Calculation of parameters of Three-Phase Induction Motor with Double Squirrel Cage with FEM 3D

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Abstract – ***The paper will be presented part of a research done over the model of three-phase induction motor with double squirrel cage. Described are methods for determining the parameters, and the emphasis is on the calculation using the three-dimensional magnetic field is obtained by the method of finite elements in the 3D domain. Made more calculations as follows: the equivalent inductance of the machine depending on the load currents and angular position of the rotor relative to the stator, and calculating their leakage reactance of certain parts of the machine as well as the calculation of the electromagnetic torque. The obtained results will be presented in tables and graphics.***

Keywords – ***Three-Phase induction motor with double squirrel cage, FEM 3D, electromagnetic analysis, Maxwell 14- 3D Design.***

I. INTRODUCTION

There are few determination methods for parameter for induction motor with double cage and they are:

- Classical (analytics) methods for determination of the parameters. Under these methods that are given in every vocational literature that is used for research and designing of electrical machines, parameter are determine bulky empirical equations obtained with idealization of electromagnetic processes in the engine. The calculations are not simple and the calculation itself is linked to the need for reading of a number of basic data diagrams and charts obtained by experimental measurements.
- Modern (numerical) methods for determination of parameters. Determination of the parameters of the motor with computer and adequate software package that in the basic has algorithms that can calculate certain characteristic magnetic magnitudes of the electric machine.
- Experimental determination of parameters. Is done in laboratory for testing of electric machines and can be done true indirect and direct method. This kind of determination required equipped laboratory and adequate machine that will be tested. In addition, the possibility to make a mistake in measuring and read is greater. Therefore numerical methods stand out as the most precise determination of the parameters.

As research subjects from which a portion is presented in the labor below, is selected three-phase asynchronous motor [1] with double cage and with the following nominal data:

$P_n = 3.5kW, U_n = 240V, f = 50Hz$

$2p = 4, \cos\varphi = 0.85, \eta = 84\%,$ and Δ winding connection. Implementted's software package Ansoft Maxwell 14. 3D Design, which is made in a suitable model of the engine which is subject in this research and is obtained allocation of the magnetic field. Knowing the allocation of the magnetic field in three dimensional domain of induction motor with double cage, or the results of the magnetic vector potential in all nodes of a network of finite elements are sufficient for determining the parameters.

II. CALCULATION OF EQUIVALENT INDUCTANCE DEPENDING OF CURRENTS LOAD AND ROTOR ANGULAR POSITIONS IN RELATION TO THE STATOR

The equivalent inductance between the stator and rotor is possible to determine if there are data for value of total co-energy W of magnetic field, which accumulate in the air gapin the induction motor with double cage. The term which is calculated co-energy of magnetic field, according to [1], [8], [9] by volume vector of current density J and the value of the magnetic vector potential A, in air gap of the engine, is given by:

$$W = \frac{1}{2}\int_{v} (\mathrm{J}\cdot\mathrm{A})dV \qquad (1)$$

The expression (1) is compared with known ratios to calculate the basic magnetic flux according to [1], [8], [9], which is determined by the density of the current loads of windings and magnetic vector potential is given with:

$$\Psi = \frac{1}{I}\int_{v} (\mathrm{J}\cdot\mathrm{A})dV \qquad (2)$$

After completion of processing, solving the relevant equations that equating model of induction motor with double cage into databases of outputs are available with the values of the magnetic vector potential, obtained after several iterative repetitions. When substituting the expression (2), in the expression (1) to calculate the total air gap co-energy is used expression:

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$$W = \frac{1}{2}\Psi \cdot I \tag{3}$$

Because during a simulation to calculate the magnetic vector potential, excited current in the engine is kept constant, the expression of the basic magnetic flux can be written as the product of inductance and current:

$$\Psi = LI \tag{4}$$

According to the last expression (4), determining the equivalent inductance of the induction motor with a double cage is:

$$L = \frac{2W}{I^2} = \frac{\Psi}{I} \tag{5}$$

The total magnetic flux in the air gap of the induction motor with a double cage Ψ_δ, depends on the currents of the motor load and position of the rotor relative to the magnetic axis of the stator. Therefore the value of the equivalent inductance of the motor depends on the same size, and that the expression that is calculated is given with:

$$L_\delta = \frac{\Psi_\delta(\theta, I)}{I} \tag{6}$$

The determination of the basic magnetic flux in the air gap of the induction motor with double cage in Maxwell 14 - 3D Design, has already been done and it made more simulations for analysis of electromagnetic processes in the engine. It is received the distribution of basic magnetic flux in the air gap of the induction motor with double cage for seven arbitrary operating points of the engine. The simulations were performed at rotation of the rotor relative magnetic axis to the stator from 0° to 90° mechanical, with mechanical step 7.5° of mechanical rotation. That is, for each operating point of making a pole twist of four full asynchronous motor with double cage. Term of points under which is made simulation electromagnetic analysis is given below:

