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The assessment of the processes of aging of the electric machines with structural unit defects using the genetic approach

Abstract. *The paper deals with the special features of the joint use of the genetic and stochastic approaches to the assessment of the processes of aging of various electric machines provided that inherited and acquired defects of the structural units are present. The authors expanded the notion of electric machine aging from the point of view of the application of the genetic approach. They offer the approach to the assessment of the degree and the special features of aging of the basic types of electric machines taking into account the interrelation between their main parameters and loads when the properties of the main unit materials alter in time. The obtained results make it possible to relate the aging symptoms to the alteration of the electric machine basic parameters determining the conditions of its use in production.*

Streszczenie. *Przedstawiono specjalne właściwości połączenia podejścia genetycznego i stochastycznego do oceny procesów starzenia maszyn elektrycznych, w których istnieją wady konstrukcyjne i nabyte w trakcie eksploatacji. Autorzy rozszerzyli pojęcie starzenia się maszyn elektrycznych z punktu widzenia podejścia genetycznego. Zaoferowano podejście do oceny stopnia starzenia maszyn elektrycznych, biorące pod uwagę związki miedzy ich głównymi parametrami i obciążeniami przy zmiennych w czasie właściwościach materiałowych. Otrzymane wyniki umożliwiają odniesienie symptomów starzenia do zmienności podstawowych parametrów maszyn elektrycznych, co pozwala określić warunki produkcji.* ***(Ocena procesów starzenia maszyn elektrycznych z defektami konstrukcyjnymi przy użyciu podejścia genetycznego)***

Key words: electric machine, aging, reliability, energy efficiency, genetic approach, defect .
Słowa kluczowe: maszyna elektryczna, starzenie, niezawodność, skuteczność energetyczna, podejście genetyczne, uszkodzenie

Introduction

Flexibility is one of the main features of contemporary production. First of all, it means a capability to quickly re-adjust to the issue of a new product. In this case, it is necessary to meet a number of basic requirements to the technological equipment foremost determining its efficiency and reliability indices.

As a rule, the most part of this equipment is partially or completely automated. This, along with the use of control facilities, implies the presence of controlled devices, first of all, various electric machines (EM). They chiefly determine energy consumption and partially – the reliability of the whole equipment. Having comparatively long mean-time-between failures, most often, such EMs are not subject to change during the modernization of the equipment [1].

However, everybody knows that their parameters and characteristics deteriorate during long-term operation and repairs due to their aging [2]. Nowadays universal approaches to the analysis of aging processes in technical systems, including EMs, are practically absent.

The idea of EM aging did not widely spread in the technical and research literature because of the impossibility of its exact description and mathematical representation. However in this case we can consider it as partial loss of the properties and characteristics by the basic structural materials, elements and whole EMs under the influence of external factors occurring in the process of operation and repairs with the course of time.

As the final stage of this process is of little practical interest, one can consider the moment of time when EM does not provide the required technological conditions or when the expenditure on their operation essentially influences the cost of the issued product to be the limit of aging.

Thus, the substantiation of the principles of taking into account the processes of EM aging is an important scientific-research problem. In the future, it will enable forecasting their indices of energy efficiency and reliability. It will also allow the determination of the conditions and intervals of planned alteration.

Theory

EM energy efficiency is directly determined by the relation of the summary constants $\Sigma\Delta P_{const}$ and variables $\Sigma\Delta P_{var}$ of the losses components, determining the maximum efficiency η [3]. During EM aging one can observe the redistribution of their separate components. Primarily, it is caused by the alteration of the properties of the basic structural materials and elements, first of all, electric steel.

The said alterations explain the general deterioration of the properties of EM magnetic steel causing the disproportionate growth of the stator steel $\Delta P_{\mu 1}$ and copper ΔP_{cu1} losses [4]. Besides, it is necessary to additionally take into account the growth of mechanical ΔP_{mec} losses in the process of the bearing units aging.

The above considered causes result in the shift of the range of high η to the lower loads domain, which should be taken into account during such EMs operation.

The conventional approaches to the assessment of EM reliability chiefly base on the postulates of the probability theory. Their use aims at the mathematical expression of the reliability via the general indices of probability $P(t)$ of faultless operation, probability $Q(t)$ of failure, failure intensity $\lambda(t)$, error-free running time T etc. Most often it is reasonable only for EM operating during the main period of the life cycle curve [1].

