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SYSTEMATIZATION AND SELECTION OF DIAGNOSING METHODS FOR THE STATOR WINDINGS INSULATION OF INDUCTION MOTORS

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Keywords: Diagnostic methods; Failure statistics; Insulation damage; Stator winding; Types of defects; Induction motor; Turn-to-turn closures of stator; Simulation; Technical condition; Residual resource.

Highlighted an extremely relevant problem of monitoring the insulation state of the stator windings of induction motors during operation. Improving the accuracy of diagnostics and the correct choice of method for assessing and predicting failure-free operation significantly increases the reliability of the equipment. The most damageable machine elements are the stator windings, where insulation faults are of prime importance. The work provides a classification of the causes of failures, insulation of windings of induction motors, and types of defects due to the reasons for their occurrence.
An analysis of ~~the~~ advantages and disadvantages of the most common in-practice methods for diagnosing the insulation of windings of induction motors during operation is given. The issues of using modeling to establish a diagnostic method are considered. The advantages and disadvantages of the considered methods are revealed, and a comparative characteristic is presented.
The work carried out the systematization and construction of a complex structural diagram linking the known types of insulation defects and methods for their determination. The resulting scheme contributes to the creation of diagnostic complexes that consider the combination of several methods for various types of defects and a rational approach to diagnostics for detecting damage at various stages of motor operation.

1. INTRODUCTION

Improving the operational reliability of electromechanical equipment is a priority task, and the solution determines the result of the effective work of industrial and transport enterprises [1–3]. It is associated with an increase in the accuracy of diagnostics, the correct choice of the method for a reliable assessment of the state, and the prediction of the failure-free operation of electrical equipment.

The most damageable element of the motor is the stator winding, where insulation damage is of prime importance.

Insulation is the most vulnerable element of electrical machines; it is relatively easily damaged at all stages of the creation and operation of motors, including such factors as accidental mechanical influences, environmental influences, oil, and dust entering the motor.

In this regard, during the operation of electrical machines, high attention is paid to monitoring the state of the insulation of the windings. For the accuracy of diagnostics, the correct choice of one or several methods is required to provide reliable information about the insulation state [4,5].

The complexity of the processes observed in the insulation of electrical machines leads, on the one hand, to the emergence of a significant number of methods for measuring its parameters and, on the other, their complexity of the application and, in certain cases, low accuracy.

The choice of the diagnostic method is directly related to the type of defect. Therefore, to build a reliable diagnostic system, it is necessary to have an accurate understanding of all types of damages, starting from the stages of development, manufacture, and operation of electromechanical equipment [6,7]. For this, it is important to study the nature of the occurrence and manifestation of various types of insulation damage, the nature of their occurrence, and the choice of appropriate methods that are optimal for their diagnosis [8,9].

It follows that the main condition contributing to the reduction of failures during the period of operation is the timely diagnosis and prediction of the current state of the windings of electrical equipment in terms of its influence on the period of failure-free operation using appropriate methods. The most rational is creating a diagnostic complex for monitoring the state of the insulation of windings at the stages of production or operation with the inclusion of the optimal number of methods covering the maximum number of possible defects.

For this, it is necessary to analyze the existing diagnostic methods, structure the types of defects, and the most appropriate methods for their accurate detection at various stages.

This work is devoted to constructing a complex structural diagram linking the types of defects and methods of their determination based on their classification and systematization. The resulting scheme contributes to the creation of diagnostic complexes that consider the combination of several methods for various defects and a rational approach for choosing diagnostic methods to identify defects at various stages of motor operation.

2. MATERIALS AND METHODS

Statistics of the operating experience of the most common type of electric machines of induction motors show that the largest share of malfunctions falls under failures in the stator and, according to various sources, accounting for the area of operation, is 77-85 %. The rotor accounts for 6-8 %, and the bearing unit – up to 8-14 % [10].

Figure 1 presents the analysis of the root causes of the damage development that led to the emergency failure of an induction motor.

