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# THE PARAMETRIZATION METHOD OF GENERALIZED INDUCTION MOTOR USING THE FIELD ANALYSIS FOR DESIGN

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*The method of determining and mathematical representation of the relationship of the equivalent circuit parameters of an induction motor (IM) with its design and operational parameters using the results of field analysis has been proposed. This method has created a polynomial mathematical model of a system of electromagnetic parameters of a generalized IM, for design, which together with the IM circular mathematical model is an analogy of a field mathematical model. On the example of calculation, according to the obtained analogy of the IM field mathematical model, the IM design condition determines the degree of its adequacy to the results of the field analysis.* References 9, table 1, figure 1.
***Keywords:*** induction motor, optimal design, macromodel, parameterization, experiment planning.

Nowadays, the improvement of technical and economic indicators of induction motors (IM) is an actual task which, despite a fairly high level of improvement of serial IM, can be solved in such areas as: integrated optimal design of general purpose IM and non-traditional design, optimal design of IM with functional and constructive the combination of its elements with the working bodies of loading mechanisms. The IM improvement in these areas is possible subject to the use of highly efficient and adequate software for optimal design.

Mathematical modeling of IM using methods of field theory are one of the most attractive, based on the universality and reliability of the results [1]. But the induction motor field mathematical models (MM) can consist of hundreds of thousands of equations, so the specification of implementing the design even using modern computational technology is not an easy specification [2,3]. A well-known path to reduce the dimension of the IM field MM is the creation of IM mathematical macromodels. So, in universal commercial software systems of the finite element analysis (Ansys, Comsol, etc.) [4,5] focus on methods of reducing the order (MRO) of model. These methods are designed to build macromodels by lowering the dimension of high order equations. The use of MRO in the IM design, significantly reduces the requirements for computing resources, but with a decrease in the adequacy of the IM field MM.

In this paper, attention is focused on the IM macromodels created using the analogy method, which provides for the availability of fundamental knowledge about the object of study. Since these models are based on intuitive-logical thinking procedures, the level of their adequacy will depend on the qualifications of the researcher. For example, the existing widely used macromodel AD is its circular mathematical model (CMM) [6]. The complexity of the practical implementation of CMM in the IM design with design and operational features lies in the determination of reliable relationships between the parameters of their equivalent circuit. Therefore, **the purpose of the paper** is to develop mathematical tools of IM design, which take advantage of field analysis and are effective in terms of calculation time, due to the developed method for determining and mathematical representation of the relationship between the parameters of the IM equivalent circuit with its design and operating parameters.

**The main material and research results.**

The IM macromodel was proposed in [7], obtained using equivalenting the quasi-3D field MM of IM and its analogy. This IM macromodel, due to the use of MM system of IM electromagnetic parameters, obtained using the field analysis, provides high accuracy calculations of the IM operating condition of

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arbitrary structure. The system of IM electromagnetic parameters is a tabular dependence of the IM equivalent circuit parameters as function of operating parameters

$$x_m = f\left(\left|\dot{F}_p\right|, s\right);\ r'_c, x'_c, r'_k, x'_k = f\left(\left|\dot{I}'_r\right|, s\right);\ x_{1n} = f\left(\dot{I}_s, s\right), \qquad (1)$$

where $x_m$ is a inductive impedance on the main field; $r'_c, x'_c$ are the normalized active and inductive impedance leakage of the rotor bars, respectively; $r'_k, x'_k$ are the normalized active and inductive impedance leakage of the rotor short-circuiting ring, respectively; $x_{1n}$ is the inductive impedance of the stator slot; $\dot{F}_p$ is the resulting MMF of the motor on the fundamental harmonic; $s$ is the slip; $\dot{I}_s$ , $\dot{I}'_r$ is a complex of the stator and rotor current normalized to the stator, respectively.

This is method of determining and representing the relationship of the parameters of the IM equivalent circuit with its operating parameters, exactly the IM tabular parameterization [7] could be extended to the region of the formation dependencies of the IM equivalent circuit parameters as a function of the design parameters and use them already in the IM design. But the creation and use of dependencies of the IM equivalent circuit parameters as a function of more than two variables in a tabular form is impractical and uneconomical in design. So, for example, to obtain the approximations of dependencies of the IM equivalent circuit parameters as a function of four variables (two operating and two design parameters) are presented in tabular form, with acceptable accuracy, it would take up to several tens of thousands of points (numerous experiments). The duration of several tens of thousands of experiments would reach, respectively, several thousand hours, if the duration of one numerical experiment is up to 5 minutes, using a two-dimensional (2D) field MM of IM.