When aging processes influence starts manifesting, the accuracy of the used comparatively simple relations considerably deteriorates. Their complication is an alternative but it does not always provide a positive result.

In this case one passes to simpler models of the reliability of EM structural units, trying to describe their real failure intensity by one of the general laws of distribution (normal, Weibull, etc.). This approach can be applied at the initial stages of aging and later requires the use of nonlinear coefficients with the ambiguous character of alteration. It considerably deteriorates its credibility and efficiency.

The creation of individual object-oriented models using the theory of experiment planning is the most universal approach to the assessment of the reliability of both separate structural units and EM on the whole. In this case the character and the degree of the development of various types of defects can be taken into account. The basic drawback of this approach consists in the limitation of the number of the considered factors, and, often, the impossibility of the transfer of the obtained results even to the analogous units of EMs of different power and version.

Thus, at the practical absence of the system approach to the solution of the posed problem, the conventional calculation methods at best provide a mere assessment of the reliability indices of EMs with certain defects with the use of the theory of experiment planning. Their use does not enable the trustworthy assessment of the indices of reliability of EM in the process of aging.

It poses the problem of working out the new approaches using the principles of systematization, which makes it possible to regard the problem of aging from the point of view of the predetermination of the development of the main directions of the deterioration of the properties of the structure during repairs and long-term operation.

From this point of view the analysis of the principles and theories applied to the assessment of the state of biological objects and systems with the substantiation of the possibilities of their transfer to technical systems, in particular, EMs, is promising.

The aging theories used in gerontology, essentially, are divided into three groups: genetic theories based on gene-controlled programmed parameters, neuro-endocrine theories and the theories of accumulation of damages. This division is rather conditional as all the presented mechanisms are important and inter-connected.

Besides, these theories are usually considered as a part of one of two big groups: stochastic (probability) theories and the theories of programmed aging.

As the results of the previous research revealed, EM aging is to be regarded as a combination of aging of the basic structural units (SU) and elements that can be considered restorable (wound coils, bearings) and unrestorable (cast rotor, cores, etc.). It allows taking into account SU wear as an accumulation of damages (defects) during the current operation basing the EM operability forecasting on genetic methods as the components of the theory of programmed aging.

According to the genetic principles of structural organization and development of EM, shown in [5], the variety of potentially possible defects is divided into the inherited and the acquired ones. Thus, based on the propositions of the theory of EM genetic evolution, it is possible to concretize the notion and the physical meaning of not only acquired but also of the inherited “diseases” (defects) of EM.

The latter refers to the genetically determined ones (being of informational nature); the information about them is in the structure of genetic codes or genetic formulae for each of the analyzed EMs. In this case, unlike the acquired defects, the inherited ones refer to the class of system defects and do not disappear provided the genetic structure is unchanged and the degree of their manifestation will be determined by the totality of the operation factors (including the operation mode and the stage of the life cycle). So, while the acquired diseases can be “cured” by traditional methods (restriction of power, extreme modes, change of insulation, restoration of the worn parts and units in the process of the repair, etc.), the inherited diseases can be eliminated only at the stages of design by means of transfer to another genetic structure.

It should be noted that in the process of EM functioning the inherited and acquired diseases manifest jointly. At the early stages of the life cycle, the inherited “diseases” prevail. The state of the objects at the late stages of the life cycle is determined by the integral (system) influence of the inherited and acquired defects.

The following should be remembered during the use of the presented approach:

The inherited diseases may manifest sharply at the excess of the maximal allowed loads or modes of EM functioning; at the violation of the correspondence of the genetic structure to the parameters of the environment; at incorrect choice of the genetic (generative) chromosome for the synthesis of EM structure.

2. In the process of the transfer of the genetic and acquired information, the transfer of inherited diseases in the form of erroneous engineering solutions containing latent genetic information that does not correspond to the design, to the parameters of the environment or the method of its technical realization, takes place at the same time. The integral totality of the said discrepancies predetermines the level of reliability of such EMs.

3. Genetic defects are of a system nature. It is possible to diagnose the inherited diseases of an arbitrary EM by the genetic information (genetic code).

An important advantage of the genetic approach in the considered case consists in the fact that it is of a most general character and can be equally applied to the study of technical systems of any complexity level. Thus, the idea of the inherited reliability can serve as the methodological basis for the research of new ways of the improvement of EM reliability as it does not impose its own solutions but just indicates the most efficient ways of its provision.

