Models of Reliability Prediction of Electric Machine Taking into Account the State of Major Structural Units

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DOI: 10.15598/aeee.v13i5.1397

Abstract. *It is shown that conventional mathematical models for calculation of the reliability of electric machine structural units, based on the theory of planning an experiment, do not take into account the peculiarities of their properties variation during the process of manufacture and long-term operation. Taking into consideration the multiple factors of the assigned problem, the prospect of the use of fuzzy logic postulates in the creation of models for calculation of reliability is substantiated. An approach to such models building is formed.*

Keywords

Electric machine, fuzzy logic, reliability, vibration.

1. Introduction

In electric machines (EM) operation, the main task is to secure required reliability along with highest possible energy efficiency. The considered problem can be solved completely only under the condition of taking into account real physical processes taking place in EM in static and dynamic operation modes, which is not always possible. This is explained by inadequacy of theoretical ideas about EM parameters change, by change of losses in certain units, and also by absence of reliable methods for their determination under uncertainty of the conditions of structural components in the process of operation [1], [2], [3].

2. Motivation

Existing models of reliability of EM structural units are mostly based on the theory of planning an experiment. They connect reliability evaluation parameters with operation modes of EM. For example, reliability of a direct current electric motor of a power wheel is determined by relation for a failure rate [4]

$$\lambda_m = V_e k_w \cdot 10^{-6} \left\{ 0.0011 \frac{t_{op}}{t_a} \exp\left[\, 0.113\varepsilon - \right.\right. \\ \left.\left. - 0.019 i_b + 0.08 \varepsilon i_b \,\right] + 0.062 \cdot 10^{3.77 k_\tau} + 0.951 \right\}, \tag{1}$$

where V_e – average operating speed of the automobile; k_w – coefficient taking into consideration operating conditions at groups of enterprises of different industries; $\frac{t_{op}}{t_a}$ – relation between time t_{op} of operation of an alive electric motor and total time t_a of transport cycle; ε – voltage between adjacent commutator bars; i_b – current density under the brush; k_τ – relative coefficient of overheating occurred during the operating cycle.

Such models are created for a certain EM types and cannot be generalized for other series and versions. Besides, the mechanism of taking into consideration the change of the properties of structural assemblies during their aging is absent in them. The most informative of the existing reliability models take into account the time of EM operation by introduction of additional coefficients [4]

$$F(t) = \sum_{i=1}^{n} c_i F_i(t) = \\ = \sum_{i=1}^{n} c_i \left\{ 1 - \exp\left[- \left(\frac{t}{a_i} \right)^{b_i} \right] \right\}, \tag{2}$$

where n – intervals number; c_i – weight coefficient; b_i, a_i – parameters of Weibull distribution at the i-th interval.

Obviously, the coefficient c_i is to be variable in this case. However, recommendations as to its determination are practically absent, which makes impossible practical use of Eq. (2).

Thus, there occurs a necessity of development of new models explicitly taking into account the indices of reliability depending on the state of the basic structural units.

The purpose of the paper consisted in the research of variations of the properties of EMs structural units and elements with the following substantiation of their influence on the parameters determining the indices of EMs reliability.

As interrelation of factors, which describe conditions of EM structural components and their interrelation with reliability factors, is not unambiguous, the promising way to solve this task is the use of fuzzy logic.

3. Theoretical Postulates

During the research, the main types of structural unit faults influencing the reliability indices were singled out. They include various types of damages of bearing unit, stator core, windings, rotor (armature) and switching points.

Factors showing during operation and characterizing the state of these units change due to presence and development of certain defects. So, for collector and bearing units these are, respectively, their temperatures θ_c and θ_b, vibration velocity ν and angular frequency ω of rotor rotation, for the winding – temperature θ_W and vibration velocity ν. Vibration velocity ν and current density J_{br} under the brush are typical of contact rings, etc. As every unit or element is influenced by its own factors, and the degree of their variation is not determined reliably, their mutual influence and connection with defects of structural units can be taken into account with the use of fuzzy logic postulates [5].