As the dependences of the IM parameters are sufficiently smooth, this allows to use the polynomials for their approximation,which will be the MM system of electromagnetic parameters of the generalized IM in a given area of the design parameters variation. The combination of the equations system of IM electric equilibrium and the approximation polynomials for determining of the equivalent circuit parameters as a function of operating and design parameters is an analogy of the field MM of generalized IM. The number of approximating polynomials will correspond to the number of the IM equivalent circuit parameters. The method of obtaining a polynomial MM system of electromagnetic parameters of the generalized IM in a given area of the design parameters will be named to as polynomial parametrization of the generalized IM.

The methods of the experiment planning theory will use to obtain approximating polynomials with a acceptable accuracy of their approximation for the design, with the minimum number of numerical experiments performed [8]. This allows to represent the relationship between all input (design and operating parameters) and output (IM equivalent circuit parameters) parameters in the form of algebraic equations (polynomial dependencies), that is, in a comfy form for solving design specifications using the results of field analysis

$$Y_1 = B_{01} + B_{11}X_1 + ... + B_{n1}X_n + ... + B_{121}X_1X_2 + ... + B_{n-1,n,1}X_{n-1}X_n + ... + B_{111}X_1^2 + ... + B_{nn,1}X_n^2 + ...$$

$$Y_2 = B_{02} + B_{12}X_1 + ... + B_{n2}X_n + ... + B_{122}X_1X_2 + ... + B_{n-1,n,2}X_{n-1}X_n + ... + B_{112}X_1^2 + ... + B_{nn,2}X_n^2 + ... \qquad (2)$$

$$Y_m = B_{0m} + B_{1m}X_1 + ... + B_{nm}X_n + ... + B_{12m}X_1X_2 + ... + B_{n-1,n,m}X_{n-1}X_n + ... + B_{11m}X_1^2 + ... + B_{nnm}X_n^2 + ...$$

where $Y_1, Y_2, ..., Y_m$ are parameters of IM equivalent circuit; $X_1, X_2, ..., X_n$ are design and operating parameters; $B_{0m}, B_{1m}, ..., B_{nm}, ..., B_{12m} ..., B_{n-1,n,m} ..., B_{11m} ..., B_{nnm}$ are coefficients of a power series.

The list of design parameters is determined by the designer at the initial stage of the IM design.

It should be noted that the features of formation the experiment plan are necessary to obtain approximating polynomials should include the requirements for the choice of operating parameters, the functions of which determine the IM equivalent circuit parameters. These parameters should be independent variables, each of which could be changed within certain limits without changing others. Such independent parameters are not the magnetomotive force and the rotor current MM of the IM (1). The need to form the parameters of the equivalent circuit as the slip function, stator current, rotor, and magnetomotive force in [7, 9] is associated with the implementation of equivalented the IM field quasi-3D model.

The IM independent operating parameters, besides the slip, include the stator current or electric voltage (depending on the specified source of the electromagnetic field). It is possible to form a " rigid " dependence of all IM equivalent circuit parameters as a function of the stator current only if the calculated field MM is used in 3D, or in 2D, with required binding to the parameters of short-circuited rings sections.

To carry out field analysis using the IM calculated field MM in 2D setting with binding to the parameters of short-circuited rings sections in the COMSOL Multiphisics package provide the ability to connect electrical circuits to the field MM of the IM (using TheElectricalCircuit interface) in order to solve them together.

Figure 1 presents the scheme of such a circle-field model with $z_2$ short-circuited rotor contours where the unit $FEM\_Z_2$ is a field MM $z_2$ bar with active-inductive properties, $r_k$,$L_k$ is an active impedance and leakage inductance of the section of the short-circuited rotor ring, respectively, which are calculated using the results of field analysis in the plane to which the motor axis belongs [7].

Thus, the parameters of the IM equivalent circuit are defined by the following expressions, which differ from [7] taking into account the parameters of the short-circuited rotor rings

$$x_m = \frac{-(P_c + P_k)}{3sI_s I_r^I}; \quad r_2' = \frac{P_c + P_k}{3\left|\dot{I}_r'\right|^2}; \quad x_{1n} = \frac{\omega_0 \operatorname{Re}\left(\dot{\Psi}_s\right)}{\sqrt{2}I_s} - x_m\left(1 + \frac{I_r^R}{I_s}\right); \quad x_2' = -x_m\left(1 + \frac{I_r^R I_s}{\left|\dot{I}_r'\right|^2}\right) \tag{3}$$