The practical use of the results

Let us consider the special features of aging during long-term operation and repairs. We are mostly interested in such a genetic factor as the structural units wear built into the very structure as in practice in the designed machine it is impossible to change the distribution of the mechanic and electromagnetic efforts as well as the specific features of heat under the conditions of certain functional and geometric limitations.

Primarily, it is explained by the fact that EM geometric parameters, overall dimensions, mass and basic cost/performance ratios are determined by the main dimensions built at the initial stages of designing. In fact, they relate EM volume to its ultimate power. Accordingly, for alternating current EM these dimensions include internal diameter D_1 and length l_1 of the stator core; for direct current EM – external diameter D_a and length l_a of the armature core.

According to [6, 7], the mentioned parameters are directly related to rotation frequency, electromagnetic loads (linear A load and magnetic induction B_δ in the air gap), as well as to EM other parameters, in particular, to current density J in the windings.

Most often this relation is expressed via Arnold’s machine constant C_a that, in spite of seeming simplicity, reflects the physical sense of the electromechanical conversion of energy. Arnold’s machine constant is universal and, with slight variations, can be used for EMs of any type. It makes it possible to directly analytically assess particular factors influence on the performance characteristics and basic dimensions, to assess the degree of the use of conductor and magnetic materials at different values of electromagnetic loads, which can be easily confirmed for EM main types.

Its analysis enables obtaining a number of important conclusions as to the initial efficiency of EM design. So, according to [6], at the given power and rotation frequency the volume of the core of respectively stator or armature of the machine mainly depends on electromagnetic loads. The higher A and B_{δ}, the smaller the main dimensions are and the higher the use of the active materials in the machine is. In this case the increase of the electromagnetic loads accompanied by the growth of the temperature of the machine active parts is limited only by the class of the insulation heat resistance. During the choice of electromagnetic loads it should be taken into account that relation A/B_{δ} is to be within the certain limits as its value influences the cost/performance ratios of alternating current machines – η, power coefficient $cos\,\varphi$, starting characteristics and mass and for DCM – η, regulating properties, commutation indices and the mass of the machine.

At the same time, the same value of the reduced volume $D_1^2 l_1$ for alternating current machines or $D_a^2 l_a$ for DCM can be obtained at different values D and l, consequently, at different relations $k_{ld} = l/D$. The latter relation determines the machine mass, the dynamic moment of inertia of the rotating part, the energy and other cost/performance ratios.

This influence can be ambiguous e.g. at the increase of k_{ld}, i.e. at the decrease of D and the increase of l the dynamic moment of inertia falls, the process of the motor starting and braking accelerates and, accordingly, the losses occurring at this process, decrease. Additionally, the mass of the end windings and losses in them decrease. Consequently, for the machines with high values of k_{ld} the mass per a unit of power or rotation moment decreases at the general growth of η.

At the same time for ventilated machines with high values of k_{ld} the cooling conditions deteriorate and there may appear a necessity for the increase of the shaft diameter to provide its sufficient rigidity and strength. At high values of k_{ld} the production labor-intensiveness and, accordingly, the cost of the machine may grow.

At the same time, according to EM similarity criteria relating their basic parameters to the geometric dimensions, the parameters of the machines included into a row according to the power increase change depending on the power in accordance with certain regularities. That is why the machines within one series can be considered as a number of geometrically similar machines, i.e. machines whose linear dimensions (LD) (the diameter, the core length, the slot height and width, etc.) change proportionally. Under this condition magnetic induction B_{δ} and current density J in the winding are assumed constant and independent of power P of the machine.

Thus, assessing the degree and special features of genetic aging of EM basic types one can efficiently use the presented interrelations between EM main parameters and loads, assuming the properties of the main units materials to be time-varying. It will allow the simultaneous taking into account the alterations of the electric, magnetic and heat parameters in the researched EM structures via the ultimate loads determined by Arnold's constant provided that EM structural volume is constant.

In this case the acquired defects should include all the structural units state alterations determined by the operation conditions (the installation defects, the load on the part of the mechanism, the conditions of the environment, etc.), the level of the perfection of the technologies of the restoration of the structural units and EM on the whole and the qualification of the service personnel.

