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The special features of the change of electromagnetic parameters of electric machines with long mean-time between failures

***Abstract.** The interrelation of the state of basic structural units of typical electric machines of general industrial purpose in the process of long operation and the change of their electromagnetic parameters is researched. A combined approach to forecasting the change of electromagnetic parameters of electric machines with long mean-time-between failures is developed. It includes the joint use of theoretical methods modified by the authors and experimental methods applied in tests, which makes it possible to solve the posed problem with sufficient accuracy.*

Streszczenie.** W artykule badane są relacje pomiędzy stanem typowych maszyn elektrycznych w procesie długiego działania a zmianami ich parametrów elektromagnetycznych. Rozwinięto specjalne podejście do prognozowania zmian parametrów elektromagnetycznych maszyn elektrycznych z długim średnim czasem między awariami. Podejście to włącza zarówno metody teoretyczne zmodyfikowane przez autorów, jak też metody eksperymentalne zastosowane w badaniach testowych. Pozwala to na rozwiązanie postawionego problemu z wystarczającą dokładnością.* ***(Specjalne właściwości zmiany parametrów elektromagnetycznych maszyn elektrycznych z długim średnim czasem między awariami)

Keywords: electric machine, breakage, electromagnetic parameters, forecasting
Słowa kluczowe: maszyna elektryczna, awaria, parametry elektromagnetyczne, prognoza

Introduction

One of the basic problems related to the operation of electric machines (EM) with long mean-time-between failures consists in the absence of reliable information about the change of their parameters and characteristics in the process of natural or forced aging. First of all, it refers to the assessment of the change of the published data determining the efficiency of EM operation in static modes approaching the rated one [1].

The analysis of the energy modes of EM operation provides a big amount of additional information, especially when losses components and energy coefficients are expressed as functional dependences on time [2], as well as the thermal and vibration parameters caused by the variation of the state of basic structural units [3].

However, the mentioned parameters and characteristics, in fact, do not allow analyzing EM transient modes and they prove to be inapplicable to the use in regulated EM and various measuring and protective systems [4, 5]. In these cases, it is necessary to additionally know the character and the features of variation of EM electromagnetic parameters mainly presenting equivalent circuit resistive impedance and inductance.

Thus, the purpose of the paper consisted in the theoretical substantiation of the method and specific features of forecasting of the variation of electromagnetic parameters of EM with long mean-time-between failures.

Theory

The results of the researching the processes of aging of EM during their long-term operation make it possible to conclude that the basic influencing factor for electromagnetic parameters is change in the magnetic system and windings parameters that to some extent break the basic structure electrical and magnetic symmetry.

It results in variation of the equivalent circuit parameters of both direct current brushed machines (DCM) and induction motors (IM) and synchronous machines (SM) in accordance with Fig. 1 [6].

Here R_{ac}, L_{ac} – armature circuit total resistive impedance and inductance; E_M – motor EMF; R_1 – IM (SM) stator winding resistive impedance; X_1 – IM stator winding dispersion inductive reactance; R_2', R_f' – IM rotor winding and SM secondary winding reduced resistive impedance, respectively; R_μ, X_μ – IM magnetizing contour resistive impedance and inductive reactance; X_{ad} – SM inter-induction inductive reactance along the longitudinal axis; X_s, X_f – SM dispersion total primary and secondary inductive reactance, respectively; s – slid $u(t), i(t)$ – respectively supply voltage and current in EM primary winding.

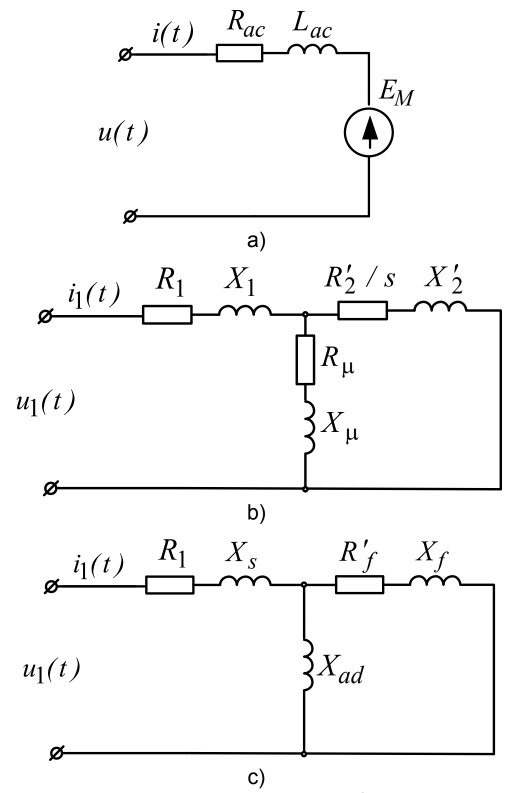
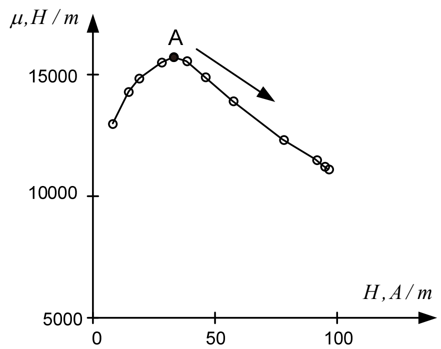


