : Radio i svyaz', 1981. – 272 s.
2. Bondarenko, I. B. Elektroradioelementy: v 2 chastyah / I. B. Bondarenko. – SPb. : SPb. NIU ITMO, 2015. – CHast' 1: Rezistory. – 2012. – 108 s.
3. Borisenko, A. I. Ohlazhdenie promyshlennyh elektricheskih mashin / A. I. Borisenko, O. N. Kostikov, A. I. YAkovlev. – M. : Energoatomizdat, 1983. – 296 s.
4. Mashiny elektricheskie vrashchayushchiesya tyagovye. Obshchie tekhnicheskie usloviya: GOST 2582-2013. – Vved. 01.04.2020. – M. : Mezhgosudarstvennyj sovet po standartizacii, met-rologii i sertifikacii: Standartinform, 2014. – 52 s.
5. Karpenko, V. V. Issledovaniya sistem izolyacii klassa nagrevostojkosti 220 °S tya-govyh elektricheskih mashin na ustojchivost' k vozdejstviyu vneshnih klimaticheskih faktorov / V. V. Karpenko, D. Yu. Vasilenko, S. I. Yacko // Fundamental'nye i prikladnye problemy tekhniki i tekhnologii. – 2015. – № 5 (313). – S. 152-159.
6. Izdeliya elektrotekhnicheskie. Metody ispytanij na ustojchivost' k klimaticheskim vneshnim vozdejstvuyushchim faktoram: GOST 16962.1-89. – Vveden 01.02.2020. – Minsk: Gosstandart, 2011. – 44 r.
7. Kompleksnaya sistema kontrolya kachestva. Izdeliya elektronnoj tekhniki, kvantovoj elektroniki i elektrotekhnicheskie. Metody ispytanij: GOST 20.57.406-81. Vveden 01.01.81 – M. : Standartinform, 2005. – 132 p.
8. Osnovy fizicheskoj himii. Teoriya i zadachi: ucheb. posobie dlya vuzov / V. V. Eremin [i dr.]. – M. : Izdatel'stvo «Ekzamen», 2005. – 480 s.
9. Tekhnicheskij katalog elektrodvigatelej Vladimirskogo elektromotornogo zavoda VEMZ (RUSELPROM). – Vladimir : OAO «Vladimirskij elektromotornyj zavod», 2007. – 108 s.
10. Yuldashev, A. A. Vliyanie vysoty nad urovnem morya i temperatury okruzhayushchej sredy na otdavaemuyu moshchnost' asinhronnogo dvigatelya / A. A. Yuldashev, Z. Sh. Yuldashev // Vestnik studencheskogo nauchnogo obshchestva. – 2014. – № 3. – S. 105–106.

Материал поступил в редакцию 20.04.2022

doi.org/10.36773/1818-1112-2022-128-2-83-86