In practice, while assessing EM state, it is necessary to take into account the winding aging due to the accumulation of various damages resulting in its break-down and corresponding failure of EM [1]. Besides, the assessment of electric steel (ES) aging is to be performed separately at long-term operation and during repairs. In the first case one can use ES aging coefficient characterizing the percentage increase of specific losses $p_{1,0/50}$ (taken at the induction of 1 T at the frequency of 50 Hz) after 600 hour heating the EM core to 100^0C [8].

In the second case one can use the results of the authors' earlier research, choosing the data out of the ranges of the alteration of the electric and magnetic parameters of the used grade of the electric steel [4].

However, in most cases, to determine the real state of EM basic units it is necessary to assess the degree of the development of their defects.

In this case the most informative methods for the determination of the properties of the electric steel laminated cores include the video control in the visible and infrared range and local induction diagnostics, for the winding – frequency-resonance methods, for the rotor and bearing units – vibration diagnostics, for the assessment of the general overheat of the structure and units accessible for the examination – the heat image control (Figs. 1 – 4).

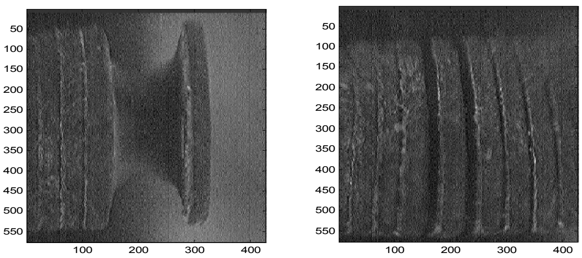

Fig. 1. The stator core teeth zone damage revealed as a result of the video control in the visible and infrared range

Fig. 2. The stator winding phase-to-phase short circuit detected by the frequency-resonance method

Fig. 3. The presence of the bearing developing damage detected due to vibro-diagnostics

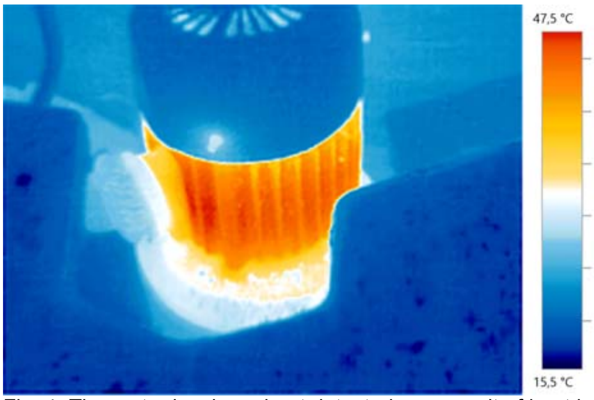

Fig. 4. The motor local overheat detected as a result of heat image control

As a result, we substantiated that practically every EM "suffers" from electrical or magnetic asymmetry explained by both irreversible deterioration of magnetic and electrical properties of the magnetic system in the course of long-term operation and by a number of reversible deteriorations, in particular, the rotor slump at the development of bearings damages (in most cases can be compensated for by their substitution) and by the development of turn-to-turn short circuits in EM windings (can be eliminated by EM rewinding).

The first and foremost symptoms of EM aging comprise the growth of the temperature of the separate units and the machine on the whole including the dynamics of its variation as well as the increase of the general level and the growth of separate spectral components of vibration.

The performed systematization made it possible to additionally single out about ten symptoms enabling the reliable determination of the localization and the degree of the development of the main types of SU defects.

From the point of view of practical application of the obtained results, in the future, it is necessary to relate the symptoms of aging to the alteration of EM basic parameters determining the conditions of its use in production.

First of all, they include the electromagnetic parameters used in the adjustment of EM control systems, energy parameters – for the assessment of the indices of EM energy efficiency as well as the very indices of reliability [9].

Conclusions

1. We have substantiated the prospects of the joint use of the genetic and stochastic approaches to the assessment of the processes of aging of EMs of various types provided the presence of the inherited and acquired defects structural units.

2. We have expanded the notion of electric machine aging and confirmed the efficiency of the application of the genetic approach to the problems of the assessment of their reliability.

3. We have proposed the approach to the assessment of the degree and special features of genetic aging of the basic types of electric machines, taking into account the interrelations between the main parameters and loads assuming the properties of the main unit material to be time-varying

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