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Computational Modelling of the Unbalanced Magnetic Pull by Finite Element Method

Martin Donát[a]*

[a]*Brno University of Technology, Faculty of Mechanical Engineering, Institute of Solid Mechanics, Mechatronics and Biomechanics, Technická 2896/2, Brno 616 69, Czech Republic*

Abstract

This paper presents a process of calculating of the unbalanced magnetic pull in the rotating electrical machines based on the electromagnetic coupled field analysis. The computational model is created in the commercial finite element software ANSYS and consists of computational model of the electrical circuit of the machine, which is directly coupled with the two-dimensional computational model of the magnetic circuit of the machine. The unbalanced magnetic pull, acting on the rotor, is calculated from results of nonlinear harmonic analysis by Maxwell stress tensor method and by Principle of virtual work. The obtained results show that both methods give identical value of unbalanced magnetic pull.

Keywords: Rotating electrical machines; Unbalanced magnetic pull; Finite element method; Maxwell stress tensor method; Principle of virtual work

Nomenclature

A_i	Area of the ring segment cross section (m^2)
L_i	ring segment inductance (H)
l_i	length of ring segment (m)
r_b	rotor bar
R_i	ring segment resistance (Ω)
s	slip of the rotor (-)
U_0	voltage source
Greek symbols	
λ_i	geometrical permeance of the ring segment cross section (-)
μ_0	permeability of air (Vs/Am)
ρ	electrical resistivity of material (Ωm)
ρ_c	electrical resistivity of ring segment material (Ωm)

* Corresponding author. Tel.: +420-721-511-230;
E-mail address: Donat.Martin@email.cz.

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1. Introduction

Rotating electrical machines have a small air gap between a rotor and a stator. Magnetic fields, operating in this air gap, induce electromagnetic forces, which act on the machine structure. Ideally, the air gap thickness is constant along a whole circumference and the electromagnetic forces cancel out each other. In fact, the air gap thickness is not constant along a whole circumference, for example due to geometric deviations of the stator and the rotor from ideal cylindrical shape, a static eccentricity or a dynamic eccentricity, therefore the electromagnetic forces do not cancel out each other and the resulting electromagnetic force is called the unbalanced magnetic pull (UMP). The UMP is composed of a radial and a tangential component. The radial component of the UMP is usually significantly larger than the tangential one. Thus the UMP acts approximately in direction of minimal air gap thickness and its magnitude depends on the air gap eccentricity. This dependence is generally nonlinear.

In the last decade, several publications, dealing with the methodology of calculation of the UMP, have been published. The computational models used in these publications can be divided in two groups. The first group are analytical computational models that are typically used in combination with the de Laval model of the rotor. Examples of the analytical computational models are shown for example in [1-3]. The advantage of these computational models is their simplicity and thus short computational time; therefore these computational models are used for study of the influence of the UMP on a stability of the rotor motion. These computational models do not include some phenomena that can significantly affect the magnitude of the UMP, for example the effect of slot harmonics and saturation effect of a ferromagnetic core of rotor and stator windings. The second group are complex computational models where the computational model of the magnetic circuit of the machine and the computational model of the electrical circuits of the machine are coupled directly together and solved simultaneously by the finite element method. These computational models allow to include a wide range of the effects, not only the slot harmonics effect and the effect of saturation but also losses caused by eddy currents etc. The disadvantage of these computational models is high demands on computing power; therefore these computational models began to be used in the last few years. Examples of the finite element computational models of the UMP are show for example in [3] and [4]. These authors are from the Department of Electrical Engineering at Helsinki University of Technology and for calculating of the UMP they used special software FCSMEK, which was developed in this Department.

The aim of this study is to create the finite element computational model of the cage induction motor, in the commercial software ANSYS, which allows to study the influence of different types of the air gap eccentricity on the UMP.

2. Methods

The ANSYS software enables a direct coupling between the electrical circuit model and the magnetic circuit model of the machine.

2.1. Magnetic circuit model of the machine

It is assumed that the magnetic field inside the machine is constant in z-direction; therefore two-dimensional model of the magnetic circuit of the machine was used, as Figure 1 shows. The magnetic circuit of the machine was discretized by PLANE 53 element. The rotor was rotated between the simulations; therefore the finite element meshes of the rotor and the stator were generated separately. On the outer diameter of the rotor winding and on the inner diameter of the stator winding the same number of nodes was generated. The air gap between the rotor and the stator was divided into three parts. The part of the air gap adjacent to the rotor was discretized with the rotor, the part of the air gap adjacent to the stator was discretized with the stator and both finite element mashes were connected by one layer of elements that have been generated directly. Figure 2 shows a detail of the mesh of the air gap. Material properties of the iron core were described by B-H curve. The material properties of the other parts of the model were described by relative permeability and resistivity of the stator windings and the rotor bars.

