CALCULATION OF FORCES ACTING ON BARS OF INDUCTION MACHINES

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Summary: This calculation is based on calculation of torque components of induction machines. Basic torque components are expanded, using knowledge of machine's geometry, to the periphery of machine's rotor. Using Fourier analysis of torque components it is possible to calculate forces acting on bars of the machine.

1. INTRODUCTION

One of greatest problems of large induction machines is breaking of bars of their squirrel cage windings. This problem appears at machines with the power about one thousand kilowatts and more. Besides "natural" technological problems this problem seems to be one of the limiting effects in construction of large induction machines.

Currently, this problem is being solved in the Czech Republic by cooperation of ŠKODA ELECTRIC a. s., ŠKODA VÝZKUM s. r. o. and two faculties of University of West Bohemia, Faculty of Mechanical Engineering and Faculty of Electrical Engineering. Ministry of Industry and Commerce of Czech Republic funds this research as research number 2A-2TP1/139. Currently this project is in a very early stage and as first researches are focused on calculation of torque characteristics and forces acting on bars of machine's rotor winding.

In an ideal case the induction machine should have an infinite number of slots both on stator and rotor and it should have been fed by sinusoidal voltage. Any imperfection in geometry or in feeding leads to pulsations of machine's torque. These pulsations are related with forces acting on bars of the machine. In an ideal case these forces should have sinusoidal shape, but imperfections in machine's geometry and in feeding change their shape. Now let us focus on imperfections in feeding.

2. CALCULATION PRECONDITIONS

For obtaining most accurate results it is needed to consider all effects which influence parameters of machine's equivalent circuits, namely the leakage reactance and the resistivity of machine's rotor. These parameters are affected both by the temperature in the machine and by the eddy currents which are induced by harmonic components of current which flows through bars of machine's winding.

Let us consider an induction machine with squirrel cage rotor winding which is used for traction purposes. In this case it is a traction machine with output power about 1500kW. It is possible to presume that greatest magnitude of pulsations will appear for rectangle-shaped voltage feeding. In this case it is needed to perform Fourier analysis of the voltage, select harmonic components of the voltage with greatest magnitude and consider them in further calculations.

According to calculations performed in [1] the temperature of the machine's winding has been considered as

$$t = 180°C\,. \tag{1}$$

Then the resistivity of the winding changes according to coefficient

$$k_R = 1 + \frac{1}{234{,}45 + t}\cdot\left(t - t_0\right), \tag{2}$$

where t_0 is reference temperature t_0=20°C.

The impact of eddy currents has been considered according to [2] using calculations for one-layered winding. The resistivity of the winding has to be adjusted by coefficient

$$\varphi = \xi\frac{\sinh 2\xi + \sin 2\xi}{\cosh 2\xi - \cos 2\xi}, \tag{3}$$

and the reactance by coefficient

$$\varphi_j = \xi\frac{\sinh 2\xi - \sin 2\xi}{\cosh 2\xi - \cos 2\xi}\,. \tag{4}$$

The value of variable ξ is given by relation

$$\xi = \frac{h}{a}, \tag{5}$$

where h is the height of the conductor,
and a is the depth of penetration of eddy currents for corresponding harmonic component given by,

$$a = \sqrt{\frac{2}{\nu\omega_1\gamma\mu_0}}\,, \tag{6}$$

where ν is the degree of the harmonic component,
ω_1 is the angular speed of basic harmonic,
γ is the specific electrical conductivity of copper,
and μ_0 is the permeability of vacuum.

3. CALCULATION OF TORQUE COMPONENTS AND FORCES ACTING ON BARS OF THE WINDING

Using equivalent circuit of induction machine in its Γ-shape it is possible to calculate current both in stator and in rotor winding of the machine. The torque of the machine is then according to [3]

$$M = \frac{3}{2} L_h p \Im\left\{\underline{i}_1 \underline{i}_2^*\right\}, \tag{7}$$

where i_1, i_2 are currents of stator and rotor,
p is the number of machine's poles,
L_h is the machine's magnetizing inductance.

This calculation leads to resulting time dependency of torque which includes harmonic torque pulsations. Fourier analysis of these pulsations shows that they include further harmonic components on frequencies equal to even folds of 3. The magnitude of these pulsations may be, depending on the values of equivalent circuit's parameters, up to 20% of the magnitude of machine's nominal torque.

