

ANNOTATION

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– "Electric Power Engineering"

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DEVELOPMENT OF METHODS FOR IDENTIFYING DAMAGED SECTIONS IN THREE-PHASE WINDINGS OF ELECTRICAL MACHINES

This dissertation is devoted to development of a highly sensitive method for detecting a damaged section in three-phase windings of electric machines. The research was carried out within the framework of the priority directions for development of science "Energy and Mechanical Engineering" approved by the Higher Scientific and Technical Commission under the Government of the Republic of Kazakhstan.

Relevance. Three-phase electric machines are used in electric power engineering to convert electrical energy into mechanical energy and vice versa. This energy conversion is typically carried out using three-phase synchronous generators (SG), motors (SM) and compensators (SC), as well as asynchronous motors (AM) with squirrel-cage and wound rotors. A characteristic feature of all these electric machines is the identical design of the stator and wound rotor windings.

From the operational practice of three-phase electric machines, it is known that turn-to-turn faults (TTF) in sectionalized and random-wound windings of stators and wound rotors account for up to 35% and 93% of all failures of these electric machines, respectively.

Traditionally, fuses and circuit breakers are used to protect low-voltage electric machines from short circuits in stator and wound rotor windings, while in high-voltage electric machines, overcurrent or differential protections are used, which employ current transformers as measuring transducers. Such protections have low sensitivity to TTF.

As non-traditional protections for these purposes, protections using a ring-type measuring transducer (RMT) as a measuring transducer can be used. Such protections have increased sensitivity to TTF. When such a protection operates, sections with "hidden" faults in the form of short-circuited turns almost always appear in the three-phase windings. As the operational practice of electric machines shows, if such a section appears, its identification will allow the repair of the damaged stator to be reduced to "cutting out" this section without significant damage to the further operation of the electric machine. As a result, the cost of its repair will decrease by tens of times.

There is a method for visual identification of a section with "hidden" faults. In this way it is revealed by darkening its insulation. If the damaged section cannot be found in this way, it is recommended to connect the machine to a reduced voltage until the darkening of the insulation of the damaged section appears. The main

disadvantage of this method is that overheating of the damaged section can lead to heating and damage to the insulation of adjacent sections.

This disadvantage is absent in those methods for identifying a section with "hidden" faults in which the controlled quantity is the magnetic field of the short-circuited turns, where the current is created using special electromagnetic inductors.

A significant contribution to the development of such methods for detecting a damaged section in three-phase windings of electric machines was made by scientists such as Dero A.R., Vinogradov N.V., Perel'muter N.M., Bunevichus B.A., Ebralidze R.V., Ginkas M.L., Al'peravichus Kh.A., Novozhilov T.A., Novozhilov A.N, Kletsel' M.Ya., and a number of others.

However, implementation of known methods for identifying a section with "hidden" faults, in which the controlled quantity is magnetic field of the current in the short-circuited turns, also has significant disadvantages.

For instance, the method in which a magnetic flux is formed through the plane of the section being diagnosed using an electromagnetic inductor placed on adjacent teeth of the stator magnetic core at one of its ends, and the current in its turns is measured using a similar electromagnetic inductor located on the same teeth at the other end of this magnetic core, has low sensitivity. This is because in this case not only the magnetic field from the current in the short-circuited turns is measured, but also the magnetic field in the stator magnetic core from the electromagnetic inductor creating the magnetic field is. This magnetic field is present in the stator magnetic core even in the absence of short-circuited turns in the diagnosed section.

A method for detecting short-circuited turns in the stator winding of electric machines is constructed somewhat differently. For its implementation, a complex structure of inductors and magnetic field sensors located in the area of the end windings during diagnosis is used. In this regard, this method can only be used on an assembly line for production of the same type of electric machine. Furthermore, it is not able to indicate the location of the section with a "hidden" fault in the stator winding. This leads to a significant limitation of its scope.