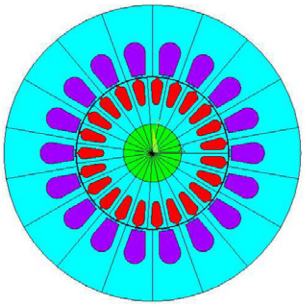

Fig. 1. Model of the magnetic circuit of the machine

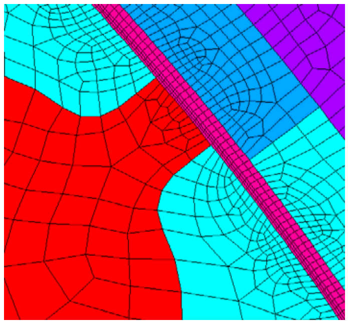

Fig. 2. Detail of the air gap mesh

2.2. Electrical circuit model of the machine

The electrical circuit model of the machine is composed of the electrical circuit of the rotor and the electrical circuit of the stator. The electrical circuits were created by CIRCU124 elements. The electrical circuit of the stator is shown in Figure 3. This circuit consists of three phase AC voltage source - U_0, connected in the star, and stranded coils. Each stranded coil represents one slot of the stator winding.

The electrical circuit of the rotor consists of massive conductors, which represents the rotor bars – r_b, connected by shorting rings. Elements R_i represent the ring segment resistances and elements L_i represent the ring segment inductances. A part of the rotor circuit model is in Figure 4. According to [6], the ring segment resistance and the ring segment inductance can be calculated from equations (1) and (2).

$$R_i = \rho_c l_i / A_i \quad (1)$$

$$L_i = \mu_0 l_i \lambda_i \quad (2)$$

Where ρ_c is the electrical resistivity of the ring segment, l_i is the length of the ring segment, A_i is the area of the ring segment cross section, μ_0 is the permeability of air and λ_i is the geometrical permeance of ring segment.

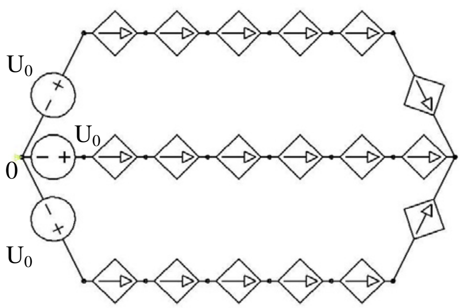

Fig. 3. The electrical circuit model of the stator

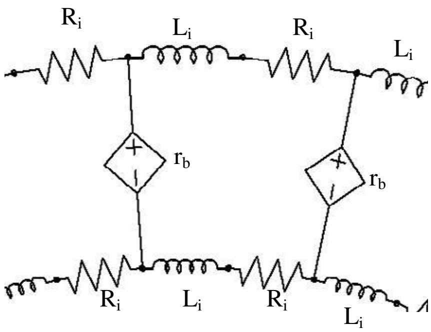

Fig. 4. Part of the electrical circuit model of the rotor

2.3. Coupling of the magnetic circuit model with the electrical circuit model

The ANSYS software allows a direct coupling between the electrical circuit model and the magnetic circuit model of the machine. The elements that represent the stranded coils in the stator circuit model are determined by three nodes, as shown in Figure 5. The nodes I and J are the nodes of electrical circuit and have a degree of freedom of voltage. The node K is any node of the area that represents slot of stator winding in the magnetic circuit model. According to [7], the node K has the degrees of freedom CURR and EMF. CURR represents the current flowing per turn of the coil and EMF represents the potential drop across the coil terminals. Since the coil has only one unique current and one potential drop across the coil terminals, a single value for each of these degrees of freedom unknowns is required. Therefore, all nodes of the coil region in the magnetic circuit model must be coupled in the CURR degree of freedom and EMF degree of freedom. The same procedure was used for coupling the massive conductors of the rotor circuit model with the rotor bars in the magnetic circuit model.

