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Determination of power indices for a three-phase induction motor with a phase-wound rotor through particular losses components

***Abstract**. A method of determination of power indices for a three-phase induction motor with a phase-wound rotor through particular losses components in the function of their integral and instantaneous values is developed. The adequacy of the method is confirmed. The prospect of its use is grounded for the situation when the state of structural assemblies and motor elements changes in the process of long-term operation and after repair.*

Streszczenie.** Przedstawiona została metoda określenia wskaźników trójfazowego silnika indukcyjnego z wirnikiem uzwojonym poprzez poszczególne składniki strat w funkcji ich integralnych i chwilowych wartości. Odpowiedniość metody została potwierdzona. Perspektywa stosowania tej metody oparta jest ukierunkowana na sytuacje kiedy konstrukcyjny montaż i elementy silnika zmieniły się w procesie długotrwałego działania oraz po remoncie.* ***(Określenie wskaźników mocy dla trójfazowego silnika indukcyjnego z uzwojonym wirnikiem poprzez poszczególne składniki strat).

Key words: induction motor, phase-wound rotor, losses components, power indices.
Słowa kluczowe: silnik indukcyjny, wirnik uzwojony, składniki strat, wskaźniki mocy.

Introduction

In a competitive market, which is especially acute during crisis years, the industrial production aims at considerable decrease of various kinds of expenditure influencing the prime cost of manufactured goods. For most enterprises of metallurgic, chemical and other adjacent industries electric power costs, coming to 30-35 % in the total cost, are considerable. This poses the problem of optimization of power costs in control of various technological objects and processes at an enterprise.

It is possible to optimize power consumption in an electric drive by means of control systems estimating real power conditions of electric machines operation and their efficiency. The prospect of the use of such systems is determined by availability of reliable methods of finding power and moment on the electric machine shaft, as well as particular power losses components under different operational conditions. In this case directly controlled values are to be easily determined according to the reading of as few standard sensors used in the electric drive system as possible.

In a number of cases this problem is aggravated due to absence of methods taking into account both particular losses components and their total value, which can be explained by complexity of mathematical description of real power processes in different electric machines types. Besides, the existing power processes analysis methods are mostly based on simplified notions and take into consideration neither motor natural parameter variation within one series nor the fact of their change during the process of long-term operation and repair. However, there exist a number of electric machines for which this problem can be solved with admissible errors. As to AC machines, first of all they include phase-wound rotor induction motors (PRIM).

Problem statement

The aim of the paper is to substantiate the method of determination of PRIM power indices through power losses components according to values of integral parameters and through instantaneous variables functions. In this case losses components are to be determined taking into account the state of the main PRIM structural assemblies and elements and are to be unambiguously expressed by the parameters measured with a minimal number of typical sensors.

Theory

Let us assume the current values of power coefficient $\cos\varphi$ and efficiency coefficient η to be PRIM power indices. Their determination and expression through particular losses components is the most accurate method of their finding in any operation conditions [1].

In PRIM the following losses components can be singled out: iron losses in stator P_{m1} and rotor P_{m2}, copper losses in stator P_{cu1} and rotor P_{cu2}, mechanical P_{mac} and additional P_{add} losses [1].

According to [2], in the process of long-term operation and repair of electric machines a considerable change of electric and magnetic properties in stator core iron takes place. It results in the increase of the degree of magnetic material saturation, growth of nonlinear distortions coefficient THD_{e1} of stator EMF curve e_1 and redistribution of losses P_{m1} in stator iron [2].

Losses P_{m10} in idle running iron can be determined according to the results of no-load test for supply voltage variable frequency, separating them from losses P_{cu10} in idle running copper and mechanical losses P_{mac} [1]. To divide them into hysteresis and eddy currents components it is necessary to use the expression obtained in [3]:

$$P_{m10} = \sum_{i=1,5,...}^{n} \left(c_h f_i^* E_{10i}^{\ 2} + c_{ec} f_i^{*2} E_{10i}^{\ 2} \right) \qquad (1)$$

where f_i^*, E_{10i} – values of i-th relative frequencies and EMF harmonic components, respectively; c_h, c_{ec} – coefficients taking into account the division of iron losses into hysteresis and eddy current ones, respectively.

Iron losses P_{m10} value obtained from no-load test can be used later to determine them under any load [3]:

$$P_{m1} = P_{m10} \left(E_1 / E_{10} \right)^2 \qquad (2)$$

where E_1– stator winding EMF in the mode for which value P_{m1} is determined. Its value for PRIM can be found on the basis of directly measured rotor EMF E_2 and motor rotation angular frequency ω.

Rotor iron losses P_{m2} are usually neglected due to their small amount, as rotor current frequency f_2 in the area of operating slip is not large. In case of high degree of saturation of PRIM magnetic system losses P_{m2} grow because of high slips of current higher harmonics. This phenomenon can be taken into account during spectral analysis of rotor EMF curve $e_2(t)$ [3].