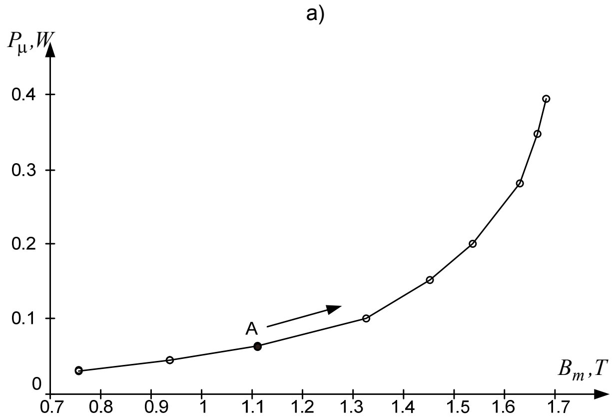
Fig. 1. EM equivalent circuits: a) brushed DCM armature circuit; b) IM; c) SM

As to violation of electrical symmetry, first of all, it is necessary to take into account possible changes of the windings parameters, in particular, their electric resistance R_i, both due to the change or variation of the number W_i of turns at wrong structural modifications or partial damages and because of the change of different phases windings temperature θ_i caused by their different heating conditions. For brushed DCM it is necessary to additionally take into account the change of resistive impedance R_{ac} of the armature circuit due to the variation of the collector-brush device properties during the aging process (irregular pressure and beating caused by the brushes wear and the collector ellipticity, change of the collector plate resistance due to their partial burning, etc.). Analogously, but to a somewhat smaller extent, the properties of the current pickup units in induction machines with a phase rotor and synchronous machines change, which is also liable to account.

Violation of magnetic symmetry is caused by two basic factors. First, during the process of mean-time-between failures the properties of the laminated electrical steel cores, being the basis of EM magnetic system, deteriorate. As shown in [7], it is manifested in the shift of EM operating point into the area of higher saturation at the general decrease of the value of saturation magnetic induction, growth of the magnetic field strength and sharp increase of steel losses. With regard to electromagnetic parameters, the analyzed phenomena are taken into consideration via assignment of the magnetic permeability real dependence on the magnetic field strength and by taking into account the influence of steel losses according to [2]. It is explained in Fig. 2.



a)



b)

Fig. 2. Special features of variation of magnetic (a) and electrical (b) properties of laminated electrical-sheet steel cores

It is seen in Fig. 2,a that the increase of magnetic circuit saturation causes a shift of EM operating point A in the direction of reduction of magnetic permeability μ with the growth of magnetic field strength H. Thus, the new operating point is characterized by a lower value of magnetic induction B when values H and steel losses P_μ grow (Fig. 2, b).

For alternating current EM (Fig. 1, b) it means that, first of all, magnetizing contour inductance X_μ reduces proportionally to μ at the general increase of the degree of its nonlinearity. The magnetizing contour resistive impedance R_μ changes proportionally to steel losses. Simultaneously mentioned regularities determine the impedance reduction with the following redistribution of energy between the stator and rotor circuits, which eventually influences the growth of their leakage inductances X_1, X_2', respectively.

The second factor that results in magnetic asymmetry consists in the violation of the air gap regularity due to breakage of bearings, bearing units slump and the influence of different types of imbalance caused by the rotor. The mentioned phenomena result in variation of resistance in the formed contours of the magnetic circuit at the rotor turn, which causes changes of the value of the magnetic flux. It also results in the change of electromagnetic parameters mainly caused by their irregular distribution across the phases and stator circumference.