From Fig. 1, it follows that most emergency failure of induction motors (31 %) occurs due to overheating or overloading the motor. These reasons relate to violations of the operating conditions of an induction electric motor, such as a discrepancy between the characteristics of the motor and the operating conditions, frequent starts, violation of the cooling mode, delayed overload protection, etc. This contributes to the destruction of the insulation of the windings and the insulation of the slot and interphase insulation, which subsequently leads to electrical breakdown.

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The second leading cause (15 %) of emergency failures is the turn-to-turn short circuit in the stator winding (Fig. 2). Turn-to-turn faults are the most common stator failure. Accounting for this defect with the appearance of short-circuited turns in the stator winding, the motor continues to operate in working condition. At the same time, the performance characteristics and energy indicators of electric motors deteriorate. However, due to the increase in current in the damaged phase, this defect is characterized by the progression of damage with a further increase in the number of short-circuited turns, and the electric motor fails in emergency mode.

Insulation damage (11 %) is caused by various factors (constructive, technological, operational) and is also not critical at starting stage of the defect. But in the development of the damage, the electric motors go out of service.

Thus, most motor failures occur when the stator winding insulation is damaged.

The main types of damage to the insulation of the stator winding are the result of the development of the considered causes of failures: turn-to-turn short circuits in the winding phase, short circuits of the winding to the housing, and breakdown of the interphase insulation.

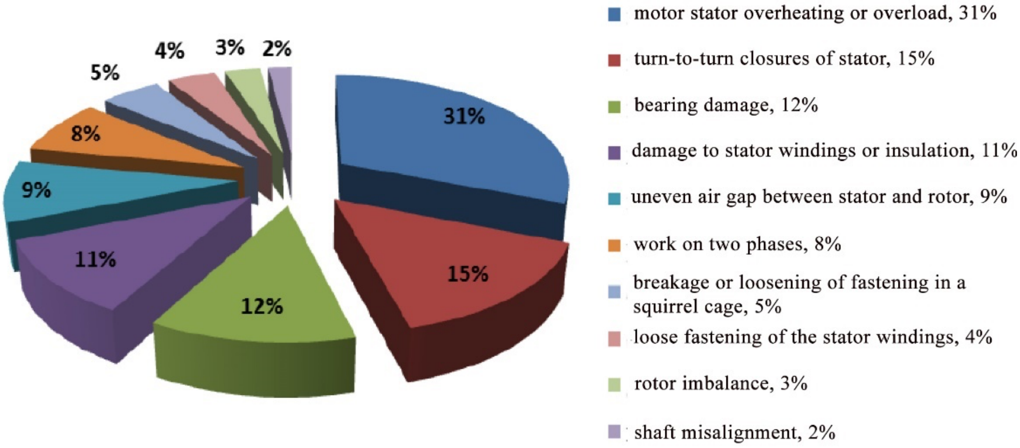


Fig. 1 – Results of the analysis of the causes of emergency failures of induction motors with a squirrel-cage rotor.

The rest of the damage is in the rotor and mechanical parts of the motor, which contribute to vibration. The vibrational action accelerates the destruction of the winding insulation.

Thus, the highest failure rate of electric induction motors is due to damage to the stator winding, which is a consequence of the degradation of dielectric materials due to various impacts during operation.

The study of the types of insulation damage and the optimal choice of methods for their detection, considering the origin and typical operating conditions as part of diagnostic systems, will help to avoid emergency failures and increase the reliability of the most used type of electrical motors.

There is a significant number of methods for monitoring the state of insulation for diagnosing winding damage, which is associated with the nature of occurrence and type of damage, where the causes may be not only defects during the operation of the electric motor.

During an induction motor's operation, insulation damage can be divided into three groups according to their origin: structural, technological, and operational.

Figure 3 shows the systematization of the causes of insulation damage for various stages of the operation of an electric machine.

If the share of structural and technological damage to the insulation of induction motors has recently decreased significantly, the problem of identifying operational defects remains relevant.

The type and rate of development of damage will depend on external operating factors and the internal characteristics of the induction motor insulation system. In modern industries, during operation, induction motors are subject to a wide range of external influences that can significantly deteriorate the insulation properties. These are high vibration, high pressure, high temperature, frequent overloads, etc. The development of an insulation defect occurs under the influence of humidity, thermal destruction, mechanical damage, the electric field of operating voltage and overvoltage, pollution, *etc*.

