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Evaluation of Discrete Modeling Efficiency of Asynchronous Electric Machines

Abstract. *In the paper the problem of effective mathematical macromodels in the form of state variables intended for asynchronous motor transient analysis is considered. Their comparison with traditional mathematical models of asynchronous motors including models built into MATLAB/Simulink software was carried out and analysis of their efficiency was conducted.*

Streszczenie. *W artykule przedstawiono matematyczne makromodele silników asynchronicznych w postaci równań stanu przeznaczonych do analizy czasowej. Porównano je z tradycyjnymi modelami matematycznymi, w tym modelami wbudowanymi w MATLAB/Simulink (**Ocena efektywności dyskretnych modeli maszyn asynchronicznych**)*

Keywords: asynchronous motor, transient process, discrete macromodel
Słowa kluczowe: maszyna asynchroniczna, stany nieustalone, makromodele dyskretne

Introduction

The creation of effective mathematical models intended for analysis of transient processes in electromechanical systems (EMS) elements is an important and relevant scientific problem.

In the presented paper the research of the effectiveness of existing mathematical models of the electromechanical systems elements on the example of mathematical models of asynchronous motor was carried out. Traditionally, asynchronous motor is considered as a system of windings with magnetic coupling, which parameters are active resistances and inductances, and the processes in the electric machine must be analyzed using equations of electrical and mechanical equilibrium.

The algorithm intended for calculation of the electric equilibrium equations makes it possible to define dependence of these parameters as a function of magneto motive force and machine slipping. These dependencies are presented in the form of mathematical models of the electric machine for the transient processes analysis [4,6].

Determination of parameters of electric and mechanical equilibrium equations, provided the correct processing of the results of the calculation of electromagnetic field, enables providing of the necessary reliability of dynamic modes calculation for the produced asynchronous motors and improving of the existing motors design .

In some cases for the study of dynamic modes of EMS the simplified linear or lìnearized modeling can be used that reflects particularly dynamic properties of the modeled object. In most cases they are created in the form of single phase equivalent circuits [5].

At the same time modern methods of mathematical and digital simulation allows you to create a model of AC electric machines at different levels of complexity – starting from linear and up to nonlinear continuous simulation. The last ones are quite complex and make the identification the instant values of all the coordinates both the rotor and the stator possible.

The goal of the research

Frequently when mathematical models of electromechanical object with the asynchronous motor in its structure are under design the information about all coordinates are redundant and not always used. In some cases it can slow down the process of the transient's calculation that is important during the transient processes analysis in real time mode. The effective ways to solve this problem is to create a mathematical macromodel. Application of macromodels, i.e., mathematical models, where only external variables of the object are used has significant advantages including the ability to replace the description of several complex electrical systems with one macromodel that allows to reduce significantly the time of rhe calculation [2,3].

The goal of the research is to create the macromodel and analyze the efficiency of most used mathematical models on the example of asynchronous motor of 4AX80B2У3 type (in Ukrainian classification) by comparing of their accuracy.

The essence of the research

In order to create the mathematical macromodel it is necessary to define its structure and identify its parameters using known characteristics of the transient processes caused by external disturbances. In their own turn macromodels can be created as continuous or discrete ones. Discrete macromodels are built using some values of external variables defined at some time moments. The procedure of discrete macromodeling is based on mathematical apparatus of difference equations [1,2,3].

Discrete macromodels in the state variables form can be created using the following equation:

$$\begin{cases} \vec{x}^{(k+1)} = \mathbf{F} \cdot \vec{x}^{(k)} + \mathbf{G} \cdot \vec{v}^{(k)} + \mathbf{\Phi}(\vec{x}^{(k)}, \vec{v}^{(k)}) \\ \vec{y}^{(k+1)} = \mathbf{C} \cdot \vec{x}^{(k+1)} + \mathbf{D} \cdot \vec{v}^{(k+1)} \end{cases} \tag{1}$$

where **F, G, C, D** are matrices of corresponding dimensions; $\vec{\Phi}$ is some vector-function of several variables, $\vec{x}^{(k)}, \vec{v}^{(k)}, \vec{y}^{(k)}$ are vectors of discrete internal, input and output variables respectively, *k* is time discrete number.