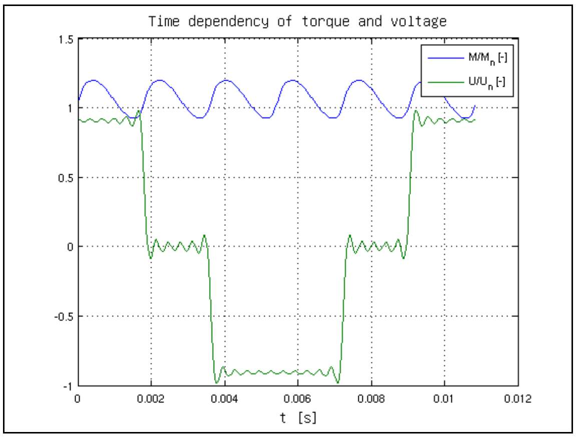

Fig. 1. Time dependency of toque and voltage

Using knowledge of machine's geometry and previous results it is possible to calculate forces acting on bars of the induction machine. In case of an ideal induction machine with infinite number of slots both of the rotor and of the stator the force acting on bars of the machine would change harmonically along the machine's rotor periphery. In this case the mean value of force acting on a bar would be equal to value which products from equally divided value of nominal torque on all bars. These preconditions lead to following expression (generally for ν-th harmonic)

$$F_{1\nu} = \frac{M_\nu}{m_2 r}, \tag{8}$$

where M_ν is the torque of ν-th harmonic,
m_2 is the number of rotor's bars,
r is the distance of the centre of the bar from the axis of the rotor.

As said before, the force acting on bar of the machine changes according to the position of the bar on the rotor and it is also time-dependent. Both dependencies are considered in following equation

$$F_{\nu t}(t) = 2F_{1t}\cos^2\left[2\pi f_n s_n t + \nu p \varphi_t (t-1) + \psi_\nu\right]. \tag{9}$$

Graphical interpretation of results is shown in figures 2 and 3.

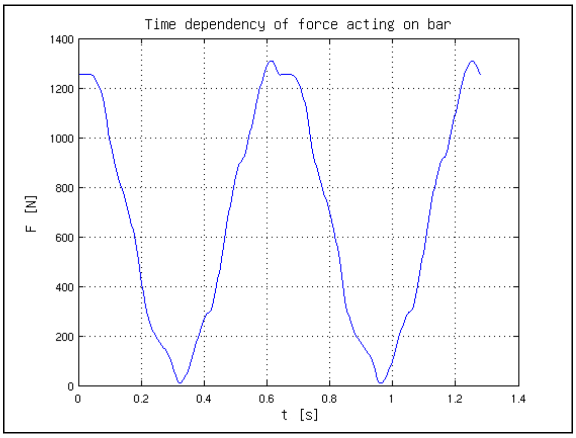

Fig. 2. Time dependency of force acting on bar

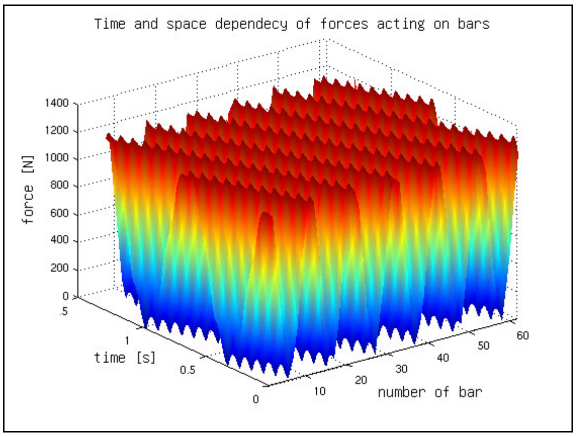

Fig. 3. Time and space dependency of force acting on bar

4. CONCLUSION

As shown in the figures, the force acting on bars changes non-harmonically hence there are certain sections with sharp changes of the force acting on nearby bars. These may cause high stresses in these bars and also the frequencies may interfere with mechanical frequencies of parts of bars between the packet of the machine and the shorting ring. Both these effect may lead to higher mechanical tension of these bars and precocious damage.

Further progress of the research will be focused on analysis of pulse width modulation and its influence on pulsations of torque. It seems that a suitable way of supplying of the machine could decrease the magnitude of torque pulsations. Together with increasing of rotor's bars' stiffness the breaking of rotor bars could be avoided or at least reduced.

Acknowledgement

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