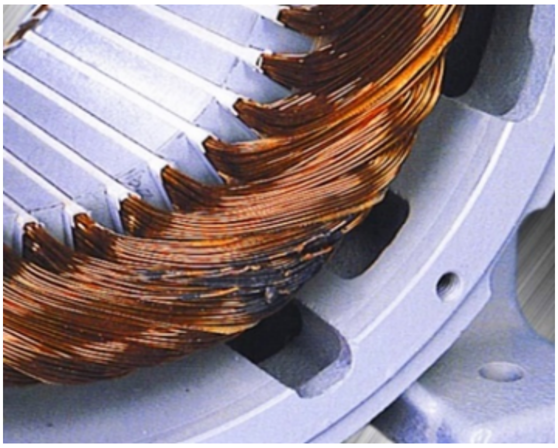


Fig. 2. Turn-to-turn short circuits in the stator winding.

According to [13], in the list of factors that are the causes of electric motor accidents, insulation damage is more than 40 %.

Despite the constant improvement of the insulation of stator windings, usage of new materials, the improvement of technologies for applying varnish insulation on the wire, usage of special methods of impregnation and drying, high-precision methods of laying windings and assembling machines, today it is not possible to cope with the problem of low reliability of insulation of electrical machines due to structural and technological reasons.

The problem of reliability, above all, of turn insulation, concerns machines of low and medium power with many turns in a phase since the specific strength of inter-turn insulating overlaps is reduced significantly because of various technological operations with a thin enameled wire.

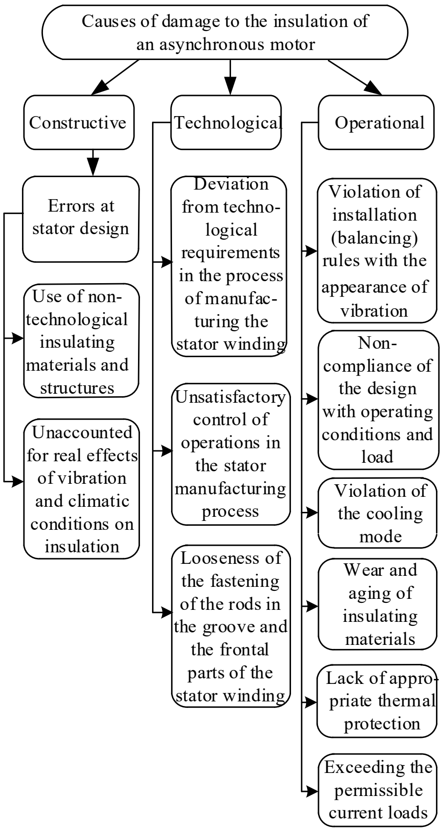


Fig. 3 – Systematization of the causes of insulation damage.

To determine and improve the most reliable method for diagnosing the current state of the insulation of an asynchronous motor, as well as establishing the possibility of further operation of a damaged machine, a set of theoretical studies, modeling, and a detailed comprehensive analysis of the processes associated with the occurrence of each malfunction and its manifestations at various stages of development is required. Turn-to-turn short circuits in the stator winding, caused by insulation damage, are among the most frequent and difficult-to-diagnose defects that cause a deviation of the motor parameters from the nominal values and contribute to the transition from a gradual failure to an emergency stop. With this defect, with a small number of short-circuited turns of the damaged phase of the winding, the asynchronous motor can be in working condition for some time with a deviation in operating parameters and characteristics. With a further inevitable increase in the number of short-circuited turns in the winding phase due to the consequences of a critically increased value of the phase current in the damaged phase and, accordingly, temperature, the electric motor goes into an inoperable state.

To establish specific diagnostic methods for the main types of damage, it is advisable to study the manifestation of an insulation defect using simulation. Mathematical modeling methods are widely used in studying the characteristics and parameters of induction motors at all stages of their design and operation. The authors in the article [14] researched using simulation to develop an optimal design solution that increases productivity and reduces costs for the production and operation of asynchronous motors.