Table 1 Description of operating points at which it is made simulation analysis

Work point	$s(\%)$	$P_1[\mathrm{W}]$	$P_2[\mathrm{W}]$	$I_1[\mathrm{A}]$	$I_D[\mathrm{A}]$	$I_G[\mathrm{A}]$	$\cos\varphi$	$\eta(\%)$
1.	0.1	416	33	2.11	4.90	1.84	0.27	7.8
2.	0.7	120	804	2.69	33.9	12.8	0.62	66
3.	1.3	196	152	3.55	62.1	23.4	0.76	75
4.	1.9	268	219	4.51	89.2	33.8	0.82	81
5.	2.5	336	279	5.48	115	43.9	0.85	83
6.	3.3	419	349	6.74	147	56.7	0.86	83
7.	3.7	456	380	7.35	162	62.9	0.86	83

In Table 1 are given values for each operating point of: overrun percentage $s(\%)$, the power that the engine taken from the network $P_1[\mathrm{W}]$, the power that as useful develops axle $P_2[\mathrm{W}]$, stator coil currents $I_1[\mathrm{A}]$, currents that flow in the lower $I_D[\mathrm{A}]$ and currents that flow in upper cage rotor $I_G[\mathrm{A}]$, power factor and coefficient of efficiency $\eta(\%)$.

It notes that five points for load below headline, point number six is at rated load and point seven is greater than the nominal load. In each analysis, each set point change is required loads in the model engine for each position of the rotor relative to the stator. The time required for the analysis of each operating mode is 9h 9min 43sek. In this network the generated finite element is identical for each individual computation [1].

The results of calculation are stored in a table (because of the sheer volume is represented), from which follows the graphic interpretation of the dependence of the equivalent inductance of the motor in function of the angular position of the rotor relative to the magnetic axis of the stator, for all seven examined setpoints and it is represented in Figure 1. Figure 2 shows the dependence of the equivalent inductance of the induction motor with double cage of load currents for each of the seven examined set points at constant position of the rotor relative to the stator magnetic axis.

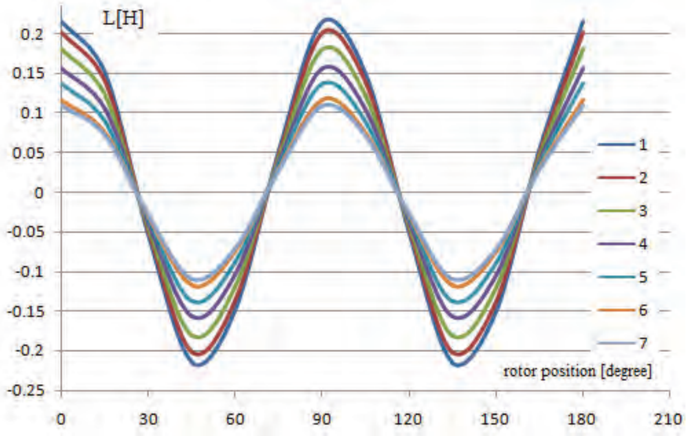

Fig.1. Equivalent inductance of air gap of induction motor with double cage at different angular positions of the rotor relative to the stator magnetic axis

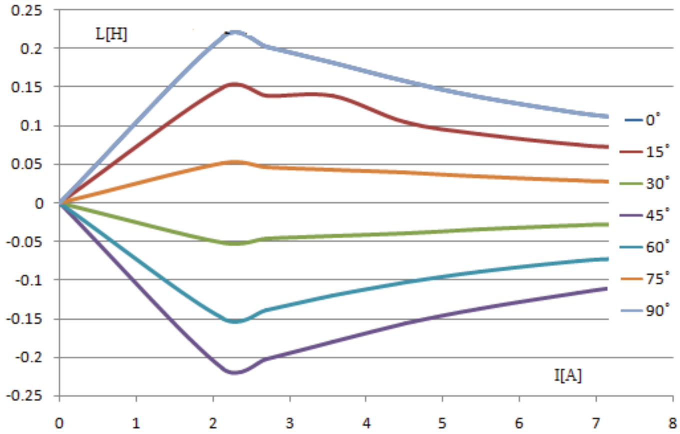

Fig. 2. Equivalent inductance of the induction motor with double cage for various load currents and constant position of the rotor relative to the stator magnetic axis

From Figure 1, it may be noted that the equivalent inductance monitors changes of magnetic flux in the air gap, and that at constant current loads have the greatest value when the rotor is facing with its magnetic axis. In particular rotation of rotor, the inductance value falls close to zero when the rotor act de magnetization or reaches a maximum value when the directions of exited flux of the stator and rotor coincide. Also, the feature is noted that the change in the equivalent inductance is greater when burdens stator coils are smaller and the engine operates in the linear part of the characteristic of magnetization. From Figure 2, it may be noted that the equivalent inductance less change with increasing load, so that in loads that are close to the nominal changes are more pronounced in the function of the position of the rotor. The impact of the load on the value of the equivalent inductance is minimized because of saturation of the magnetic circuit of stator and rotor.