In this case, the most efficient approach consists in direct realization of interconnection of the state of units and influencing factors with reliability indices. It enables obtaining a generalized model of EM reliability in a rather simple form. However, this approach cannot always be applied because of a high degree of uncertainty of interconnections between parameters of separate units when there is a relatively large number of influencing factors. So, it is more efficient to use unit models relating influencing factors to structural defects; later these models are transformed into EMs reliability models with the use of the basic postulates of reliability theory [6].

Despite seeming variety of different defects of structural units and elements, their influence on EM reliability is mainly reduced to deterioration of thermal and vibration processes.

As defects and damages of electric machines structural units are distributed in a random manner and are of different nature, it was proposed to increase the number of the analyzed parameters of thermal and vibration processes.

Relations used in calculation models and connecting the parameters of these processes with the state of structural units are to be extremely simplified and concretized. It enables singling out significant parameters influencing vibration and temperature components and relates all the rest to variable values.

As faults and damages of EM structural components are randomly distributed and have different origin, in order to extend the number of analyzed factors of vibration it was confirmed the necessity of estimation the factors of mechanical and electromagnetic nature separately.

As a result, relations for vibration velocity components, depending on parameters influencing it obtained the form:

$$\nu_r = f(\omega; \delta_e; k_{k1}), \tag{3}$$

$$\nu_z = f(\omega; \Delta_t; \Delta_a; k_{k2}), \tag{4}$$

where ν_r and ν_z – general level of vibration velocity caused by rotor and bearings imbalance in radial and axial directions; δ_e – radial clearance in bearings; k_{k1}, k_{k2} – structural coefficients; Δ_t and Δ_a – axial and face runout, respectively.

Electromagnetic vibration is described by a dependence of the form

$$\nu_m = f(f_0; B_\mu; B_\nu; k_\chi; k_{d1}; k_{k3}), \tag{5}$$

where f_0 – double frequency of the network; B_μ – amplitude of the teeth harmonic of stator field; B_ν – amplitude of the non-teeth harmonic of the stator field; k_χ – coefficient of the rotor slots slant; k_{d1} – deformation coefficient, k_{k3} – structural coefficient.

As the number of significant parameters in Eq. (3), Eq. (4), Eq. (5) does not exceed three, the final computations are based upon these parameters for every separate case using experimental design theory.

Values of vibration components obtained by Eq. (3), Eq. (4), Eq. (5) make it possible to calculate the resulting value of vibration velocity on the basis of relation

$$\nu = \sqrt{(\nu_m + \nu_r)^2 + \nu_z^2}. \tag{6}$$

When the maximum value of winding overheat is calculated, especially in the case of damaged laminated cores, it is necessary to additionally take into account the irregularity of its temperature distribution. It can be taken into account by a dependence of the form

$$\theta_{max} = f(\Delta\vartheta_{in}, \lambda_i, \Delta p_i), \quad (7)$$

where $\Delta\vartheta_{in}$ – excess of air temperature inside the machine, $\lambda_i, \Delta p_i$ – local values, respectively, of thermal conductivity coefficient and specific steel losses.

Apart from the described parameters, the use of spectral components of vibration velocity at the supply voltage frequency and rotation frequency, as well as measurement of temperature at the points of assumed maximum by means of embedded temperature indicator are also efficient.

Solution of the problem of reliability estimation in the mentioned formulation requires application of an expert system making logic conclusions of two types:

- Estimation of deviation of each parameter (temperature, vibration velocity, etc.) of the unit in relation to normal values for this machine in time and frequency domains, taking into account the operating condition (current load, environment temperature, starting condition, etc.).
- Determination of the defect type and estimation of the remaining time of operation of the unit according to the results of calculation of the first stage.