Turn-to-turn short circuit is one of the most dangerous electrical faults in induction motors, with serious consequences for the operation of the motor and its performance. The article [15] discusses the impact of an early stator short circuit on the performance and continuity of an induction motor.

To establish diagnostic methods, studies of the turn-to-turn short circuits in the stator winding were carried out using the simulation model of an induction motor given in [16], implemented in the MatLab software package with the established adequacy to the real process.

The studies were carried out on a model of a series squirrel-cage induction motor *AIR132 M4, the* main technical parameters given in Table 1.

Table 1

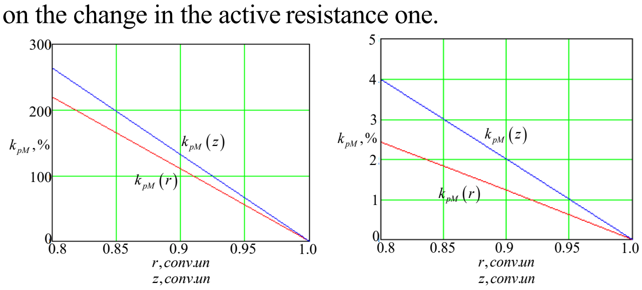
Technical parameters of an induction motor with a squirrel-cage rotor AIR132M4

Parameter	Value
Shaft Power Rating P_n, kW	11.0
Rated phase voltage U_s, V	220
Rated frequency of supply voltage f_s, Hz	50
Rated rotation speed of a motor shaft in idle mode n_s, rpm	1498
Nominal motor shaft speed n_s, rpm	1450
Rated torque on the motor shaft M_n, Nm	72.67
Idle load torque M_{idle}, Nm	0.38

The methodology for studying the effect of turn-to-turn short circuits in the stator winding of varying degrees on the motor parameters included modeling the parameters of an undamaged stator and simulating the closing of winding turns in one phase in the idle mode and then in the nominal mode of the motor. Turn-to-turn shortcircuits are organized in the model by reducing the active and complex resistance of the stator phase of the winding, at which the winding resistance is reduced up to 90 % of the nominal value and up to 80 %, which is 10 % and, respectively, 20 % of the closed turns of the winding.

Based on the simulation results, graphs of the electromagnetic torque ripple coefficient k_{pM}, % (Fig. 4 a, b) and the stator phase current unbalance coefficient $k_{mb.I}$, % (Fig. 5 a, b) depending on the change in the active *r*, *conv.un* and complex *z*, *conv.un* resistance of one phase of the stator winding for idling and rated mode.

As can be seen from Fig. 4 and Fig. 5, with turn-to-turn short circuits in the phase of the stator winding, an increase in the pulsations of the electromagnetic torque and the phase current unbalance coefficient occurs. The unbalance coefficient of the stator phase currents (Fig. 5) changes to a lesser extent when both active and complex resistance of one of the motor phases changes. In addition, from Fig. 4 and Fig. 5, it follows that the torque ripple factor and the unbalance factor of the stator phase currents are more dependent on the change in the complex resistance of the damaged phase than on the change in the active resistance one.



a) b)

Fig. 4 – The dependence of the ripple coefficient of the electromagnetic torque on the change in the resistance of the stator phase in: a) idle mode; b) rated mode.

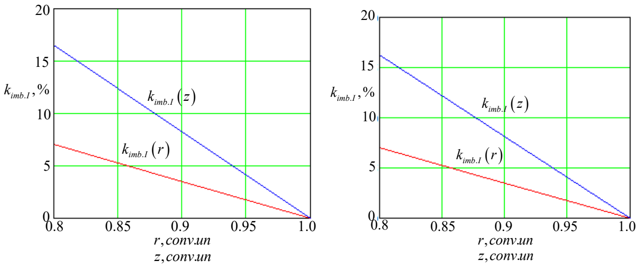


Fig. 5 – The dependence of the unbalance coefficient of the stator phase currents on the change in the stator phase resistance in:
a) idle mode; b) rated mode.