III. CALCULATION OF THE LEAKAGE REACTANCE

Own reactance of one phase of stator coil of induction motor with double cage is determined by the value of the magnetic vector potential in the three-dimensional domain of the engine when the nominal phase current flowing through only one phase winding example: phase A. Screening is the value of the total magnetic flux in the air gap to the engine under one magnetic pole. Use the value of the magnetic flux at the rated load which is: $\Psi_{AA} = 0.792\,\mathrm{Vs}$, accordingly own inductance of stator phase is: $L_{AA} = \Psi_{AA} / I_{1nf} = 0.117\,\mathrm{H}$, while the stator reactance is: $X_{AA} = \omega L_{AA} = 36.74\,\Omega$.

Leakage reactance of stator coil is the sum of the reactance of channel dissipation of magnetic flux in the active part of the conductor and the reactance of leakage magnetic flux in the top links:

$$X_{\sigma 1} = X_{k1} + X_{cv1} \tag{7}$$

In determining the reactance of break stator coil, according to the analytical empirical equations, the expression (7) is complemented by another set to leakage reactance of differential leakage up. It is the result of the existence of harmonics in the induced voltage of the stator coil. The magnetic flux distribution of mainly depends on the dimensions of the channels of stator magnetic circuit and performance of the coil. In determining the leakage reactance of the stator in the paper, the influence of one of the differential dissolution is taken into account in the scattered flux channels and one part of break flux in the frontal connections.

In this research, calculations are made using the values of leakage flux previously defined as: at rated load of the induction motor with double cage, leakage channel magnetic flux is $\sum \Delta\Psi_{k1} = 0.0335\,\mathrm{Vs}$. Inductance of the channel dispersed magnetic flux has a value: $L_{k1} = 0.00496\,\mathrm{H}$. Reactance of channel dissipation of magnetic flux can be calculated from the known expression: $X_{k1} = \omega L_{k1} = 1.56\,\Omega$.

To determine the reactance of break magnetic flux in front connections use the result given earlier. Analogously to the inductance of the prior break flux in the frontal connection and reactance effect: $L_{k1} = \dfrac{\sum \Delta\Psi_{cv1}}{I_{1nf}} = 0.00611\,\mathrm{H}$. The total value of the reactance break stator coil is: $X_{\sigma 1} = X_{k1} + X_{cv1} = 3.48\,\Omega$.

Leakage reactance of the lower cage rotor $X_{\sigma d}$, is a sum of break reactance of the active part of the lower cage (the area covered by the rods of the lower cage) - and break reactance of the front links (ring of the lower cage) - $X_{\sigma ds}$, and leakage reactance from frontal connections (ring of the lower cage) - $X_{\sigma dp}$. For calculating of the leakage reactance of the active part of the lower cage of the rotor is using the value of leakage magnetic fluxion the rotor channels in the lower cage $\sum \Delta\Psi_{2kd} = 2.57\cdot 10^{-4}\,\mathrm{Vs}$. The total value of leakage reactance of lower cage of the rotor is given by: $X_{\sigma dk} = X_{\sigma ds} + X_{\sigma dp} = 0.000589\,\Omega$. The total value of leakage reactance of the lower cage of the rotor toward stator is: $X_{\sigma dk}{}' = X_{\sigma dk} k_{12} = 9.8\,\Omega$.

For determining of the leakage reactance of the upper cage of the rotor is conducted identical procedure as in determining the leakage reactance of the lower cage. Are used already defined values of leakage magnetic flux of the active part of the upper cage (channels accommodating sticks) and magnetic flux in the ring (front link) which makes electrical connection of the active parts of the cage. Similar to the lower cage and in this case, the total leakage reactance in the upper cage $X_{\sigma g}$, is a sum of leakage reactance of the rods of the upper cage $X_{\sigma gs}$ and ring $X_{\sigma gp}$. Of the total leakage magnetic flux of channel from the upper cage which amounts $\sum \Delta\Psi_{2kg} = 0.26\cdot 10^{-5}\,\mathrm{Vs}$, are determined inductance and leakage reactance of the active part of the upper cage: $\begin{array}{l} L_{\sigma gs} = \Delta\psi_{2kg} / I_{2gk} = 0.045\cdot 10^{-6}\,\mathrm{H}, \\ X_{\sigma gs} = \omega L_{\sigma gs} = 0.0000144\,\Omega \end{array}$.

