Comparative Analysis of Spatial-Time Harmonics of Radial Forces in the Multi-Phase Synchronous Reluctance Machines of Three- Six- and Nine- Phase Winding

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The paper deals with analysis of radial forces in the multi-phase synchronous reluctance machines (SynRM). SynRM of three-, six- and nine-phase windings were studied. The field models were developed to determine normal and tangential components of magnetic flux density vector in the air-gap of the studied machines. The selected research results have been presented and discussed.

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I Introduction

Thanks to the many advantages, among others their fault tolerance as well as reduced cost of power electronic systems, a dynamic growth in interest in multiphase electric machines can be observed [2]-[4]. The paper focusses on analysis of the radial forces in the synchronous reluctance machines (SynRM) of multi-phase windings. The radial forces considered in the paper were obtained by calculating distribution of the normal component B_n and the tangential component B_t of the magnetic flux density vector. Three synchronous reluctance machines of three-, six- and nine-phase windings have been studied.

II Magnetic forces in synrm

The most important parameter derived from the forces present in an electrical machine is of course the electromagnetic torque. Considering radial and axial components of Maxwell stress tensor the radial and axial forces can be determined as well. Assuming planar symmetry of the magnetic field in the machine the axial forces are neglected, which is a common approach in analysis of electrical machines. Considering the radial forces the "local" character of this forces should be emphasized. When machines has symmetrical winding and no eccentricity the global force acting on the rotor (expressed by integral of radial component of Maxell stress tensor over air-gap circumference of is equal to 0. Figure 1 shows the components of the magnetic flux density in the machine [1].

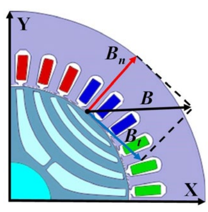

Figure 1: The components of magnetic flux density in the machine

For the analysis of the radial forces in electrical machine the distribution of tangential and radial components of the Maxwell stress tensor must be determined by means of distribution of radial B_n and tangential components of the magnetic flux density in the air-gap [1]:

$$\sigma_n = \frac{B_n^2 - B_t^2}{2\mu_0} \tag{1}$$

$$\sigma_t = \frac{B_n - B_t}{\mu_0} \tag{2}$$

where: σ_n – stress in the normal axis, σ_t – stress in the tangential axis, B_n – radial component of the magnetic flux density, B_t – tangential component of the magnetic flux density vector, μ_0 – permeability of the vacuum.

III Spatial-time harmonics

In order to comprehensively analyse the radial forces occurring in the air gap of an electric machine, it is necessary to study their spatial-time harmonics. Spatial harmonics refers to discussed above "local" character of radial forces along circumference of the air gap. In other words, with their help it is possible to observe the distribution of radial forces on the circumference of the machine within selected time instant. The time harmonics, on the other hand, show the action of the resulting stresses on a given area of the machine over the course of an assumed time. So, by analogy, it is possible to study the forces acting on a presumed area (slots, stator tooth, or rotor) in time [1]. Figure 2 shows a graphical interpretation of the spatial-time harmonic analysis.

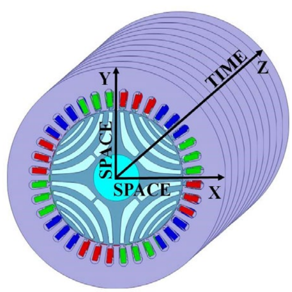

Figure 2: Graphical interpretation of the spatial-time character of radial forces

According to the graphic above, a single XY plane determines the spatial harmonics along the perimeter of the magnetic gap. In contrast, each successive layer in the Z-axis represents the next time step and thus affects the time harmonics.

IV Studied configurations

To demonstrate the effect of the number of phases on the radial forces SynRM machine, the authors proposed 3 winding configurations of three-, six- and nine-phases, respectively. In the developed field models of studied machines the planar symmetry of the magnetic field has been assumed. All models have the same geometry of the core and differ only in number of phases of the winding. The three- and nine-phase windings are single layer, while six-phase machine has double layer winding. The operating point, in term of output torque value as well torque angle are kept the same across studied variants to make feasible direct comparison of radial forces. Figure 3 shows the tested configurations of the SynRM motor models [2].