The studies show that the turn-to-turn short circuit in the stator phase can be established to varying degrees both by vibration and electrical methods. Moreover, torque pulsations are the most significant in idle mode, which is inconvenient for diagnostic systems of a running motor under load. However, it should be considered that the turn-to-turn short circuit, accompanied by torque pulsations, which are caused by the asymmetry of the stator magnetic field, is already a consequence of the electrical breakdown of the insulation.

Thus, despite the considerable interest of researchers in this issue, the problem of creating highly sensitive and reliable methods for detecting insulation defects and predicting the technical condition of electrical machines has just been fully resolved.

3. **RESULTS AND DISCUSSION**

To diagnose damage to the stator windings, several methods for monitoring the state of insulation can be classified according to the measured or calculated parameters.

These parameters include dc resistance, absorption coefficient, polarization index, dielectric loss tangent, reverse voltage level, intensity and amplitude of partial discharges, vibration frequency, etc. Insulation monitoring methods based on measurements of non-electrical quantities [17,18] require accurate information about the physical properties of materials and coefficients that are usually impossible to measure or obtain. Some state control algorithms are based on determining the parameters of an induction machine, both electrical and mechanical, using only the starting current and the corresponding phase voltage [19]. In addition, diagnostic parameters characterizing electromagnetic, vibration, and acoustic processes are not standardized [20]. The methods of vibration diagnostics, which are currently actively developed, only sometimes make it possible to obtain reliable results [16].

Table 2 shows a comparative characteristic of modern methods for diagnosing the insulation state.

Based on the systematization and analysis of the nature of origin, types of damage, and modern diagnostic methods, Fig. 6 shows the structural systematization of defects and the corresponding methods for their detection.

Table 2

Insulation monitoring methods for induction motors

№	Methods for monitoring the state of insulation of an induction motor	The advantage of the method	The disadvantage of the method
1	By overvoltage	Simplicity of the method at low cost of equipment	Destructive effect on insulation, can cause the appearance of microdefects in the winding, the possibility of premature breakdown
2	By partial discharge	High accuracy, even in hard-to-reach places	Destructive effect on insulation, leads to a decrease in the properties of organic insulation by ionization processes
3	Capacitive	Does not require the manufacture of expensive original means of control	High requirements for the accuracy of the used measuring instruments
4	By insulation resistance	The cheapest, easiest, and most common	The inability to predict the residual life at different stages of operation under different conditions of temperature, humidity and vibration
5	By measuring or calculating electrical quantities: dielectric absorption coefficient, polarization index value, dielectric discharge coefficient, dielectric loss tangent *tanδ*, relaxation time constant	Comparative simplicity and low cost. Ability to perform continuous monitoring without additional power supplies	Large dependence of the results on the impact of the environment. Difficulty in interpreting results, determining actual condition, and predicting residual life. Limitations on motor operating modes in which measurement accuracy is required
6	By vibration parameters	Reliability and prospects, simplicity, and low cost of equipment. Possibility of diagnostics while the motor is running. The high accuracy of the results	The difficulty of accurately isolating extraneous vibration effects, the absence of a complete vibration base of stator winding defects at various stages of development for the entire range of motors
7	By winding temperature	High accuracy, low cost and easy process. By controlling minor temperature deviations, it is possible to avoid insulation breakdown at an early stage	Consideration of third-party environmental influences, use of sensitive temperature sensors
8	Acoustic	The ability to predict the residual life of insulation at different stages of operation in different conditions of temperature, humidity and vibration	Low sensitivity, noise masking for a useful diagnostic signal, low reliability of the result. Suitable for low-voltage three-phase induction motors
9	Using fuzzy logic	A promising and reliable method for detecting stator winding damage based on current amplitude monitoring	Complexity of unambiguous interpretation of data, lack of an accurate analytical model for describing motor faults
10	Spectral analysis (current, modules of vectors Park current and voltage)	Enough simplicity. The ability to identify the main types of defects in the electric motor and associated mechanical device	The complexity of evaluating the results, the need to consider the influence on the electrical parameters of the drive of the parameters of the supply network, the nature of the load, the influence of external electromagnetic fields, transient processes in the drive. Suitable for motors powered directly from the mains, with little change in load