A known method for identifying a section with a "hidden" fault in the stator winding uses an E-shaped magnetic core with several windings. Some of these windings are used to form a diagnostic magnetic field, while the other part is used to measure the magnetic field of the short-circuited turns. The disadvantage of this method is that such an E-shaped magnetic core can only be used for diagnosing electric machines with the same tooth pitch, which significantly limits its scope.

Thus, the work on developing highly sensitive methods for identifying a section with a "hidden" fault in a three-phase winding, which allow for the diagnosis of electric machines with different tooth pitch values, **is relevant**.

The object of the study is the area of diagnosing damage to the stator and wound rotor windings of three-phase electric machines.

The subject of the study is the improvement of the diagnostic process for stator and wound rotor windings of three-phase electric machines through the use of an RMT.

The goal of the work is to develop highly sensitive methods for identifying a section with a "hidden" fault in a three-phase winding, which allow for the diagnosis of electric machines with different tooth pitch values. To achieve this goal, the following tasks were set and solved:

1. To analyze known technical solutions intended for detecting a section with a "hidden" fault in a three-phase winding of electric machines.
2. To develop a new highly sensitive method for identifying a section with a "hidden" fault in a three-phase winding, allowing for the diagnosis of electric machines with different tooth pitch values.
3. To develop, based on the classical method of calculating magnetic circuits, a method for modeling the parameters of a U-shaped electromagnetic inductor intended for forming a diagnostic magnetic field and current in the short-circuited turns of a damaged section with a "hidden" fault.
4. To develop, based on the Biot-Savart-Laplace method, a method for calculating the EMF at the output of an RMT from the current in the short-circuited turns of a section with a "hidden" fault.
5. To propose a method for determining the range of the tooth pitch value for stator and wound rotor magnetic cores of 20-5000 kW machines with arbitrary number of pole pairs.
6. To develop a universal design of a U-shaped electromagnetic inductor that will allow searching for a section with a "hidden" fault in machines with a power of 20-5000 kW with any tooth pitch value.
7. To develop designs for stationary and portable RMTs for searching a section with a "hidden" fault in electric machines where an RMT is not installed.

The tools for obtaining research materials:

- A number of sections of mathematics and theoretical foundations of electrical engineering;
- Basic principles of electric machine theory;
- Basic principles of relay protection and diagnostics theory;
- Theoretical research using the ELCUT and Turbo BASIC software packages.

The scientific novelty of the work is determined by the following:

1. By comparing the advantages and disadvantages of known methods for diagnosing faults in three-phase windings, it has been revealed that those in which a current is induced in the short-circuited turns using an electromagnetic inductor are most suitable for searching a section with a "hidden" fault.
2. A new method for searching for a section with a "hidden" fault in three-phase windings has been developed, according to which currents induced in the short-circuited turns using an electromagnetic inductor are measured using an RMT.
3. Based on classical method of calculating magnetic circuits, a method for modeling the parameters of a U-shaped electromagnetic inductor intended for forming a diagnostic magnetic field and current in the short-circuited turns of a damaged section with a "hidden" fault has been developed.

4. Based on the Biot-Savart-Laplace method, a method for calculating the EMF at the output of an RMT from the current in short-circuited turns of a section with a "hidden" fault has been developed.

5. A method for determining the range of tooth pitch value for stator and wound rotor magnetic cores of machines with a power of 20-5000 kW with an arbitrary number of pole pairs has been proposed.

6. A universal design of a U-shaped electromagnetic inductor has been developed, which allows searching for a section with a "hidden" fault in machines with a power of 20-5000 kW with any tooth pitch value.

7. Designs for stationary and portable RMTs have been developed for searching for a section with a "hidden" fault in electric machines on which an RMT is not installed.

Practical value of the work lies in the following:

1. The analysis of known methods for searching a section with a "hidden" fault in three-phase windings, in which the measured quantity is the magnetic field of short-circuited turns, the current in which is induced using an electromagnetic inductor, allowed to determine ways to improve them.

2. The implementation of the developed method for searching for a section with a "hidden" fault in three-phase windings, according to which the magnetic field of the current induced in the short-circuited turns using an electromagnetic inductor is measured using an RMT, allows determining the location of the section with a "hidden" fault on a magnetic core with an arbitrary tooth pitch value regardless of the number of short-circuited turns.

