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Models for electric machine reliability prediction at variation of the condition of basic structural units

Abstract. *Prospects of working out intelligent models of reliability of electric machines (EM) with long mean time between failures are substantiated and a method for their realization is presented. Limit conditions of basic structural units of low- and medium-power induction motors (IM) and their primary reliability models are determined. The obtained results enable a more accurate prediction of reliability indices and during subsequent improvement and manufacturing application make it possible to pass to maintaining and repair of EM in accordance with its factual condition.*

Streszczenie. *Perspektywy opracowania inteligentnych modeli sprawności maszyn elektrycznych z długim średnim czasem pomiędzy uszkodzeniami są uzasadnione i metoda ich realizacji została zaprezentowana. Warunki graniczne dla podstawowych parametrów konstrukcyjnych silników indukcyjnych o małej i średniej mocy i ich modeli sprawnościowych zostały wyznaczone. Otrzymane wyniki pozwalają na dokładniejszą predykcję wskaźników sprawnościowych a poprzez kolejne usprawnienia dają możliwość utrzymania i naprawy maszyny elektrycznej zgodnie z jej stanem faktycznym. (**Modele predykcji sprawności maszyn elektrycznych przy zmiennych podstawowych parametrów konstrukcyjnych**)*

Key words: reliability, model, neural network, fuzzy logic, expert system, experiment planning.
Słowa kluczowe: sprawność, model, sieć neuronowa, logika rozproszona, system ekspercki, planowanie eksperymentu

Introduction

Existing methods of prediction of electric machines (EM) reliability indices differ depending on the solved problems and special features of the used software [1]. Models on their basis are mainly the result of generalization of the available statistic data on failures of EMs of different type, power or version. The use of such models is based on analytical prediction that implies existence of interrelation between EM current and predicted state. It can be described through variation of numerous diagnostic signals, which makes it possible to extrapolate the obtained dependences on the following time moments. Credibility of such models is determined by the type of the used approximating functions and completeness of the adopted set of diagnostic parameters.

Models created according to the above described principle do not provide trustworthy prediction of the condition and reliability indices of EMs with long mean time between failures because the properties of basic structural units and elements change in the course of long operation.

Models built with the use of expert evaluation method are the alternative. However, in this case their use is restrained by absence of reliable information as to particular features of the change of EM condition in the course of long operation. It can be obtained as a result of generalization of statistic data characterizing variation of the state of homogeneous units in the time and load function. However, generalization of different EM types and versions is a complicated and ambiguous problem. A complex use of modern intellectual approaches to reliability models is one of the ways of its solution.

Thus, the purpose of the paper consisted in substantiation of development and application of intelligent models of reliability of EMs with long mean time between failures on the basis of limited sampling of statistic and current diagnostics data.

Theory

When reliability intelligent models were being developed, it was taken as the basis that they are to be applied at the last stage of normal operation and during the whole interval of aging. It is connected with the growth of intensity of failures of basic structural units and the whole EM in this period. As a rule, the run-in interval is not considered separately for EMs due to their inessential design complexity.

The research results allowed separation of reliability models creation problems into sublevels, each of which is realized by its methods, which is shown in table 1.

In this case EM was presented in the form of a structure including nonrepairable (laminated cores, body, rotor with a cast winding) and repairable (strand winding, bearings, brushes) units.

Table 1 – Principles of creation of reliability intelligent models

Solved problem (sublevel)	Mathematical support	Obtained result
Determination of EM condition	Expert system	Assessment of the limits of reliability indices variation and generation of conditions for the use of different relations for their calculation
Account of structural interrelations	Fuzzy logic	Substantiation of the limits of diagnostic parameters variation taking into account their mutual influence
Combination of models	Neural network	Determination of generalized indices of EM reliability
Models of structural units and elements	The theory of experiment planning, information statistical processing	Obtaining calculation relations for determination of indices of reliability of EM basic structural units and elements

When such approach is used, requirements to creation of primary models of structural units and elements reliability considerably decrease.

Taking into account an insignificant number of influencing factors, it is reduced to direct use of experiment planning theory for units with weak similarity criteria (collector-brush unit, stator winding) or statistic processing with the following generalization according to similarity criteria (bearing unit, shafts, rotor with cast winding, etc.) [1].

However, in this case, taking into account the properties of basic structural units and elements on the whole is to reflect their approximation to the limit condition according to the parameters that are critical for EM reliability.

For laminated steel these are growth of specific loss and magnetic properties deterioration manifested in decrease of saturation induction and permeability determining induction resistances of the windings and magnetizing circuit.

When the condition of the body is assessed, it is important to take into account its basic features determining rigidity of EM structure on the whole (e.g. matching sites integrity directly related to development of additional vibrations) and preservation of some features of geometry (to a greater extent rigidity of covers, core fit in the body and bearing cartridge wear influencing the air gap uniformity). Besides, for EM with ribbing, it is necessary to additionally take into account decrease of effective cooling surface when the body is damaged.