Due to the form of linear macromodel (2) the vector $\mathbf{\Phi}(\vec{x}^{(k)}, \vec{v}^{(k)})$ is a zero vector:

$$\begin{cases} \vec{x}^{(k+1)} = \mathbf{F} \cdot \vec{x}^{(k)} + \mathbf{G} \cdot \vec{v}^{(k)} \\ \vec{y}^{(k+1)} = \mathbf{C} \cdot \vec{x}^{(k+1)} + \mathbf{D} \cdot \vec{v}^{(k+1)} \end{cases} \tag{2}$$

The main advantage of the state variables method is a possibility to make formalization to be clear and to automize the calculation procedures. This method is convenient during the analysis of the dynamics of objects with different time constants, particularly for calculation of quasi periodic regimes.

For creation of mathematical models and estimation of its efficiency a priory information about transient processes of asynchronous motor was obtained experimentally. Experimental data are the discrete values of the transient characteristics (both electrical and mechanical) caused by variation of the existing values of voltage and mechanical torque on the shaft.

As the voltages and currents of the phases form a symmetrical tree phase system so the root-mean square values of the stator voltage just of one phase and moment on the shaft of asynchronous motor can be taken as the input values. At the same time root-mean square values of the current in the same phase and frequency of rotation of the rotor were taken as output values. As a result, vectors of input and output variables used for the asynchronous motor macromodel creation take the following form:

(3) $$\mathbf{v}^{(k)} = \begin{pmatrix} \mathbf{U}^{(k)} \\ \mathbf{M}^{(k)} \end{pmatrix}; \ \mathbf{y}^{(k)} = \begin{pmatrix} \mathbf{I}^{(k)} \\ \boldsymbol{\omega}^{(k)} \end{pmatrix}$$

In the Fig. 1 the curves of the transient process of the stator current of the phase A (curve 2) and rotor speed of the rotation (curve 1) are presented in p.u. system for the asynchronous motor of 4AX80B2У3 type using the computer experiment

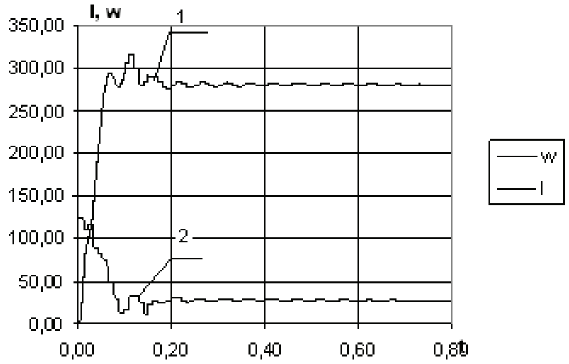

Fig.1 Time dependencies of root-mean-square values of the current (2) and speed (1)

The use of optimization algorithms appears to be very promising method for the macromodels creation. The essence of this approach is in the search of minimum of some goal function $Q(\vec{\beta})$ respectiv to the unknown parameters of the macromodel to be created that can characterize it accuracy.

In order to create the macromodel the following stages of the modelling process should be carried out:

- the selection of the form of the model under research written down using unknown coefficients that can allow describing of the object to be modeled with sufficient accuracy.
- obtaining of sufficient data set with information about the object to be modeled.
- obtaining of the row of unknown coefficients that will ensure the sufficient accuracy of the model reaction to the test signal.
- verification of the quality of the developed model reaction using another test signals.

For the macromodel parameters identification the two-stage optimization process proposed in [1, 3] was used.

During the first stage of the modeling process the linear macromodel was developed (coefficients of $\mathbf{F}, \mathbf{G}, \mathbf{C}$ matrices were found) using optimization approaches including the Ho-Kalman algorithm.

Here the goal function characterizes the difference of the model behavior from the modeled object behavior. As the goal function the root-mean square value of deviation of known transient characteristics from results obtained using macromodeling can be used.

The goal function $Q(\vec{\beta})$ can be defined in the following way $Q(\vec{\beta}) = E(\vec{y}, \vec{y}^*) \ \Rightarrow \min$ >T, where $\vec{\beta}$ is a vector of the model parameters, $E(\vec{y}, \vec{y}^*)$ – root-mean square deviation of transient characteristics, $\vec{y}$ is a reaction of the model to the test signal, $\vec{y}^*$ is a reaction of the object to the same test signal.

For the fixed set of test signals the goal function is a function just of vector of the model parameters $\vec{\beta}$ and looks as $Q(\vec{\beta}) = \sum_i \left| y_i - y_i^* \right|^2$. So, if we have the minimum of the function $Q(\vec{\beta})$ we will obtain the values of the vector of the model parameters $\vec{\beta}$ when deviation of the model behavior on given test signal set from behavior of the modeled object using the criterion $E(\vec{y}, \vec{y}^*)$ is minimal.