In this case combination of the classical expert system with fuzzy logic in assigning specialized rules of

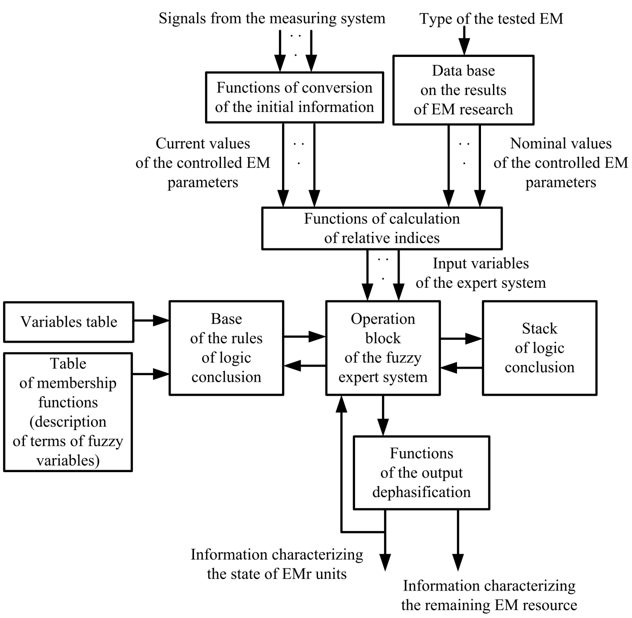

Fig. 1: Diagram of an expert system for estimation of the reliability of EMs with functions of fuzzy conclusion.

diagnostics of the state of EMs enables a more complex approach to the problem of calculation of their reliability, which is explained by Fig. 1.

As an example the bearing unit was analyzed (Fig. 2).

It can be seen in Fig. 2 that it consists of a case cap 1 with a bearing interface 3 and the bearing proper including rolling elements 4, an inner race 5 rigidly mounted on shaft 2 and an outer race 6. Due to manufacture defects and improper installation of the bearing, as well as when the case cap is flashed or skewed, such defects as crumpling of working surfaces of races and rolling elements (plastic deformation under the action of vibration, shock or statistical loads), destruction of separator (under the action of centrifugal force and impact on the separator of various-size rolling elements), destruction of races, rolling elements and the body of the machine (races skews, shock overloads) occur in the unit. In this case gaps δ appear in interfaces, there occur shifts of the axis of bearing mounting (angle α), forces F, determining the application of the load and friction intensity, redistribute.

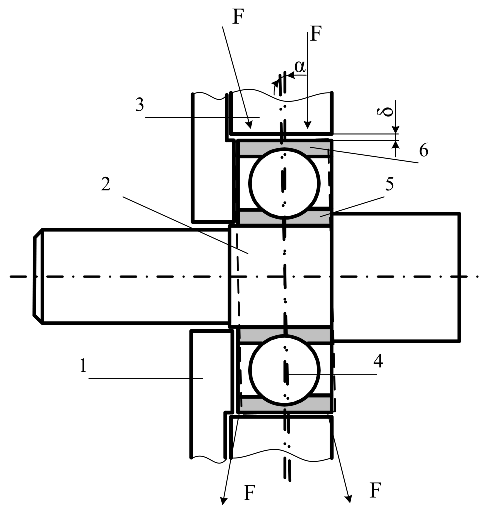

Fig. 2: Design diagram of a bearing unit.

The input parameters of fuzzy logic include vibration components ν, ν_m, ν_r, ν_z, calculated according to Eq. (3), Eq. (4), Eq. (5), Eq. (6) both for absence and presence of damage, two harmonics of the radial component of vibration velocity at the supply frequency and two harmonics of the axial component of vibration velocity at supply voltage frequency determined by the parameters of the installed bearing, temperature θ_l of the end parts on the side of the unit damage in accordance with Eq. (7).

The operating principle of the model consists in comparative analysis of the input parameters with the following recalculation of error-free running time T depending on exceeding of one of three installed levels by one of them or by some of them simultaneously.

The model was created with the use of the possibilities provided by the application package for the work with fuzzy logic [7]. The general view of the model is presented in Fig. 3. Fuzzy conditions are formed according to the values of nine input variables and the assignment of the membership function corresponds to their three levels (low, medium and high).