Experimental research

As it is rather difficult to assess the considered phenomena experimentally with the use of the existing testing methods and ways of parameter determination due to the ambiguity of their manifestation, the authors propose to use a number of modified methods of electromagnetic parameter determination. Therefore, it is proposed to determine the parameters of the windings connected directly to the power supply on the basis of the direct-current transient processes analysis enabling determination of the primary winding electromagnetic parameters with sufficient accuracy excluding the magnetic circuit saturation.

The method is explained in Fig. 3. It consists in the charge of capacitor C from constant voltage source E with closed key K_1 and open key K_2 with its further discharge at the researched EM winding representing a RL circuit at the opposite state of the keys.

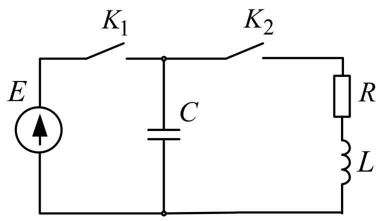


Fig. 3. Special features of realization of the method for the winding parameters determination

In this case the circuit is adjusted to the oscillation character of the transient process at the discharge, as shown in Fig. 4, by the correct choice of the value of capacitor C capacitance.

Such transient process is characterized by voltage at capacitor C changing according to the law

(1) $$u_c(t) = U_{c0} e^{\delta t} \sin(\omega_0 t + \psi_0),$$

where U_{c0} – capacitor charge voltage, δ – attenuation decrement, ω_0 – oscillation frequency, ψ – initial shift angle, t – time.

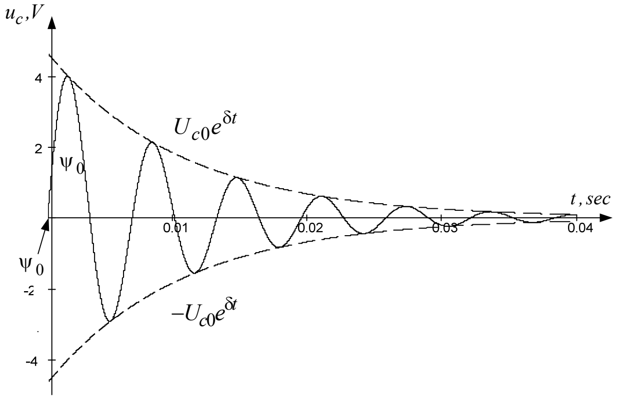


Fig. 4. The character of the transient process at determination of the winding parameters by a pulse-resonance method

Parameters δ and ω_0 are, respectively, the real and the imaginary parts of the roots of the characteristic equation $p = \delta \pm j\omega_0$, and accurately define parameters R_1, L_1 of the researched winding at the known value C. In its turn, they can be determined rather accurately by the results of direct computer measurements or expressing them via U_{c0} and ψ (Fig. 4). To guarantee high accuracy of parameter determination it is necessary to set the voltage at source E within the range of 5-10 V to exclude the saturation of the magnetic circuit and to choose the correct value of capacitance C providing a sufficient number of oscillations at their low frequency.

It is proposed to take into consideration of electric steel properties via generalizing trends formed for its basic grades used in mechanical engineering and reflecting their change in the process of EM long operation and repairs is substantiated.

Generalizing results of the research performed by the authors for grade 2312 electrical-sheet steel are given in Figs 5-6. Here dependences 1 and 3 correspond to EM initial state and its state after the first major overhaul for the cores made of insulated sheets 0.5 mm thick and curves 2 and 4 – to the same states for the sheets when insulation is taken-off.

It is seen in Figs. 5-6 that laminated steel aging is manifested in the reduction of the level of magnetic induction at decrease of angle β_1 of slope of the magnetizing curve saturated section (Fig. 5) and also a sharper growth of specific losses characterized by increase of angle β_2 (Fig. 6).

In this case, availability of induction B'_m is typical for the presented dependences. It corresponds to the breakpoints of both the magnetizing curve and the dependence for the specific losses.

Correcting the obtained results for the required level of magnetic induction in the parts of EM magnetic circuit it is possible to determine the real degree of the deterioration of their properties. An analogous situation is typical for all the steels used in the manufacture of general-purpose EMs.

The obtained results are used later for recalculation of the alternating-current EM magnetizing contour parameters. It is based on a parallel representation of the magnetizing contour as the one that corresponds to the real physical processes in the best way (Fig. 7, a) unlike the serial representation used in most equivalent circuits (Fig. 7, b) [7].