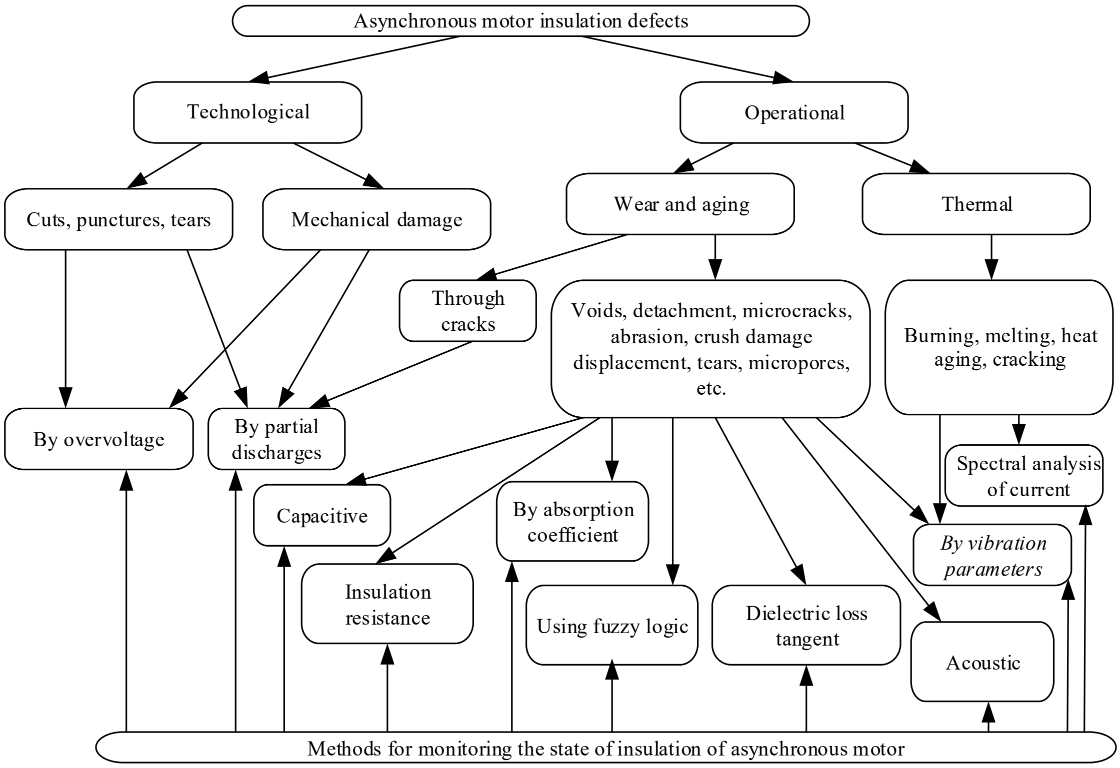


Fig. 6 – Classification of insulation defects and diagnostic methods.

For the most part, operational defects of insulation, which are manifested in turn-to-turn short circuits, are subdivided into thermal and those caused by wear and aging of the insulating material (Fig. 6).

Thermal damage includes damage to the insulation caused by prolonged exposure to high temperatures of the winding wires, which manifests in burning or melting. They can be detected by spectral analysis.

For motors that are in continuous operation or are suitable for the service life to the limit state, the diagnosis of the current state of the interturn insulation, caused by the processes of natural wear and aging, is of decisive importance. The structural sign of the onset of the phase of the insulation's limiting wear and the induction motor's transition to the expected failure is the formation of through cracks in the interturn insulating layer. This requires timely and reliable monitoring of the state of this type of damage.

The most reliable diagnosis should be considered the sensitivity to damage to the insulating layer, which is responsible for the electrical breakdown. This condition is satisfied by the overvoltage and partial discharge methods (Fig. 6). However, it should be borne in mind that these methods, by the nature of the impact on the winding, also have a destructive effect of high voltage and can lead to a decrease in the durability of worn insulation or damage to a completely high-quality winding. Therefore, it is advisable to use control methods with increased voltage or partial discharges only for mass inspection of motors after manufacture or overhaul with replacement of the stator winding.