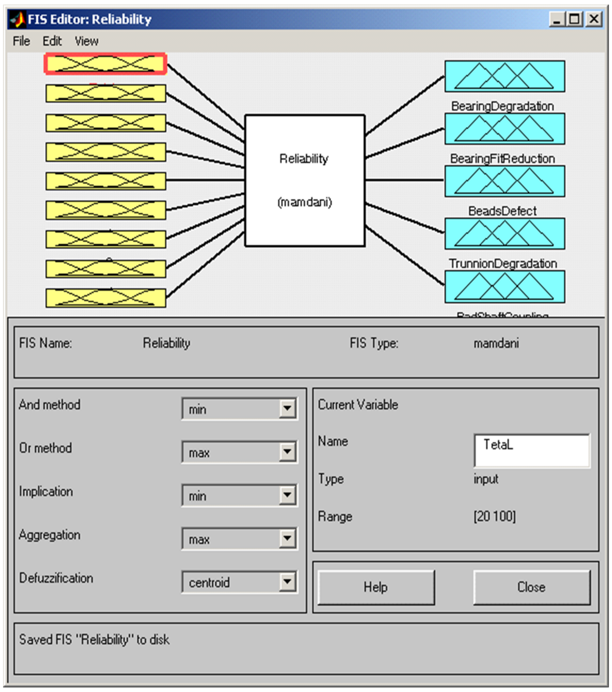

Fig. 3: General view of a fuzzy model for a bearing unit.

Under the condition of structural faultlessness of all the other structural components of the EM the developed model enables determination of: slackening of the bearing fit according to growth of the radial component and winding heating; balls defects – at additional increase of spectral components at the frequencies divisible by the supply frequency; pivot destruction – according to growth of vibration in the axial direction and other types of defects.

4. Experimental Researches

During the research the main types of structural unit faults influencing the reliability indices were singled out. They include various types of damages of bearing unit, stator core, windings, a rotor (armature) and current collection units.

Theses offered in the paper were tested during experimental research when the efficiency of reliability model was being estimated for a bearing unit of AOL12-4 induction motor with a fed-in fault of the outer ring. The fault was obtained by a uniform decrease of the ring diameter due to its grinding off. This defect results in the static and dynamic eccentricity of the air gap, as well as in partial magnetic saturation of the active core because of the motor overload. It becomes apparent in the increase of vibration components at the double frequency of power supply and the basic rotation frequency.

Besides, the position of the axis the cap was changed by its improper installation. Parameters δ and α, as well as the required structural parameters were directly taken into account in the model proper.

Experimental data were obtained on the basis of a computer-aided complex with the structure shown in Fig. 4. A measuring part of the complex is built on the basis of a certified measuring module LCard E14-440, including an analog-digital converter (ADC) and channels of discrete input/output (DIO) connected to a personal computer (PC).

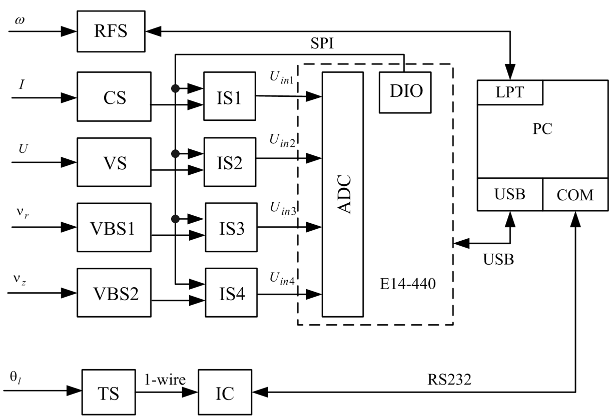

Fig. 4: Structure of the measuring complex.

ADC block has 16 differential channels of analog input to which the sensors for measurement of basic parameters can be connected through interfaces schemes (IS 1–4): alternate current sensor (CS) with operating range 0..100 A and reduced error of 1.5 %, alternate voltage sensor (VS) with operating range 0..750 V and reduced error of 1 %, vibration sensors (VBS1, 2) with operating range up to 4000 Hz, and measuring inaccuracy of vibration parameter at working bank not more than 1.5 %. Control of IS characteristics is performed through DIO channels. Temperature sensors (TS) 700-101BAA-B00 with operating range -70..+500 °C and sensibility ±0.06 %, and a rotation frequency sensor (RFS) based on optical tachometer BE-5H with $z = 1000$ rot^{-1} and frequency measurement unit, are connected to PC separately through an interface converter (IC).

Input parameters of the fuzzy model were determined by means of fivefold measurement with the following statistic processing of the results. Magnetic vibration was separated from the overall one due to switching off the EM supply voltage.