Stator copper losses are usually determined by means of experiment on the basis of relation:

$$P_{cu1} = 3I_1^2 r_1 \quad (3)$$

Where I_1– stator current effective value; r_1– stator phase resistance.

Ambiguity of taking into account the stator winding resistance is typical of this losses component. As its value is determined at constant current for an idle IM, it is to be corrected taking into consideration the actual condition of windings heating.

Rotor copper losses P_{cu2} are determined according to measured value E_2 on the basis of relation

$$P_{cu2} = 3E_2^2 / r_2 \quad (4)$$

where r_2– rotor phase resistance.

In case of unsymmetry of PRIM structure or supply voltage unsymmetry, relations (3) and (4) are to be transformed into the losses power sum at three separate phases. In some cases it is necessary to take into consideration the influence of the stator winding type [4], as well as the condition and integrity of rotor winding [5], as it significantly affects IM parameters.

Mechanical losses P_{mac}, taking into account the ambiguity of their separation from no-load test losses P_{m10}, according to [3], should be determined separately using the retardation method. Later they are considered constant at fixed rotation frequency ω, and, when it is necessary, they are recalculated for another frequency according to the known power dependences [1].

As to additional losses P_{add}, the information is contradictory. On the one hand, during designing and testing calculations they are assumed to be within 0.5-1% of IM consumed power P_1. On the other hand, some sources point out the incorrectness of this approach and give the figure of 5-7% of P_1 [6]. Taking into account the P_{add} unknown share, it was proposed to find their value by reverse rotation method and later assume them to be constant.

Thus, power P_2 on PRIM shaft is determined from relation:

$$P_2 = P_1 - P_{cu1} - P_{m1} - P_{mec} - P_{add} - P_{cu2} \,. \quad (5)$$

In this case $\cos\varphi$ and η can be found from classic relations [1].

To determine losses components in accordance with the proposed method it is sufficient to use standard sensors for stator phase voltages and currents, rotor EMF and rotation frequency. To specify components P_{cu1} and P_{cu2} values it is possible to install additional sensors for stator and rotor, respectively, windings temperature, but in most cases there is no need in it, as the values of corresponding temperatures for PRIM can be obtained by an indirect way [1].

When losses components change in time is estimated, it is possible to use relations analogous to (1)-(5) and change effective values of E_1, E_2, I_1, I_2 for functions of their instantaneous values $e_1(t), e_2(t), i_1(t), i_2(t)$ and all the computations stated above. As a result, time t dependences of instantaneous values of some losses components and power P_2 on PRIM shaft can be obtained.

Experimental research

The aim of experimental research was to estimate the adequacy of the proposed method and the possibilities to use it in practice. A block diagram of the test unit is shown in Fig. 1.

Fig. 1 shows that an electromagnetic powder brake (EMPB), which is a calibrated device assigning the required moment of resistance, was used as a load for PRIM. The system provides for PRIM power supply by both an induction voltage regulator (IVR) and a transistor frequency converter (TFC), alternately switched to the tested motor through power circuit commutator (PCC). It insures a complete spectrum of tests covered by the developed method.

Voltage sensors (VS1 – VS3) and current sensors (CS1 – CS3) measure instantaneous values of stator phase voltages and currents, respectively, and voltage sensors (VS4 – VS6) measure rotor EMF, optical tachometer (TC) is used for control and measurement of rotation frequency. The measured signals were taken by a certified input-output module (IOM) and processed by a computer (PC). Parameters of the used equipment: PRIM of the type MTF 012–6 ($P_{2n}=2.2\ kW$), powder brake PT16-2M ($P_n=5\ kW$), frequency converter of the type Altivar 21 (Schneider), voltage sensors LV25 and current sensors LT15-P (LEM), optical tachometer TO-25 M, input-output module E-14-440 (L Card).

A number of experiments carried out with the use of the developed method resulted in determination of numerical values of components in (5), total losses and power indices. The load on PRIM shaft changed within 0.5 to 1.25 of P_{2n} with an increment of 0.25 P_{2n}. The results of measurements and calculations are shown in Table 1.

The accuracy of the method was estimated on the basis of comparison of shaft power calculated according to the developed method (P_{21}) with the results obtained from direct determination of the power (P_{22}) on PRIM shaft by brake moment M_{br} of powder brake and PRIM rotation frequency ω. Data in Table 1 show that under various operation conditions calculation error values do not exceed 8.27%, which confirms the possibility to use the developed method for control of losses components and power indices in systems of industrial electric drive.

Change of PRIM losses components is shown in Fig. 2. The presented results allow one to estimate power consumption and particular features of power conversion in PRIM in real time mode.