In case of cast rotor the integrity of bars and the cage ring is assessed and the critical number and the degree of their breakages are the limit values from the point of view of EM operability

The mentioned parameters and characteristics are assessed in both time function taking into account their current condition and in the function of the number of taken repairs (restorations) of EM as each of these parameters is characterized by abrupt variation of values under the conditions of almost complete ambiguity of influencing factors.

For repairable units practically the same principles of creation of reliability models remain, except for taking into account repairs/restorations as in most cases the units are substituted by new ones during these events.

So, the windings condition is determined by their heat temperature θ_w corrected by value ν of vibration velocity, short-circuit turns presence determined via windings resistance and reactance. For the bearings it is, accordingly, their external ring temperature θ_b and vibration velocity ν related to balls number k and rotor rotation frequency n and for the collector-brush unit it is collector temperature θ_c vibration velocity ν and current density J_{br} under the brush.

There are three ways of generalization of the obtained results for different EM series and variants.

The first one provides for availability of certain trends characterizing deterioration of the structural unit properties in the course of long-time operation and repairs. It is most efficient in case of the use of limited amount of structural materials with certain properties. Trends of deterioration of the properties of laminated cores made of separate sheets of electric steel may be regarded as an example. In this case magnetic circuits of all commercial EMs of main overall dimensions are based on up to six steel grades with properties whose variation can be easily systemized.

The second way implies availability of similarity of design of homogeneous units used in EMs of various overall dimensions.

An example of such units can be seen in bearings of the same version, subjected to homogeneous load in EM, with limit characteristics changing proportionally with growth of EM power. In this case parameters characterizing wear can be analyzed using the chosen sample and transferred to other overall dimensions with minimum specifications according to the postulates of the similarity theory [2].

The third way provides break from all generalizations and similarities when there is a possibility of direct prediction of reliability indices according to diagnostics parameters measured in the process of operation.

An example of a model realizing this way can be presented by a model of strand winding reliability in which availability of short-circuited turns and temperature is directly controlled when there is information about EM vibration.

In practice the mentioned methods can be combined aiming at simplification of the model form, improvement of the degree of their adequacy and elimination of ambiguity problems when there is no information about the time of previous operation of EM.

Another peculiar feature of the developed models consists in the necessity for taking into account the mutual influence of structural units in the process of defects development. For example, deterioration of the properties of the bearing unit results in appearance of eccentricity of the air gap in EM, which causes unevenness of winding heat, etc.

For solution of such problems the efficiency of the use of fuzzy logic was proved, which makes it possible, as a result, to take into account the interrelations influence by correlation of admissible ranges of diagnostic parameters variations [3].

It is possible to take into account these interrelations to the full by instruction of neural networks used in combination of separate models of structural units and elements [4]. Besides, this method allows obtaining calculation relations for reliability indices taking into consideration the time variation of EM failures intensity.

A final conclusion as to EM reliability is made by expert system that determines one of five conditions depending on the type and stage of the defects of EM structural units and elements: 1 – perfect – defects are completely absent; 2 – good – incipient defects of replaceable structural units are determined, they do not influence EM operability; 3 – satisfactory – non-limit defects of replaceable or incipient defects of irreplaceable structural units are present (maintenance is required); 4 – unsatisfactory – limit defects of replaceable structural units are revealed (corrective maintenance is required); 5 – limit – considerable or limit defects of irreplaceable structural units (change of EM for a new one is required).

Experimental research

During the research the proposed approach to creation of reliability intelligent models has been approbated on IM of low and medium power.

Basic structural units in the analyzed IM include a stator winding (SW) and a bearing unit (BU) causing most cases of their failures.

As demonstrated above, SW reliability model can be obtained by real-time direct control of parameters determining presence of short-circuited turns. In this case SW condition is determined by its temperature θ_s taking into account the influence of vibration factor by variation of vibration velocity average value ν_m. The winding limit condition is characterized by excess of product $a\theta_s$, where a – number of short-circuited turns for each of assigned values ν_m.

According to [2, 5], BU condition can be expressed via the function of aging of light radial bearings applied in low- and medium-power IM.

In this case a bearing of any IM in the considered range is taken as the analyzed one. Later the obtained model is recalculated for bearings of less or more powerful IMs with the use of similarity theory postulates as to condition of keeping constant relation $R_a/2Br$ of supporting load R_a and area $2Br$ of the external ring cross section, where B – bearing width, $2r$ – height of the external ring. Limit condition of the bearing can be determined from expression $\nu_m c/(k2Br)$ related to temperature θ_b. Here c – the number of damaged balls; k – total number of balls in the bearing.