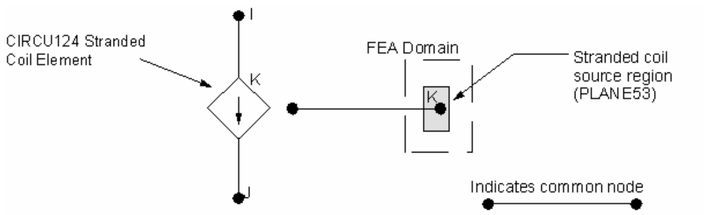

Fig. 5. Principle of coupling [7]

2.4. Calculation of UMP

UMP is the resultant of electromagnetic forces acting on the rotor of the machine. Ansys software allows to calculate the electromagnetic forces acting on the rotor by Maxwell stress tensor method or by Principle of virtual work. Both methods were used in this paper.

Application of Maxwell stress tensor method in Ansys software requires designation of Maxwell surface on which the electromagnetic force distribution is to be calculated. In this case is that surface boundary between the rotor and the air gap. Application of Principle of virtual work in Ansys software requires prescribing virtual displacements equal to 1 at all nodes of the rotor and virtual displacements equal to 0 at all nodes of the air gap.

2.5. Boundary conditions

A zero conductor, in the computational model of the electrical circuit of the stator, was modeled by prescribing zero voltage to the node 0, see Figure 3.

In order to ensure the convergence of the solution of the magnetic vector potentials, enclosed surrounding area along the magnetic circuit model must be created. This enclosed surrounding area was modeled by INFIN110 elements, as shown in Figure 6.

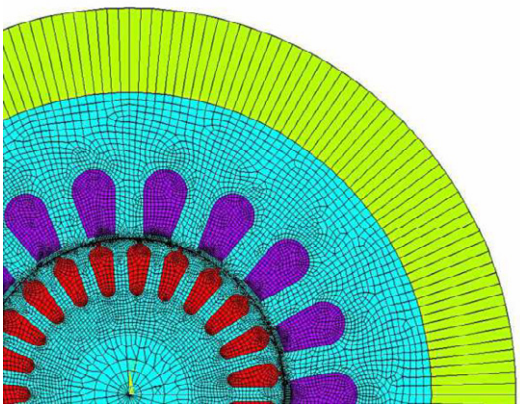

Fig. 6. Magnetic circuit model with enclosed surroundings area

3. Results

The cage induction motor with eccentric rotor was considered, see Figure 7. The influence of the air gap eccentricity on the UMP acting on the rotor of the three phase cage induction motor was studied by nonlinear harmonic analysis. In order to consider the relative motion between the stator and the rotor for fixed split *s*, the rotor can be treated as stationary, and the resistivity of rotor bars and end rings has to be scaled to ρ/s, as it is written in [8]. Due to consider the slot harmonics effect, UMP was calculated in ten different positions of the rotor bars due to the stator slots for each value of air gap eccentricity, as shown in Figure 8. The parameters of the studied induction motor are shown in Table I.

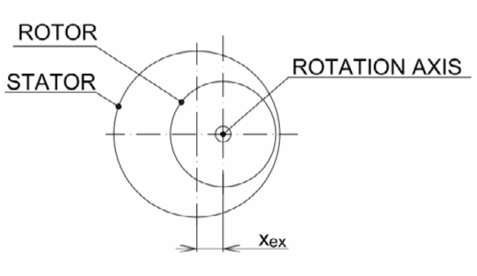

Fig. 7. Type of air gap eccentricity

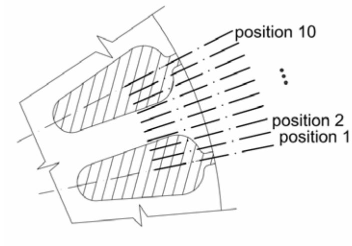

Fig.8. Rotor positions

Table 1. Parameters of cage induction motor

Item	Value	Unit
Rated power	1.1	kW
Rated line voltage	230	V
Supply frequency	50	Hz
Rated speed	2845	rpm
Number of stator slots	18	-
Number of rotor slots	23	-
Number of pole pairs	1	-
Number of turns of stator coils	83	-
Stator outer diameter	62.5	mm
Stator inner diameter	32.25	mm
Air gap thickness	0.25	mm
Stator core length	74	mm
Connection of stator coils	star	-

Figures 9. - 11. shows a dependence of UMP on the position angle for three values of the rotor eccentricity x_{ex}=0.01, 0.06 and 0.12mm. It can be seen that if the rotor eccentricity is small the dependence of UMP on the position angle of the rotor is approximately sinusoidal. Increasing of the rotor eccentricity leads to increasing of the magnitude of UMP and the effect of saturation affects strongly the dependence of UMP on the position angle of the rotor.