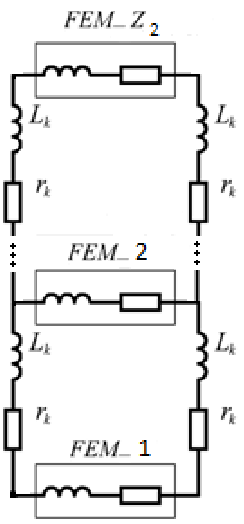


Fig.1

where $\dot{\Psi}_s$ is the first symmetrical component of the amplitude values the time complexes of full flux linkages of the stator phases $\dot{\Psi}_i$, ($i$=A,B,C); $P_c, P_k$ are powers of electrical losses in the rotor bars and in both regions of the rotor ring ; $I_s$ is a complex of stator current, which according [7] has only really component; $I_r^R, I_r^I$ are real and imaginary components of the rotor current complex $\dot{I}_r'$ by the operating harmonica with the number of pairs of poles $p$ normalized to the stator. The impedance of the the frontal parts leakage of the stator $x_{1л}$ is determined by known methods [6]. The obtained parameter from expressions (3) are based on the integral characteristics of the field analysis

$$\dot{\Psi}_i = \frac{2l_\delta W_s}{S}\int_s \dot{A}ds; \quad P_c = l_\delta \sum_{i=1}^{z_2}\left(\int_{sci}\frac{J_{mi}^2}{2\gamma_{c2}}ds\right); \quad \dot{I}_{ci} = \frac{1}{\sqrt{2}}\int_{sci}\dot{J}_{mi}ds;$$

$$\dot{I}_r' = \sum_{i=1}^{z_2}\frac{\dot{I}_{ci}e^{j(i-1)p\delta_k}}{6W_s K_{об}}; \quad \dot{I}_c = e^{jp\delta_1}\sum_{i=1}^{z_2}\dot{I}_{ci}e^{j(i-1)p\delta_k}; \quad P_k = 2r_k\left(\frac{\left|\dot{I}_c\right|}{2\sin\left(p\pi/z_2\right)}\right)^2, \tag{4}$$

where $\dot{I}_{mi}$ is the current value of the time maximum current density complex within the intersection area $i$-th bar $sci$; $\dot{I}_{ci}$ are effective values of currents time complexes of all rotor bars ($i$=1,…$z_2$), what is determined by integrating over the conductor area $sci$ of current density $\dot{I}_{mi}$ ; $\gamma_{c2}$ is the specific conductivity of rotor winding; $l_\delta$ is the length of the motor's magnetic circuit; $K_{об}, W_s, S$ is the winding coefficient and the number of stator phase turns and the area occupied by one of the parties ; $\delta_k = 2\pi / z_2$ is the angle between neighboring bars.

The degree of the polynomial MM system adequacy of IM electromagnetic parameters is determined due to the example of comparing the results of calculating the IM 4A80A2U3 design condition with its use, according to the results obtained by the IM circle-field MM and catalog data.

The procedure for obtaining the MM system parameters of CMM IM 4A80A2U3 is the following:

1. An orthogonal central composition plan of the second order is formed [8] with the following interval of variation of the regime parameters: $I_s = (2.5 \div 3.75)A,\ s = (0.016 \div 0.045)$. The IM constructive parameters in this case will be unchanged, therefore, this group of variables is absent in the CMM system parameters of generalized IM in MM (2).

2. According to the second-order central composition plan, it is enough to conduct 9 numerous experiments using the circle-field MM of the IM 4A80A2U3. The parameters of the equivalent circuit are calculated using the results of numerous experiments and according to expressions (3, 4).

3. According to the algorithm [8], polynomials of the parameters of the equivalent circuit in the function $I_s$ and $s$ are formed, the totality of which is the MM system of parameters CMM 4A80A2U3 IM in the given range of change the regime parameters $I_s$ and $s$

$$x_m = 101.4502+39.9504\cdot s -34.0767\cdot I_s+15.1169\cdot s^2+5.0412\cdot I_s^2-18.2837\cdot s\cdot I_s$$

$$x_{1n} = 2.4363+0.0455 \cdot s-0.1144\cdot I_s+0.0012\cdot s^2+0.0124\cdot I_s^2+0.0092\cdot s\cdot I_s$$

$$r_2' = 3.0987 +0.0014 \cdot s-0.0007\cdot I_s + 0.0009\cdot s^2+ 0.0002\cdot I_s^2-0.0009\cdot s\cdot I_s$$

$$x_2' = 4.6109 +0.1651\cdot s-0.2574\cdot I_s+ 0.1438 \cdot s^2+0.0322\cdot I_s^2-0.1668\cdot s\cdot I_s$$

The table shows the comparison of the calculating results of the IM operating condition parameters for the polynomial MM system of the IM electromagnetic parameters with the catalog data and with the results for the IM circle-field MM.