The stator laminated core is another structural unit affecting SW and BU operating mode and condition. Deterioration of the core electric properties calls forth increase of steel loss P_μ, which causes additional heat of the stator winding due to worse heat removal through the stator magnetic system. Variation of its magnetic properties results in redistribution of electromagnetic vibration exciting force F_{em}, which causes growth of one-way magnetic attractions accompanied by increase of vibration velocity ν_m.

Thus, the core limit condition can be assessed by admissible levels of magnetic and electric properties on the basis of trends of their change in the process of long-time operation and repair for the used steel grade.

As at present there are no recommendations and systemized research as to the problem of the choice of parameters characterizing the limit condition of the stator cores, this problem remains unsolved.

Taking into account the above said, IM SW reliability model is a two-factor model of the form

(1) $$T = b_0 + b_1 a\theta_s + b_2\nu_m + b_3 a\theta_s\nu_m ,$$

where T – mean time between failures.

Using instead of a, θ_s and ν_m their dimensionless values in relation to number w of stator winding turns, the maximum allowable temperature $\theta_{s\,max}$ for the used insulation class and rated average value ν_{mn} of vibration velocity, it is possible to unify the obtained models for windings of the same type. For example, for a random winding used in low- and medium-power IMs it can be performed by determination of unknown coefficients for IM stator winding with average value of power for the considered range.

When BU reliability models were worked out, information obtained as a result of experimental research of samples whose general view is shown in Fig. 1 was used.

This method enables separation of IM body cover cartridge damage influence on informative parameters variation and concentration on bearings themselves.

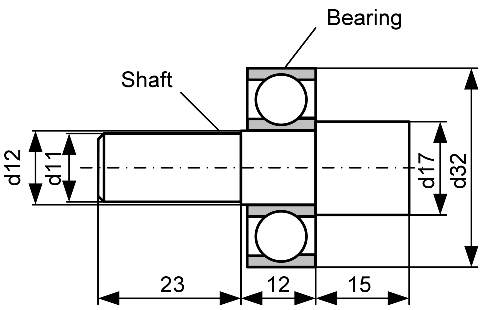

Fig. 1. Form and parameters of the researched BU sample

Geometric dimensions indicated in Fig. 1 correspond to the parameters of the shaft and the type of bearing of IM of the minimum power of the analyzed range.

The researched samples were fixed on a lathe as it is shown in Fig. 2. Due to spatial displacement of support various technological conditions of EM operation were assigned; they corresponded to accelerated test at changing load on the shaft. Besides, temperature of the external ring and spectrum of vibration velocity ν_m were measured. Additionally, variation of lubrication level at different conditions of external and internal heat was simulated during the research.

The degree of wear of bearings and their structural elements was assessed by fault detection and subsequent metallographic analysis. It enabled relating the measured parameters to the degree of development of main defects.

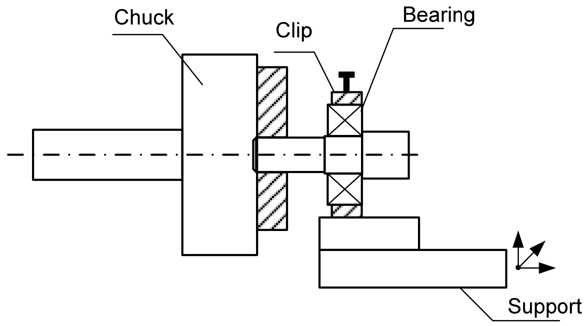

Fig. 2. Explanation of the specific features of BU sample test

The results of the test confirmed functional sufficiency of two-factor reliability model of the form

(2) $$T = b_0 + b_1\frac{\theta_b}{\theta_{b\max}} + b_2\frac{\nu_m}{\nu_{mn}}\frac{c}{k2Br} + b_3\frac{\theta_b}{\theta_{b\max}}\frac{\nu_m}{\nu_{mn}}\frac{c}{k2Br},$$

where $\theta_{b\,max}$ – marginal temperature of bearing heat; ν_{mn} – value of vibration velocity for BU healthy condition.

Besides, the problem of variation of magnetic and electric properties of electric steel laminated cores was considered during experimental research.

Grade 2013 steel used for creation of low- and medium-power IM magnetic circuits was taken as an example.

Research was carried out using ring-shaped samples (state standard GOST12199.1-98), each of which consisted of 10 pressed sheets of grade 2013 cold-rolled anisotropic electric steel with external diameter of 120 mm and internal diameter of 100 mm. Sheet-to-sheet insulation was removed in some samples, which was aimed at additional assessment of eddy currents influence.

To research natural ageing the samples were heated during 120 hours at120°C by magnetizing winding at its alternating magnetization reversal by current of commercial frequency of 50 Hz.