Verification of obtained macromodeling results of reactions to the test signals comparing with data obtained experimentally can be calculated using the following formula: $\varepsilon = \sqrt{\frac{b}{a}} \cdot 100\%$,

where $a = \sum_{i=1}^{n} \left| y_i \right|^2$, $b = \sum_{i=1}^{n} \left| y_i^* - y_i \right|^2$, y_i is an actual value and y_i^* is the calculated value of the object reaction.

To obtain non-linear macromodel we must enlarge the equation (2) using the non-linear polynomial vector-function $\mathbf{\Phi}(\vec{x}^{(k)}, \vec{v}^{(k)})$ which coefficients can be found using optimization too [2,3].

During all the stages of the macromodel creation the values found at previous stages (or equal to zero) were used as a starting point.

For the given set of experimental data the following macromodel was developed:

(4) $$\begin{cases} X_1 = 0.9967 \cdot X_1 + 0.0483 \cdot X_2 - 0.171 \cdot V_1 - 0.0576 \cdot V_2; \\ X_2 = -0.0483 \cdot X_1 + 0.9967 \cdot X_2 - 0.6386 \cdot V_1 + 0.1418 \cdot V_2; \\ X_3 = 0.9913 \cdot X_3 - 0.2951 \cdot V_1 + 0.0081 \cdot V_2 + \\ \quad + 0.0006 \cdot X_3^2 + 0.0002 \cdot X_3 \cdot X_4 - 0.0002 \cdot X_4^2; \\ X_4 = 0.9814 \cdot X_4 + 0.5125 \cdot V_1 - 0.0052 \cdot V_2 - \\ \quad - 6.4609 \cdot X_3^2 + 0.0011 \cdot X_3 \cdot X_4 + 0.0009 \cdot X_4^2; \\ Y_1 = 0.0581 \cdot X_1 - 0.1834 \cdot X_2 - 2.4825 \cdot X_3 - 1.1633 \cdot X_4; \\ Y_2 = 0.0544 \cdot X_1 - 0.0569 \cdot X_2 + 1.4846 \cdot X_3 + 1.0991 \cdot X_4 + 12 \cdot V_1 \end{cases}$$

The macromodel (4) reproduces the transient characteristics obtained experimentally with accuracy 5,8% as it is shown in the Fig. 2 (experimental characteristics are depicted using the solid line and characteristics obtained by the macromodel test– using the dashed line).

For the further evaluation of the macromodels efficiency the mathematical models used for the electromechanical systems modeling and built into such programs as ATP, EMTP, MATLAB/Simulink were analyzed. MATLAB /Simulink is the most effective tool intended for simulation of complex electric and electromechanical systems, it contains all required models and toolboxes needed for the simulation of non-stationary processes in electromechanical systems [1]. Creation of the asynchronous machine model in

Simulink using its traditional equations usually is not complex process.

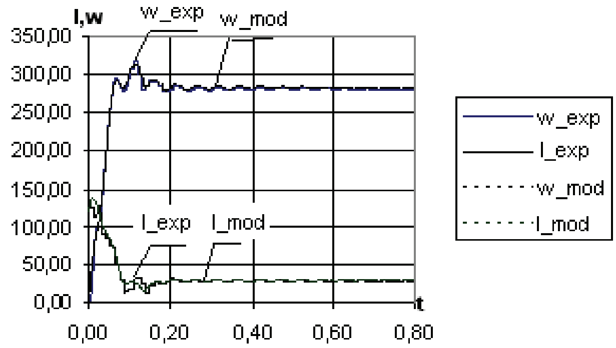

Fig. 2 Time dependencies of transient characteristics obtained experimentally and using macromodel in p.u. values

Let us analyze the efficiency of the *MATLAB/Simulink* asynchronous motor mathematical models in comparing with developed macromodel using the model *Asynchronous Machine* from *SimPowerSystems Blockset*. Parameters of the equivalent circuits were found out using the nameplate data of the analyzed asynchronous motor. As a result the simulation model with the same qualitative characteristics of transient processes as for the developed macromodel was obtained.

For the quantative analysis the mathematical model of asynchronous motor of 4AX80B2У3 type (in Ukrainian classification) using MathCAD 14 based on T-shape equivalent circuit shown in the Fig. 3 was created.