It has been established that turn-to-turn closures of stators cause a change in both vibrational and electrical parameters of the motor to varying degrees for the operating mode of an induction motor and make it possible to differentiate damage already at the stage of manifestation.

A common disadvantage of the above methods is their low versatility, which is associated with the type of defect and the limitation of the types of machines on which they can be used, as well as with the limitations of the motor operating modes, at which the required measurement accuracy is possible. To improve the accuracy of control results, it is necessary to consider the measured values not separately but as part of a diagnostic complex [21].

At the same time, operating conditions and classes of machines require new insulation diagnostics methods, including in the operating mode.

The complexity of the interpretation of the measurement results for each parameter is associated with the dependence of these results on the measurement conditions (temperature, humidity) and the nature of defects (physical aging, chemical «aging», contamination, etc.). These conditions create discrepancies in the results for various parameters when establishing the actual state of the insulation.

4. **CONCLUSIONS**

The paper analyzes the modern problem of determining the state of insulation of operating electrical equipment. Monitoring the insulation's technical condition increases the motors' reliability and efficiency and helps reduce emergency failures. Based on the analysis, the systematization of defects and detection methods was carried out with the construction of a single block diagram. The resulting scheme can be used to create diagnostic complexes, considering the combination of several methods for various defects, as well as for a rational approach to diagnostics to identify defects at various stages of engine operation.

In the absence of monitoring systems that control the condition of the insulation of electric motors during their operation, it is necessary to pay considerable attention to preventive maintenance and insulation control. The main way to control the condition of the insulation is to periodically measure its resistance in an operating electric motor after repair, installation, or extreme operating modes with the voltage removed. The prevention of insulating materials of electric motors during the operation period includes excluding mechanical effects, moisture, chemical effects, dusting, and overheating of the winding.

In addition, under normal operating conditions, the insulation gradually loses its original dielectric properties ("aging"). This contributes to the development of local defects, a decrease in insulation resistance, and an increase in the leakage current, which must be detected promptly by one of the methods listed in work during the period of motor maintenance.