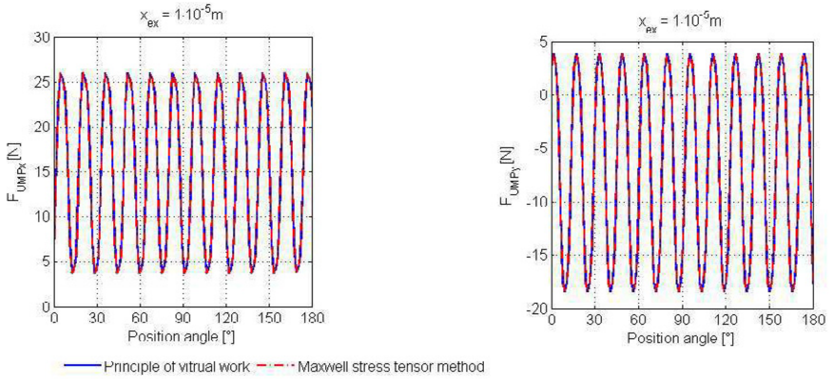

Fig. 9. UMP as a function of the position angle of the rotor, xex=1·10-5m

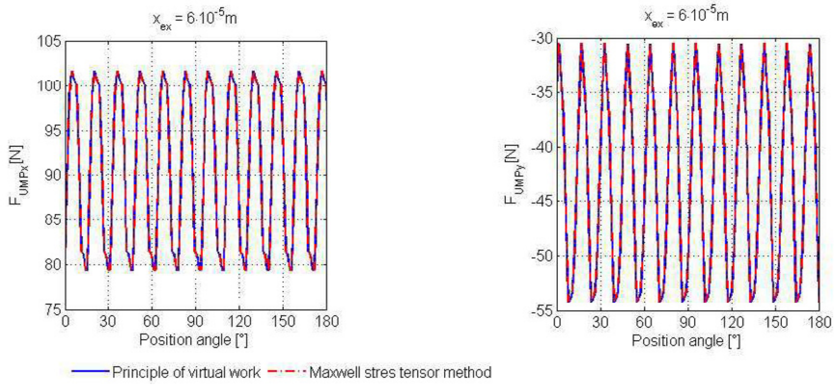

Fig. 10. UMP as a function of the position angle of the rotor, xex=6·10-5m

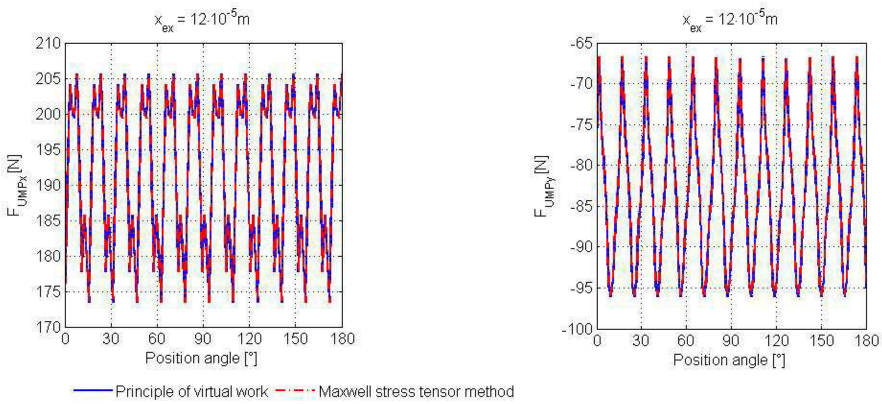

Fig. 11. UMP as a function of the position angle of the rotor, xex=12·10-5m

4. Conclusion

An efficient way to assess the influence of the air gap eccentricity on UMP, based on electromagnetic coupled field analysis in Ansys software, has been presented. The UMP acting on rotor was calculated by Principle of virtual works and by Maxwell stress tensor method. The obtained results show that both methods give identical value of UMP for different value of air gap eccentricity and we can also see that the saturation effect of ferromagnetic core affects the UMP amplitude at higher value of air gap eccentricity

The next step will be to couple this computational model with the structural model of the rotor and examining the influence of the air gap eccentricity on the dynamic behavior of the rotor of the rotating electrical machine.

Acknowledgement

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