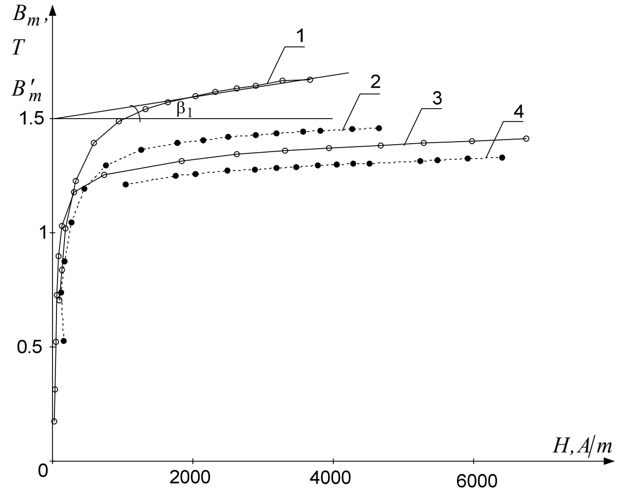


Fig. 5. Magnetic induction dependences $B_m = f(H)$ on magnetic field strength

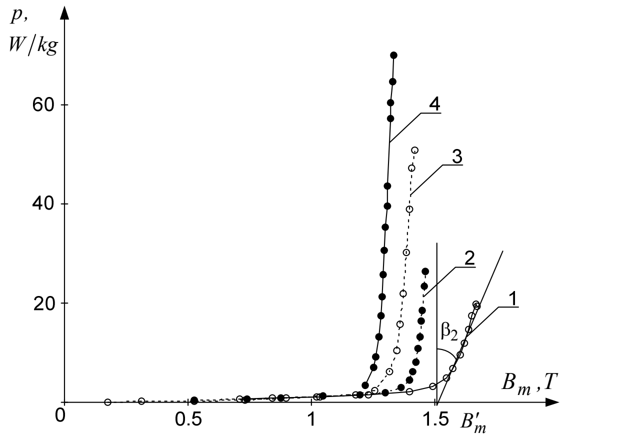


Fig. 6. Specific losses dependences $p = f(B_m)$ on magnetic induction

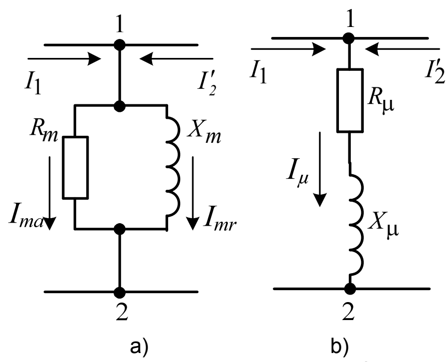


Fig. 7. Parallel (a) and serial (b) representation of the magnetizing contour in the equivalent circuit

In Fig. 7 $I_1, I'_2, I_{ma}, I_{mr}, I_\mu$ – respectively the primary winding current, reduced current of the second winding, active and reactive components of magnetizing current for the circuit in Fig. 7,a, magnetizing current for the circuit in Fig. 7,b; R_m, X_m, R_μ, X_μ – magnetizing contour resistive impedance and inductive reactance for the circuits in Fig. 7, a and 7,b, respectively.

The value of resistive impedance R_m is unambiguously determined from steel losses P_μ, specified by the given losses trends at the set EMF E_1

(2) $$R_m = \left(m_1 E_1^2\right) / P_\mu \ ,$$

where m_1 – number of EM phases.

Inductive reactance X_m at $f = const$ reduces proportionally to μ with the growth of the degree of core saturation, which can be determined from the trends of deterioration of magnetic properties

Then the parameters of the magnetizing contour are specified for Fig. 7, b

(3) $$R_\mu = X_m^2 R_m / \left(R_m^2 + X_m^2\right);$$

(4) $$X_\mu = R_m^2 X_m / \left(R_m^2 + X_m^2\right).$$

The irregularity of the air gap is taken into account by introduction of relevant adjustments into the calculation of the correcting coefficients for dispersions inductances. Its influence is especially significant for implicit-pole synchronous machines with a big basic value of the air gap. Irregular heat of the winding phases is taken into consideration by a calculation-experimental method based on determination of their resistive impedance variation. The parameters of the EM rotating parts are obtained with use of Kirchhoff's laws at the known rotation frequency ω, found by an indirect method from the flux linkage value ψ of EM primary winding.