The obtained values of vibration velocity:

$$\nu_{er1} = 0.74\ \text{mm} \cdot \text{s}^{-1};\ \nu_{er2} = 1.16\ \text{mm} \cdot \text{s}^{-1};$$

$$\nu_{ez1} = 0.8\ \text{mm} \cdot \text{s}^{-1};\ \nu_{ez2} = 0.95\ \text{mm} \cdot \text{s}^{-1},$$

where $\nu_{er1}, \nu_{er2}; \nu_{ez1}, \nu_{ez2}$ – respectively radial and axial root-mean-square values of vibration velocity of EM without damages (1) and with damaged (2) bearing unit (Fig. 5).

Corresponding values of temperature θ_l are respectively 67 and 70 °C (Fig. 5).

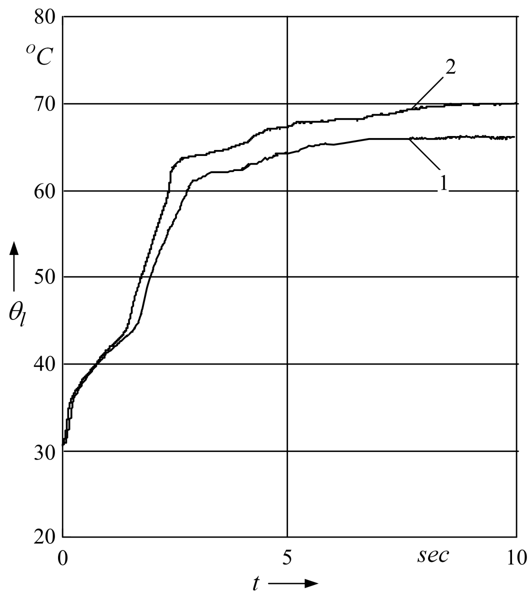

Fig. 5: Results of the change of the EM winding slot temperature: 1 – undamaged EM; 2 – EM with a damage.

In this case admissible value ν_e for tested EMs, according to Standard 20815-93 is 1.12 MM/C, and value of the excessive temperature of the winding for the prescribed insulation class B in EM – 80 °C.

To increase the reliability of identification of the considered defects the results of spectral analysis of radial component of vibration for k harmonics in relation to voltage supply frequency (the 3rd and the 17th harmonics in Fig. 6, which change under damage present shows appearance of unbalance and electrical asymmetry of EM structure) were used.

Results of determination of error-free running time, according to simulation data using fuzzy logic, differ from experimental values obtained through mean values of vibration velocity and temperature using experimental design theory within 17 %. Taking into consideration the ambiguity of the condition of other structural components, such an error is admissible in this case.

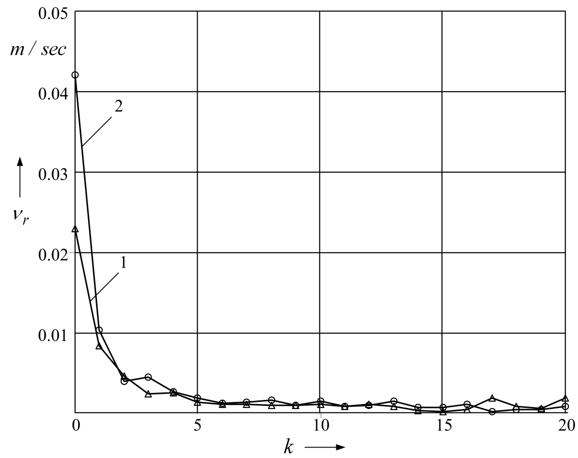

Fig. 6: Results of spectral analysis of a radial component of vibration: 1 – undamaged EM; 2 – EM with a damage.

Besides, the modeling results enable evaluation of the mutual influence of the input parameters and, thus, identification of manifestation of basic defects. It provides the possibility of accurate determination of the damage type and the state of the considered unit after relevant improvement of the model.

5. Conclusion

The efficiency of the use of fuzzy logic postulates in the creation of electric machine reliability prediction models has been proved. It provides the possibility of taking into account the variation of the state of major structural units and elements by estimation of their thermal and vibration parameters.

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