In the determination break reactance of the ring of upper cage rotor is used break flux in the ring of the upper cage $\sum \Delta\Psi_{2pg} = 0.76\cdot 10^{-5}\,\mathrm{Vs}$, and analog in the sticks calculation is based on: $L_{\sigma gp} = 0.000000133\,\mathrm{H}$, $X_{\sigma gp} = \omega L_{\sigma gp} = 0.0000421\,\Omega$. Leakage reactance of the upper cage of the rotor is given by: $X_{\sigma gk} = X_{\sigma gs} + X_{\sigma gp} = 0.0000568\,\Omega$ and its reduced value to the stator in: $X_{\sigma gk}{}' = X_{\sigma gk} k_{12} = 0.945\,\Omega$.

IV. STATIC PROPERTIES OF THE ELECTROMAGNETIC TORQUE OF THREE-PHASE ASYNCHRONOUS MOTOR WITH DOUBLE CAGE

Determining the static characteristic of the electromagnetic torque of induction motor with double cage is one of the most important goals in such research. Knowledge of this feature is particularly important because it provides a representation of the behavior of the engine in various operating modes. Determining the static torque of the engine with applied software package Maxwell 14 - 3D Design, is easy and fully automatic, and is performed before setting the parameter to determine the static torque in terms of before processing.

The calculations performed by the program in a way that uses the values of the magnetic vector potential in this specific case in the area covered in the air gap of the motor. Because complete electromagnetic analysis is made of seven different operating points, which in the previous chapters were given values of magnetic flux characteristic set points at different de-phased of the rotor relative to the stator, in this section will be determined the static characteristic of the electromagnetic torque for them seven set points, depending on the angular position of the rotor in the range of $(0^0$ - $180^0)$ electric. The actual determination of the torque which develops induction motor with double cage in Maxwell 14 - 3D Design, is based on the principle of virtual work, by applying the energy method, using already defined basic values of magnetic flux in the air gap of the motor.

Processing and obtaining the value of the electromagnetic torque is through the values of the magnetic vector potential in all the nodes of the three-dimensional domain quasi static model of asynchronous motor A_x, A_y, A_z, in particular given values of the currents of the load through the coils and a defined step of turning the rotor relative to the stator $\Delta\theta$. The accuracy of the determined value of the static electromagnetic point directly connected on one side to the size of the step that a change in the currents of the load on the engine and change the angle (position which covers the rotor relative to the stator), and on the other side with precision determination of the magnetic vector potential. The complete analysis is in direct relation to the accuracy of the mathematical model adaptation engine with real bike.

Data on the value of the electromagnetic torque are render the characteristics of the electromagnetic torque for various positions of the rotor under certain constant currents of load in stator coil and are presented in Figure 3. From the characteristic of Figure 3, under nominal current of the load on the induction motor with double cage (it's operating point marked with number 6) can be seen value of the electromagnetic torque $M = 23.27Nm$, under angular de-phased of the rotor relative to the stator of 15º degrees mechanical or 30º electrical. Compared with the nominal value of the analyzed time asynchronous motor with double cage obtained by analytical calculations that is $M = 23.67Nm$, it shows the great opportunity offered by the method of finite element calculation of the electromechanical characteristics of electrical machines.

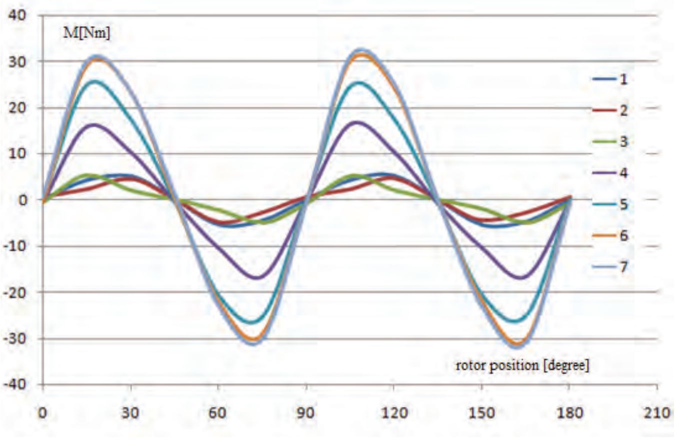

Fig.3. Characteristics of the electromagnetic torque

VI. CONCLUSION

All made calculations and simulation analyzes on the model of induction motor with double cage can be generalized and similarly be applied to any other electric machine. As a target in further research is required to develop the area transient analysis or consideration of dynamic characteristics and transient phenomena in induction motor with double cage with the method of finite elements in three dimensional domains. Generating of a mathematical model for dynamic analysis, getting the starting mechanical characteristics and optimizing the design of asynchronous motors.

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