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REFERENCES

1. M. Nawaz, F. Zulfiqar, M. Bilal. *Performance evaluation of digital governor for improving operational efficiency and reliability of power plant*, Sarhad University International Journal of Basic and Applied Sciences, **4**, *1*, pp. 1–9 (2017).
2. V.P. Meshalkin, S.P. Kurilin, M.I. Dli, V.I. Bobkov, A.S. Fedulov. *Ways to increase the energy efficiency and reliability of induction electric motors in chemical plants*, Theoretical Foundations of Chemical Engineering, **55**, *2*, pp. 215–224 (2021).
3. B. V. Malozyomov, M. E. Vilberger, M. V. Rozhkova, A. A. Shtang. *Diagnostics time intervals of electric transport systems using time between failures*, International Conference "Actual Issues of Mechanical Engineering", Atlantis Press, pp. 458–466 (2017).
4. A. Nosenko, A. Domnitskiy, E. Shemshura. *Predictive reliability assessment of loading and transport modules of tunneling equipment during construction of road tunnels*, Procedia Engineering, **206**, pp. 1661–1666 (2017).
5. Y.L. Zhukovskiy, N.A. Korolev, I.S. Babanova, A.V. Boikov. *The probability estimates of the defects of the induction motors based on the complex method of diagnostics*. In: IOP Conference Series: Earth and Environmental Science, **87**, *3*, p. 032055, IOP Publishing (2017).
6. A. Aboulian, D.H. Green, J.F. Switzer, T.J. Kane, G.V. Bredariol, P. Lindahl, J. S. Donnal, S. B. Leeb. *NILM dashboard: A power system monitor for electromechanical equipment diagnostics*, IEEE Transactions on Industrial Informatics, **15**, *3*, pp.1405–1414 (2018).
7. J. Yang, Y. Guo, W. Zhao. *Long short-term memory neural network based fault detection and isolation for electro-mechanical actuators*, Neurocomputing, **360**, 85–96 (2019).
8. M. Singh, A.G. Shaik. *Incipient fault detection in stator windings of an induction motor using Stockwell transform and SVM*, IEEE Transactions on Instrumentation and Measurement, **69**, *12*, pp. 9496–9504 (2020).
9. A. Khechekhouche, H. Cherif, A. Menacer, S.E. Chehaidia, H. Panchal. *Experimental diagnosis of inter-turns stator fault and unbalanced voltage supply in induction motor using MCSA and DWER*, Periodicals of Engineering and Natural Sciences (PEN), **8**, *3*, pp. 1202–1216 (2020).
10. I. Culbert, J. Letal. *Signature analysis for online motor diagnostics: Early detection of rotating machine problems prior to failure*, IEEE Industry applications magazine, **23,** *4*, pp. 76–81 (2017).
11. R. H.C. Palácios, I.N. da Silva, A. Goedtel, W.F. Godoy, T.Lopes. *Diagnosis of stator faults severity in induction motors using two intelligent approaches*, IEEE Transactions on Industrial Informatics, **13**, *4*, pp. 1681–1691 (2017).
12. B.C.F. de Oliveira, R.C.C. Flesch, M.B. Demay. *Development and experimental evaluation of a vision system for detecting defects of stator windings in induction motor assembly lines,* 13th IEEE International Conference on Industry Applications (INDUSCON), pp. 858–863 (2018).
13. I.Y. Braslavsky, V.P. Metelkov, D.V. Esaulkova, A.V. Kostylev. *Simplified method of taking into account temperature fluctuations influence on durability of induction motors stator winding insulation*, In: 2018 17th International Ural Conference on AC Electric Drives (ACED), pp. 1–4, IEEE (2017).
14. M-A. Enache, I. Vlad, A. Campeanu, E. Erina (Spunei). *Optimization of operation characteristics for asynchronous motors used in coal mills.* Rev. Roum. Sci. Techn. – Électrotechn. Et Énerg., **64**, *1*, pp. 27–32 (2019).
15. S.Y. Cherif, D. Benoudjit, M.S. Nait-Said, N. Nait-Said, *Incipient shortcircuit fault impact on service continuity of an electric vehicle propelled by dual induction motors structure*. Rev. Roum. Sci. Techn. – Électrotechn. Et Énerg., **67**, *3*, pp. 265–270 (2022).
16. O. Gubarevych, S. Goolak, O. Daki, V. Tryshyn. *Investigation of turn-to-turn closures of stator windings to improve the diagnostics system for induction motors*. Problems of the regional energetics. E-Journal, **2**, *50*, pp. 10–24 (2021).
17. N.J. Jameson, M.H. Azarian, M. Pecht, *Impedance-based condition monitoring for insulation systems used in low-voltage electromagnetic coils*, IEEE Transactions on Industrial Electronics, **64**, *5*, pp. 3748–3757 (2017).
18. C. Zoeller, M. Vogelsberger, M. Bazant, H. Ertl, T.M. Wolbank. *Diagnostic technique for traction motor insulation condition monitoring by transient signal assessment*, In: PCIM Europe 2018; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, pp. 1–8, VDE (2017).
19. E.G. Habbi et al. *New dynamic genetic selection algorithm: application to induction machine identification.* Rev. Roum. Sci. Techn. – Électrotechn. Et Énerg., **66**, *3*, pp. 145–151 (2021).
20. R. Varbanets, O. Fomin, V, Píštěk, V. Klymenko, D. Minchev, A. Khrulev, V. Zalozh, P. Kučera, *acoustic method for estimation of marine low-speed engine turbocharger parameters*, Journal of Marine Science and Engineering, **9**, *3*, pp. 321 (2021).
21. S. B. Jiang, P. K. Wong, R. Guan, Y. Liang, J. Li. *An efficient fault diagnostic method for three-phase induction motors based on incremental broad learning and non-negative matrix factorization*, IEEE Access, **7**, pp. 17780–17790 (2019).