3. The developed method for modeling the main parameter of a U-shaped electromagnetic inductor in form of the dependence of current in its winding on the magnetic flux in the air gap and the program Ind1 in the Turbo BASIC editor allow modeling it with an error of 5.6%.

4. The developed method for modeling the main parameter of a U-shaped electromagnetic inductor in form of the dependence of current in its winding on the magnetic flux in the air gap using the ELCUT software package ensures a modeling error not exceeding 2%.

5. The proposed method for calculating the current in short-circuited turns of a section with a "hidden" fault arising under the influence of a magnetic flux Φ_{δ} crossing the plane of this section created by an electromagnetic inductor and the program Tok-1 in Turbo BASIC for its implementation made it possible to calculate its magnitude depending on the winding connection diagram and the number of short-circuited turns.

6. The developed method for calculating the EMF at the output of a multi-turn RMT from current in the short-circuited turns of a section with a "hidden" fault and the program E1-kip in Turbo BASIC made it possible to calculate its magnitude depending on the location of this RMT relative to the end parts of three-phase winding.

7. The proposed method for determining the tooth pitch value of stator and wound rotor magnetic cores depending on the power of electric machine

shows that in the power range of 20-5000 kW, regardless of the number of pole pairs, its value can be in the range of 0.01-0.038 meters.

8. The developed universal design of a U-shaped electromagnetic inductor with legs of various shapes allows its use for searching a section with a "hidden" fault in three-phase windings of practically all electric machines produced by the industry.

9. The developed universal design of stationary and portable RMTs makes it possible to search for a section with a "hidden" fault in practically all electric machines produced by the industry that do not have an RMT installed.

Connection of the dissertation topic with general scientific (state) programs. The research on the topic of the dissertation was carried out within the framework of the priority directions for development of science "Energy and Mechanical Engineering" approved by the Higher Scientific and Technical Commission under the Government of the Republic of Kazakhstan.

Implementation of results.

Theoretical and practical results of the work can be successfully used in production and in educational process of bachelors, masters, and PhD students. Production tests of the method for diagnosing the condition of stator windings of electric machines were carried out at B. Nurzhanov JSC "Ekibastuz GRES-1". There is an acceptance certificate available (Appendix B).

Approbation of research results:

The main provisions of the dissertation were reported and discussed at: – The 12th International Scientific and Practical Conference of Young Scientists "Energy and Energy Equipment and Technologies" (Moscow, 2024).

Publications. The content of the dissertation is reflected in 8 printed works, including one in the journal "Russian Engineering," which is indexed in Scopus, three in journals recommended by the Higher Attestation Commission (HAC) of the Republic of Kazakhstan, one in a journal recommended by the HAC of the Russian Federation, one in proceedings of international conferences, and two invention patents were obtained (Appendix A).

Structure and volume of the dissertation. The dissertation consists of an introduction, three chapters, and a conclusion, presented on 85 pages of typed text. It contains a list of 55 references, 52 figures, 6 tables, and five appendices.

The introduction substantiates the relevance of the dissertation topic, defines the goals and objectives of the research, reflects the scientific novelty and practical significance of the obtained results, and indicates the ways of implementing the tasks formulated in the dissertation.

The first chapter discusses the design features of electric machines with three-phase windings. It is established that the three-phase synchronous generators, motors and compensators, as well as three-phase asynchronous generators and motors with squirrel-cage and wound rotors used in electric power engineering have an identical design of the stator and its winding.

It is established that the main cause of turn-to-turn faults in a three-phase winding is damage to its insulation, arising under the influence of electrical, thermal, and mechanical stresses, as well as environmental factors.

In this regard, in low-voltage electric machines with random-wound three-phase windings, turn-to-turn faults account for up to 93% of all short circuits in these windings. In turn, in high-voltage electric machines with sectionalized stator windings, turn-to-turn faults account for up to 33.3% of all short circuits in these windings.