A combined joint use of the described methods was assumed as a basis for forecasting of the change of the electromagnetic parameters of EM with long mean-time-between failures.

The approaches presented in the paper were tested during the research of the change of particular electromagnetic parameters of general-purpose EM of various power ranges within 0.5 – 10 kW. The total amount of the sample is 5 machines (2 DCM, 2 IM, 1 SM), the sample by power is arbitrary.

With the aim of imitation of the long-term operation the researched EMs underwent major overhauls twice during the test and were subjected to forced loading between the overhauls at the increased values of the consumed current, humidity and vibration in accordance with the methods of the accelerated reliability test [8].

The obtained results reveal the growth of the primary windings resistive impedance at the level from 2-5 % in direct current machines to 10-17 % in alternating current machines in relation to the values obtained with the use of the proposed method of the winding parameters determination.

As all the researched EMs are characterized by the growth of the consumed current at the level of 3-7 % in the nominal mode, the mentioned variations are mainly caused by the deterioration of the properties of magnetic system electric steel, which results in windings overheat. This is confirmed by the growth of inductive reactance X_1, X_s, X_f of alternating current EM dispersion by 15-27 % on average, as well as the decrease of resistive impedance R_m and reactance X_m of the IM magnetizing contour by 73-122 % and 27-44 % respectively.

In the future the above said will require the correction of the values of the EM primary windings resistive impedance in accordance with their real values depending on the operation thermal mode.

Conclusions

1. The problems of the variation of the state of the basic structural units of typical general-purpose EM in the processes of their long-term operation have been researched, which enabled singling out the basic factors and processes causing electrical and magnetic asymmetry of EM structure and thus influencing the change of their electromagnetic parameters.
2. The regularities of the change of the basic electromagnetic parameters of EM with long mean-time-between failures, caused by the influence of their aging, have been theoretically substantiated.
3. A method for forecasting the variation of the electromagnetic parameters of EM with long mean-time-between failures, including a combination of typical parameter-determination methods modified by the authors and applied to EM tests, has been developed. The simultaneous use of the methods makes it possible to solve the posed problem with sufficient accuracy.
4. Further research in this direction will include the development of the methods for determination of dynamically changing nonlinear electromagnetic parameters of the magnetizing contour and EM transient and supertransient resistances, etc.

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REFERENCES

[1] Hamid A. Toliyat, Subhasis Nandi, Seungdeog Choi, Homayoun Meshgin-Kelk. Electric Machines: Modeling, Condition Monitoring and Fault Diagnosis, CRC Press, October 30, (2012).

[2] M. Zagirnyak, V. Prus, I. Kolotylo, D. Miljavec, Determination of power indices for a three-phase induction motor with a phase-wound rotor through particular losses components. *Przeglad Elektrotechniczny* (*Electrical Review*), (2012), No 12b, 80–82.

[3] M. Zagirnyak, V. Prus, I. Kolotylo, D. Miljavec, Taking stator cores into account when induction motors vibration parameters are calculated. *Przeglad Elektrotechniczny* (*Electrical Review*), (2013), No 12, 192–195.

[4] T. Prauzner, P. Ptak, Analiza parametrów pracy wybranych czujników pola magnetycznego. (Analysis of selected operating parameters of the magnetic field sensors). *Przeglad Elektrotechniczny* (*Electrical Review*), (2014), R. 90, No 12, 273–276.

[5] P. Ptak, L. Borowik, Diagnostyka zabezpieczeń antykorozyjnych na potrzeby elektroenergetyki. (Diagnostics of anticorrosive protections for electroenergetics). *Przeglad Elektrotechniczny* (*Electrical Review*), (2012), No 09a, 142–145.

[6] Kostenko M. P., Piotrovskii L. N. Electric machines, 2nd edition, Leningrad, Energiia, part 1 (1964); part 2 (1965), (in Russian).

[7] V. V. Prus, M. V. Zagirnyak, I. A. Kolotylo, D. Miljavec, Estimate and taking into account change of steel losses in induction motors in process of their aging. *Proceedings of International IEEE Conference EUROCON 2009*, Saint Petersburg, Russia, (2009), 790–795.

[8] Kotelenets N.F., Kuznetsov N.L.. Testing and reliability of electric machines, Moscow, Vysshaia shkola, (1988), (in Russian).