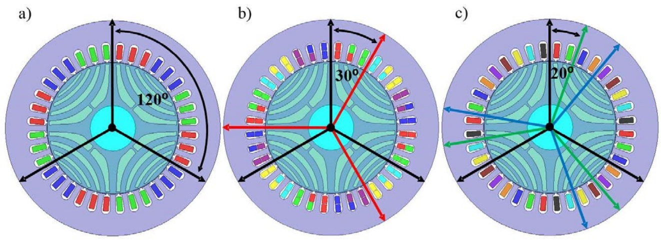

Figure 3: Model configurations: a) three-phase, b) six-phase, c) nine-phase

The phase vector diagrams of studied SynRMs are indicated in the figure above. The analysed multi-phase windings are asymmetric systems [2]. This means that the vectors cannot duplicate in the counterphase (they cannot repeat for a given vector + 180^0). Asymmetric multi-phase systems for integer value of m/3=k can be presented by k three-phase systems shifted in phase by:

$$\theta = \frac{\pi}{m} \tag{3}$$

where θ – phase angle of the three-phase systems forming multiphase system, m – number of phases.

From this, it can be deduced that a six-phase system can be formed by two three-phase systems shifted by 30^0 while a nine -phase system of three three-phase systems shifted by 20^0[3].

V Results

When studying radial forces occurring in an air gap, one can find similarities to the analysis of relativistic considerations in the context of time dilation. By analogy with a moving and stationary observer, we can relate to a stationary stator and a moving rotor. This fact makes it possible to observe the same radial forces in two ways, depending on which frame of reference we are in. Figure 4 shows the differences in the perception of radial forces depending on the reference system.

a) b)

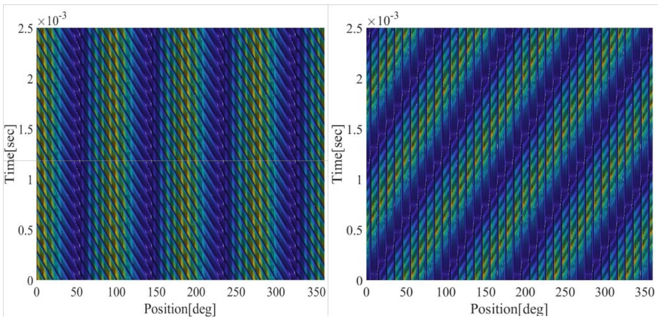

Figure 4: Differences in the perception of radial forces depending on the reference point: a) rotor reference, b) stator reference

Fig. 4(a) shows the radial forces seen from the perspective of observer on a moving rotor which maintains time invariant stresses while changing position of the slots in time. On the other hand, Fig. 4(b) shows the same radial forces seen from the perspective a stationary stator which shows the stress pulsations of the individual slots resulting from rotor rotation.

Based on Figure 2, a spatial-time study of the stresses occurring in the air gap was carried out. Analogous analyses were conducted for the 3 winding variants, taking into account the reference of the observation point (rotor and stator) and distinguishing between normal and tangential stresses. Figure 5 shows a comparison of the spatial-time distribution of the normal stresses for the 3-phase and 9-phase variants observed in a stationary reference frame linked with stator of the machine.

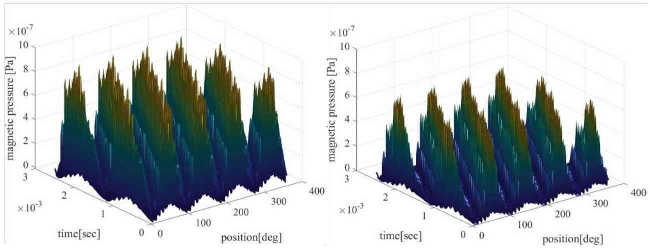

Figure 5: Spatial-time characteristics of magnetic stresses: a) three-phase winding, b) nine-phase winding

Based on the data in Figure 5, the multi-phase variants are compared. Figure 6 shows the difference between the reference 3 phase winding and the 6 and 9 phase windings.

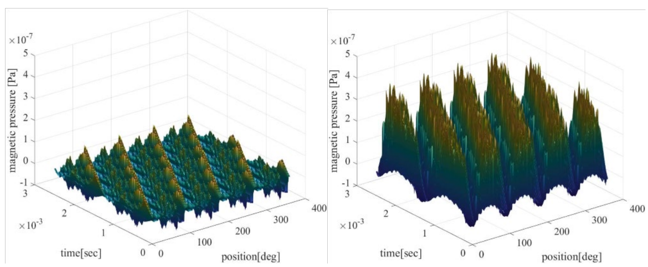

Figure 6: Magnetic stress difference with respect to three-phase winding: a) for six-phase winding, b) for nine-phase winding

As can be seen above, increasing the number of phases significantly reduces the radial forces in the air gap (see increased difference in Fig. 6(b)) by up to a third compared to the 3-phase variant.

VI Conclusions

The paper deals with analysis of radial forces in the synchronous reluctance motor (SynRM) with multiphase windings. Spatial-time analysis of magnetic stresses was carried out for tree- six- and 9-phase windings.

The detailed description of the approach including implemented analysis of spatial-time harmonics will be presented during the conference and included the scope of the extended version of the paper.

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