Table 1. Results of experimental research

Parameter	Load on PRIM shaft			
	0,5 P_{2n}	0,75 P_{2n}	1,0 P_{2n}	1,25 P_{2n}
P_{m1}	59.49	57.84	55.44	52.04
P_{cu1}	261.3	344.1	486.8	738.5
P_{cu2}	27.13	66.87	133.8	250.2
P_{mac}	26.9	26.1	25.11	23.75
P_{add}	8.45	12.68	16.91	21.14
P_{21}	1072	1622	2173	2724
P_{22}	1084	1657	2101	2516
$\frac{P_{21}-P_{22}}{P_{22}}100$	-1.29	-2.11	+3.43	+8.27
η	0.737	0.762	0.752	0.715
$\cos\varphi$	0.483	0.617	0.704	0.753

As in the process of repair and long-term operation the properties of PRIM main structural assemblies and elements change, for practice it is necessary to have a simplified formula making it possible to easily estimate changes of both separate losses components and their total sum.

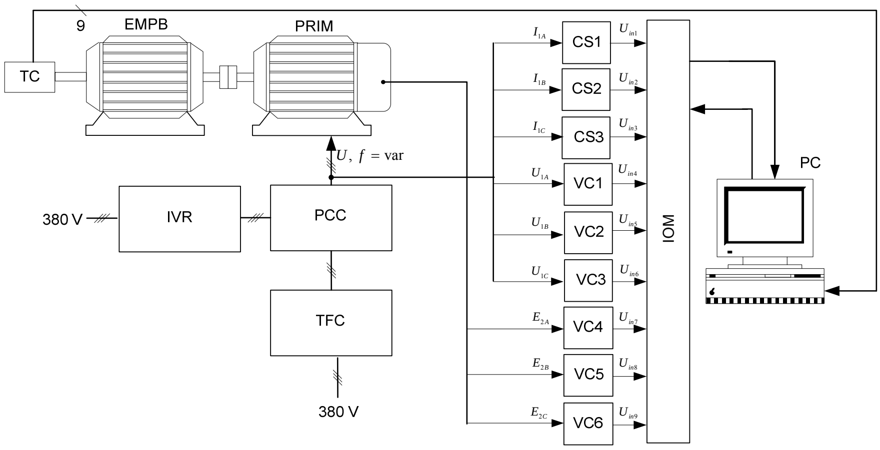

Fig. 1. Block diagram of the test unit

This relation was obtained for the case of PRIM supply from frequency converter. It is based on the results presented in [7], which are closest to the ones obtained during the work, preserving the dependence of losses components on the measured parameters.

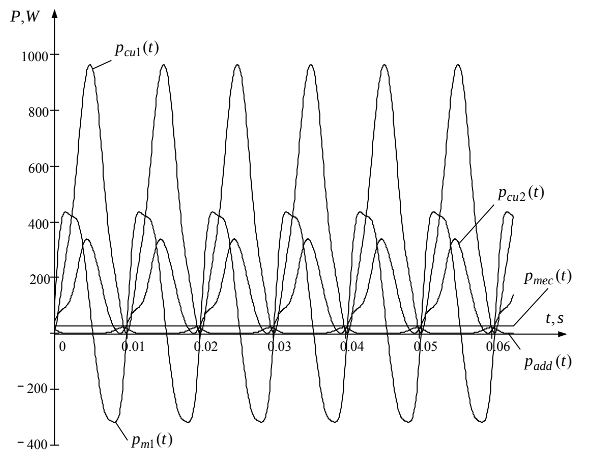

Fig. 2. Change of PRIM losses components in a time function

So, total losses can be calculated from the relation:

$$\Delta P = \rho_1 i_2'^2 + \sigma_1(\alpha)\varphi^2 + a_{e0} i_\mu^2 + a_{mec}\alpha^n \quad (6)$$

where i_2' – relative reduced rotor current; i_μ – relative magnetizing current; $\rho_1 = (a_{e1} + a_{e2})$ – coefficient of variable loss in stator and rotor copper from reduced rotor current; $\sigma_1(\alpha) = (a_h\alpha + a_{ec}\alpha^2)$ – coefficient of iron hysteresis and eddy current losses; $\alpha = f_1 / f_{1n}$ – relative frequency of stator current; $\varphi = \Phi_\alpha / \Phi_n$ – motor relative flux; Φ_n – nominal value of the main magnetic flux; a_{mec} – mechanical losses coefficient; n – index of the degree of mechanical losses dependence on frequency ($n = 1 \div 1{,}5$).

When additional losses are taken into account, expression (6) does not change its structure only values of some coefficients are adjusted. Coefficients $a_{e1}, a_{e2}, a_{e0}, a_h, a_{ec}, a_{mec}$ used in (6) for every separate motor of a certain power range and version characterize relative values of particular losses components in stator and rotor copper, respectively, in magnetizing circuit, in iron from hysteresis and eddy currents, mechanical losses.

To provide the required accuracy of determination of power losses components taking into account the real characteristics of units and elements in this case it is sufficient to determine these coefficients in accordance with the developed method.

Conclusions

A method of determining PRIM power indices through particular power losses components and their expression according to the measured parameters of standard sensors used in electric drive system has been proposed. The correctness of the developed method and possibility of its use during the change of the state of PRIM main structural assemblies and elements has been confirmed. The calculation results can be used in making feedback loops according to power parameters in regulated electric drive systems and in methods of improved PRIM thermal calculations.

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