| Parameters of regimes | Catalog data | Considering $P_s$, $r_{1л}$, $x_{1л}$, $k_{st}$ | | Excluding $P_s$, $r_{1л}$, $x_{1л}$, $k_{st}$ | | |
|---|---|---|---|---|---|---|
| | | Polynomial MM system parameters of IM | Δ, % | Calculation using a circle-field MM of IM | Polynomial MM system parameters of IM | Δ, % |
| $I_s$, $A$ | 3.3 | 3.298 | 0 | 3.3 | 3.3 | - |
| $\eta_н$ | 0.81 | 0.814 | 0.5 | - | 0.854 | - |
| $\cos\varphi_н$ | 0.85 | 0.841 | 1.0 | - | 0.833 | - |
| $M$, $Н\cdot м$ | 4.98 | 4.98 | - | 5.38 | 5.35 | 0.5 |

To compare the calculation results using a polynomial MM system of IM electromagnetic parameters losses with catalog data, the MM of IM takes into account losses in the magnetic conductor $P_s$, parameters of the frontal parts of the stator winding $r_{1л}$, $x_{1л}$, steel fill factor $k_{st}$. According to the calculation results at the design condition, the parameters deviations of the IM operating condition using the polynomial MM system of the IM electromagnetic parameters in relation to the catalog data do not exceed Δ= 1%.

The error of the calculated moment on the shaft $M$ in the IM A80A2U3 design condition for the MM polynomial system of the IM electromagnetic parameters is Δ = 0.5% (Table), compared with the moment by the IM circle-field MM.

**Conclusions**

A necessary condition for the implementation of effective optimal design of IM is the use of highly efficient and adequate mathematical modeling. In this paper proposes a method for forming a polynomial MM system of electromagnetic parameters of a generalized IM for the purposes of design, which is called the polynomial parametrization of a generalized IM in a given region of change the constructive parameters. This method provides the creation of a polynomial MM system of electromagnetic parameters of generalized IM, which, in complex with CMM of IM, is an analogy of the field MM of generalized IM.

The duration of the IM polynomial parametrization is hundreds of times less time consuming compared to the table parameterization of IM. So, to obtain a generalized IM, MM system of IM generalized electromagnetic parameters in a given range of variation of both two regime and two design parameters, using a polynomial parameterization, up to 100 numerical experiments will be required. For the formation of dependences of the IM parameters in a tabular form will require up to several thousand numerical experiments. With repeated use the system of equations (2), the efficiency of the IM optimal design will certainly be significantly higher compared with the direct use of IM field models, while maintaining the accuracy of the obtained results at the level of accuracy of the field analysis results.

On the example of calculating the IM 4A80A2U3 design condition, was determined the discrepancy between the results obtained by analogy of the IM field MM, with the results for the circle-field MM did not exceed 0.5%.

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**МЕТОД ПАРАМЕТРИЗАЦИИ ОБОБЩЕННОГО АСИНХРОННОГО ДВИГАТЕЛЯ ПО РЕЗУЛЬТАТАМ ПОЛЕВОГО АНАЛИЗА ДЛЯ ЦЕЛЕЙ ПРОЕКТНОГО СИНТЕЗА**

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*В работе по результатам полевого анализа предложен способ определения и математического представления связи параметров схемы замещения асинхронного двигателя с его конструктивными и режимными параметрами. Для целей проектного синтеза по данному способу создана полиномиальная математическая модель системы электромагнитных параметров обобщенного асинхронного двигателя, которая в совокупности с цепной математической моделью асинхронного двигателя является аналогией полевой математической модели. На примере расчета по полученной аналогии полевой математической модели АД номинального режима асинхронного двигателя определена степень ее адекватности по результатам полевого анализа.* Библ. 9, табл. 1, рис. 1.
***Ключевые слова****:* асинхронный двигатель, оптимальное проектирование, макромодель, параметризация, планирование эксперимента.

**МЕТОД ПАРАМЕТРИЗАЦІЇ УЗАГАЛЬНЕНОГО АСИНХРОНОГО ДВИГУНА ЗА РЕЗУЛЬТАТАМИ ПОЛЬОВОГО АНАЛІЗУ ДЛЯ ЦІЛЕЙ ПРОЕКТНОГО СИНТЕЗУ**

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*В роботі за результатами польового аналізу запропонований спосіб визначення і математичного представлення зв'язку параметрів заступної схеми асинхронного двигуна з його конструктивними і режимними параметрами. Для цілей проектного синтезу за даним способом створено поліноміальну математичну модель системи електромагнітних параметрів узагальненого асинхронного двигуна, яка в сукупності з коловою математичною моделлю асинхронного двигуна є аналогією польової математичної моделі. На прикладі розрахунку за отриманою аналогією польової математичної моделі АД номінального режиму асинхронного двигуна визначено ступень її адекватності до результатів польового аналізу.* Бібл. 9,табл. 1, рис. 1.

***Ключові слова:*** асинхронний двигун, оптимальне проектування, макромодель, параметризація, планування експерименту.

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