At the same time, it is established that traditional protections against short circuits in three-phase stator and rotor windings, operation of which is based on measuring phase currents or their components, have low sensitivity to turn-to-turn faults. Only non-traditional protections, operation of which is based on measuring the leakage magnetic fluxes of the end windings of these windings, are capable of disconnecting a fault of a small number of turns in three-phase windings. Moreover, use of such highly sensitive protections is usually accompanied by formation of a section with a "hidden" fault.

The analysis of known methods for determining a section with a "hidden" fault carried out in this work shows that those methods in which the detection of a damaged section is accompanied by its heating cannot be considered acceptable. In this regard, those methods in which a magnetic field is used to search the damaged section, excited, for example, using a special magnetic inductor can be considered more promising.

Thus, the relevant task of developing a new highly sensitive, non-destructive, and universal method for finding a section with a "hidden" fault has been formulated. The most promising direction is determined to be an approach based on exciting current in the damaged turns using a U-shaped inductor and measuring the magnetic field of the currents in short-circuited turns using a ring-type measuring transducer.

The second chapter discusses theoretical aspects of developing methods for detecting damaged sections in three-phase windings based on use of a ring-type measuring transducer (RMT) and a U-shaped electromagnetic inductor.

Based on the analysis of existing methods, new methods for diagnosing stator and wound rotor windings are proposed. The essence of them lies in exciting current in short-circuited turns of the damaged section using a magnetic flux created by an inductor installed on the teeth of the magnetic core, and the subsequent non-contact measurement of the magnetic field of this current using an RMT. Schemes for implementing the methods have been developed and analyzed, both for machines equipped with an RMT and for machines without it, including diagnostics of a wound rotor.

Mathematical methods for designing and modeling the key elements of the diagnostic system have been developed and substantiated, which will allow:

Modeling the magnetic field in the air gap of the U-shaped inductor using the developed program Ind4 in Turbo BASIC and using the ELCUT software package with modeling errors of 5.6% and 2%, respectively;

Calculating the magnitude of the current induced in short-circuited turns of the damaged section using the developed program Tok-1 in Turbo BASIC;

Calculating the magnitude of the RMT EMF from the field of the damaged turns using the developed program E1-kip in Turbo BASIC depending on the distance between this RMT and the stator core.

Thus, the second chapter forms a comprehensive theoretical and methodological apparatus that ensures the design and calculation of all key components of a highly sensitive system for diagnosing "hidden" turn-to-turn faults in three-phase windings of electric machines of various designs.

The third chapter discusses the issues of calculation, design, and practical implementation for diagnosing "hidden" turn-to-turn faults in three-phase windings.

To implement this, it was revealed that the main parameter determining the possibility of using an electromagnetic inductor for diagnosing an electric machine is the tooth pitch of its magnetic core, the distance between its legs, and the contact area of these legs with the stator or rotor magnetic core.

To determine these parameters, a method for determining the tooth pitch value depending on the power of electric machine, voltage, and number of pole pairs has been proposed. An analysis of the calculation results of the tooth pitch values of stator and wound rotor magnetic cores showed that in the power range of electric machines of 20-5000 kW, its value can be in the range of 0.01-0.038 meters.

Based on this, mathematical expressions have been obtained that, under the accepted assumptions and a minimum tooth pitch value of 0.01 meters, allow calculating the distance between the legs of the electromagnetic inductor and the maximum tooth pitch value that can be diagnosed with such a distance between the legs of this inductor. It has been established that in accordance with these mathematical expressions, the distance between the legs of the electromagnetic inductor should be 0.016 meters, and the maximum tooth pitch value that can be diagnosed with such a distance between the legs of this inductor is 0.38 meters.

Taking these data into account, an electromagnetic inductor has been developed that allows changing the configuration of the magnetic core and the distance between them. This allows it to be used for diagnosing three-phase windings of practically all electric machines produced by the industry.

In addition, designs for stationary and portable ring-type measuring transducers have been developed, which make it possible to diagnose three-phase windings of practically all electric machines produced by the industry that were not equipped with such a transducer during their manufacture.