For research of temperature annealing influence, when IM winding was removed in the process of an overhaul, the samples were subjected to annealing at 400°C during four hours.

The results of the research are selectively presented in Figs. 3–4. Here curves 1 and 3 correspond to the initial condition and the condition after the first annealing for a core made of insulated sheets, curves 2 and 4 correspond to the initial condition and the condition after the first annealing for a core made of sheets with removed insulation.

It is seen in Figs. 3-4 and additionally confirmed by the results of metallographic research that laminated steel ageing is manifested in decrease of magnetic induction with decrease of angle α of inclination of magnetizing curve saturated section (Fig. 3), and also with sharper growth of specific losses, which is characterized by increase of angle β (Fig. 4). In this case presence of induction B'_m corresponding to kinks of both magnetizing curve and dependence for specific losses is typical for Figs. 3-4.

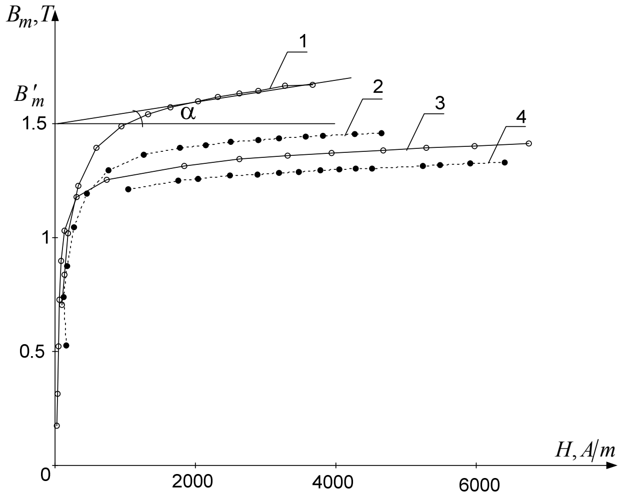

Fig. 3. Magnetic induction $B_m = f(H)$ dependences on intensity for grade 2013 electric steel in the process of repairs and long-term operation

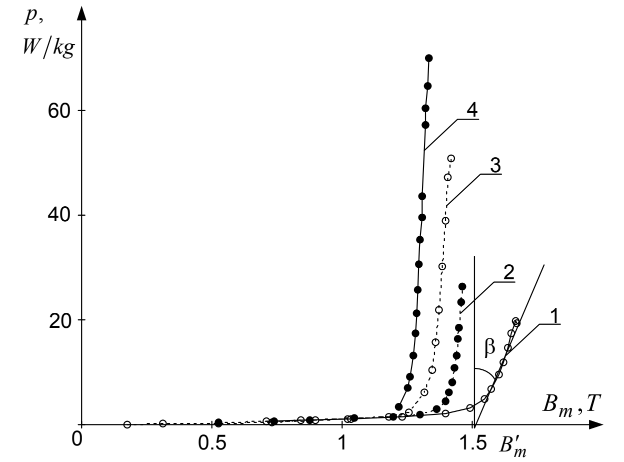

Fig. 4. Specific losses $p = f(B_m)$ dependences on magnetic induction for grade 2013 electric steel in the process of repairs and long-term operation

As working value B_{mw} of magnetic induction is assumed to be constant in IM, the said variations result in essential increase of working value H of intensity, which causes growth of magnetizing component I_μ of stator current and growth P_{st} of steel losses, which results in additional increase of stator winding temperature θ_s

Thus, the limit conditions of the core can be expressed via relative values B'_m, α, β by substantiation of irrationality of the use of the core due to rapid increase of I_μ and P_{st}.

It enables obtaining a three-factor model of laminated cores reliability in the form

$$T = b_0 + b_1 \frac{B'_m}{B'_{mn}} + b_2 \frac{\alpha}{\alpha_n} + b_3 \frac{\beta}{\beta_n} + b_4 \frac{B'_m}{B'_{mn}} \frac{\alpha}{\alpha_n} + b_5 \frac{B'_m}{B'_{mn}} \frac{\beta}{\beta_n} + b_6 \frac{\alpha}{\alpha_n} \frac{\beta}{\beta_n} + b_7 \frac{B'_m}{B'_{mn}} \frac{\alpha}{\alpha_n} \frac{\beta}{\beta_n}, \quad (2)$$

where B'_m, α_n, β_n – parameter values corresponding to the condition of a healthy core.

Conclusions

1. A method of creation of intelligent models of reliability of EMs with long mean time between failures has been proposed.
2. Limit conditions have been determined and primary models of low- and medium-power IM reliability have been experimentally substantiated for the stator random winding, bearing units based on radial single-row bearings and the stator core.
3. Further development of the proposed method will make it possible to predict reliability indices more accurately and to pass to IM maintenance and repair according to factual condition.

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