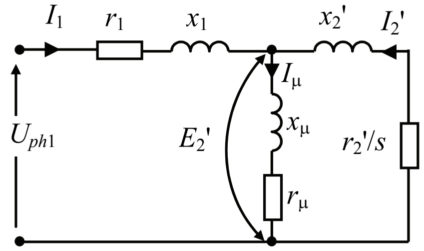

Fig.3 . T-shape equivalent circuit of one phase of the asynchronous motor

Based on the electric equilibrium equations for dynamic regimes the mathematical model (taking into account r_2'/s) was created and transient characteristics were obtained. Parameters of the equivalent circuit were found out using nameplate data:

(5) $$U_{ph1} = i_1 \cdot |z_1 + z_e| + \frac{x_1 + x_0}{\omega_1}\frac{di_1}{dt}$$

(6) $$\frac{di_1}{dt} = \frac{\omega_1}{x_1 + x_e}\left(U_{ph1} - i_1 \cdot |z_1 + z_e|\right)$$

(7) $$\frac{di_2'}{dt} = \frac{\omega_1}{x_2'}(e_1 - i_2'|z_2'|) = \frac{\omega_1}{x_2'}(U_{ph1} - i_1 \cdot |z_1| - i_2' \cdot |z_2'|)$$

(8) $$M = 3 i_2'^2 r_2' / (\omega_0 - \omega),$$

(9) $$\frac{d\omega}{dt} = \frac{M - M_c}{J_\Sigma}.$$

where U_{ph} is the phase voltage, i_1 and i_2 are currents of stator and rotor respectively, z_1, z_2 are active resistances of the stator windings, x_1, x_0 are the stator and rotor windings reactances respectively, w_0, w_1 are initial and normal frequency of the rotor rotation respectively, M and M_c are dynamic and static mechanical moments, J is a moment of inertia.

In order to analyze the macromodeling efficiency let us show the transient curves obtained using the mathematical model developed in MathCAD 14 and compare them with the transient characteristics obtained as a result of the computer experiment. Obtained curves are presented in the Fig. 4.

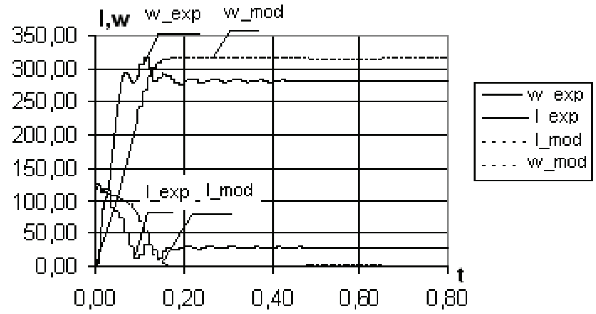

Fig.4 Time dependencies of transient characteristics obtained using MathCAD model and computer experiment presented in p.u.values

In MathCAD/14 the mathematical models based on T-shape equivalent circuits of the asynchronous motor was created and compared with the macromodel. For the previously mentioned transient characteristics their tolerance is higher than 10%.

Conclusions

Basing on results obtained using the proposed macromodel (Fig. 2) of three-phase asynchronous motor transient curves give lower tolerance (5,7%) than model obtained based on T-shape equivalent circuit in MathCAD software (Fig. 4). It will allow to improve the tolerance of transient processes calculation of electromechanical systems with asynchronous motors in their structure using their mathematical macromodels.

REFERENCES

[1] Stakhiv P., Hoholyuk O., Byczkovska-Lipińska L. Mathematical models and macromodels of electrical power transformers, *Przegląd elektrotechniczny*, 2011, №5, 163–165

[2] Kozak Yu., Melnyk B., Nadych I. Macromodelling components of electromechanical systems, *Przegląd elektrotechniczny,* 2010, №1, 112–114

[3] Kozak Yu., Melnyk B., Selepyna Yo. Accelerating of the process of discrete macromodels identification by gradual increase in their complexity, *11th International Workshop "Computational Problems of Electrical Engineering",* Lázně Kynžvart, Czech Republic, September 13-16, 2010, Pg.64

[4] Копылов И.П. Математическое моделирование электрических машин, М.: *Высшая школа*, 2001, 327с

[5] Костинюк Л.Д, Мороз В.І. Математичні та структурні моделі асинхронних двигунів, побудованих на основі однофазних заступних схем, *Вісник національного університету "Львівська політехніка" Електроенергетичні та електромеханічні системи,* 2008, № 615, С.46–50

[6] Мазуренко Л.І., Попович О.М., Гребеніков В.В., Бібік О.В., Головань І.В., Джура О.В., Шуруб Ю.В., Вербовий А.В., Романенко В.І. Електричні машини змінного струму та машинно-вентильні комплекси на їх основі, *Праці ІЕД НАНУ*, 2010, Вип. 26, С.63–72

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