Research Article

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New elements within finite element modeling of magnetostriction phenomenon in BLDC motor

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Abstract: Reluctance forces are the main cause of vibration in electrical machines. The influence of magnetostriction is still the matter of controversy. In the article, program Ansys (typical for finite element method) was used to analyze stator deformation due to magnetic forces (Maxwell and magnetostriction) for the different boundaries and different methods by taking into account the windings in the mechanical model. Different parameters of numerical model are important factors affecting the level of magnetostriction deformation.

Keywords: BLDC motor, magnetic forces, Maxwell forces, magnetostriction

1 Introduction

The reluctance forces are known to be a major cause of vibrations for rotating electric machines. Magnetostriction effect is a potential cause of additional vibration and noise. The reluctance forces act in the air gap on the stator teeth, while magnetostriction acts inside the material of stator and rotor core. Both Maxwell and magnetostriction forces are a quadratic function of the flux density, and the forces operate at the same frequency. It is not possible to distinguish the origin of the vibrations by measurements. Numerical methods are used to calculate; however, there are also differences between the researchers. Belahcen used finite element method to calculate stator vibrations due to Maxwell forces and the magnetostriction for synchronous and induction machines. The magnetostriction effect significantly increases the amplitude of

vibrations at some frequencies and dump some other frequencies [1].

Delaere calculated vibrations due to magnetic forces for an synchronous and induction machines. The magnetostriction effect does not exceed the 2% level in comparison to vibrations due to Maxwell's forces.

Mohammed performed a numerical analysis of vibrations for a permanent magnet motor based on magnetic forces. The effect of inverse magnetostriction was also taken into account. The deformation of stator due to magnetomechanical effects increased about two times when compared to deformation only from Maxwell forces [2,3].

The researchers use different numerical parameters in simulation models (boundary conditions and modeling windings). Mechanical boundary conditions are applied in for nodes of the outer edge of the stator core, which are prohibited from moving in the tangential direction [1]. In the second instance, the nodes – placed in the motor base – have the zero displacement in both directions. In the third case three points on the outer edge of stator tangential movement equal to zero [3].

The material of winding consists of a composite structure formed from conductors coated with an electrical insulation. It is not fully possible to reflect the finite element in the mechanical model. The calculations are performed using two cases. In the first one, the windings are neglected [1]. In the second case, windings are taken into account using the composite material structure made of wire and insulated copper [4].

2 Modeling magnetostriction

In the modeling of magnetostriction in 3D for plane material with isotropic magnetostriction, the strains in the local frame are given by [4,5]:

$$\lambda = \begin{bmatrix} \lambda_x & 0 & 0 \\ 0 & \lambda_y & 0 \\ 0 & 0 & \lambda_z \end{bmatrix}. \quad (1)$$

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The local xy axis is rotated in such a way that the flux density vector coincides with the local axis. The magnetostrictive strain is described as [4]:

$$\lambda_x = \lambda, \quad (2)$$

$$\lambda_y = \lambda_t = -\lambda/2, \quad (3)$$

$$\lambda_z = \lambda_t = -\lambda/2, \quad (4)$$

where $\lambda = \lambda(B)$ is the magnetostrictive strain in direction of B (x direction) and λ_t magnetostrictive strain in the transverse y and z directions [4].

The property of null volume change in magnetostriction is manifested by zero value of the sum of diagonal magnetostriction strain component.

The magnetostriction curve is based on the material characteristics of the isotropic steel estimated from the experimental data of the isotropic steel (first kind of magnetostriction) [4]:

$$\lambda_x = 10^{-6} B^2, \quad (5)$$

where B is the amplitude of flux density (x direction).

The magnetostrictive strain is found using the element's flux density and the characteristic of the material. In a 2D plane strain analysis, the thickness (direction) of the material has to remain constant and an additional tensile z stress needs to be applied in order to obtain $\lambda_z = 0$ [4]. The strains in the local frame are then given by [4,5]:

$$\lambda_x = \lambda + \nu \lambda_t, \quad (6)$$

$$\lambda_y = \lambda_t + \nu \lambda_t, \quad (7)$$

$$\lambda_z = \lambda_t - \lambda_t = 0, \quad (8)$$

where $\nu = 0.3$ is mechanical Poisson modulus of the material and $\lambda_t = -\lambda/2$.

The results of 2D magnetic field simulations are used to calculate magnetostrictive strains. The magnetostriction deformation model was applied in finite element program Ansys; and in each element, a local coordinate system was rotated in such a way that the x -axis is parallel to the direction of the magnetic induction vector B and the y -axis is perpendicular. The coefficients of thermal expansion of the stator material calculated from equations (5)–(7) are:

$$\alpha_1 = 0.85 \times 10^{-6} [1/K], \quad (9)$$

$$\alpha_2 = -0.65 \times 10^{-6} [1/K]. \quad (10)$$

Temperature was applied in every element of numerical mesh in such way that the strain due to temperature in element was equal to the magnetostriction strain.

Figure 1: One quarter of FEM magnetic model.

3 Magnetic calculations

The magnetic field equations [2,3] are as follows:

$$[S][A] = [J_e], \quad (11)$$

where $[S]$ – electromagnetic stiffness matrix, $[A]$ – magnetic potential matrix, and $[J_e]$ – current density excitation matrix (the current density in the coils).

The BLDC motor (brushless direct current motor with permanent magnets) with surface-mounted magnets is

Figure 2: Magnetic flux density for selected position of the rotor.

Figure 3: Temperature distribution in stator modeling magnetostriction for one quarter of the model (K) for selected position of the rotor.

presented more detailed in ref. [6]. The magnetized Nd2Fe14B permanent magnet is attached to the surface of the rotor made of solid iron. The stator is fabricated from the limited iron (isotropic steel type EP 600-50). The permanent magnets have a cylindrical shape.

The modeling analysis is based on the 2D finite element techniques and the field is considered to be magnetostatic. The current density within the cross section of the coils is uniform and equals: $J = 3.18 \times 10^6$ [A/m²]. The residual flux density and coercive force are equal: $B_r = 1.21$ T, $H_c = -892$ kA/m. One quarter of the magnetic model is presented in Figure 1.

Figure 2 shows flux density distribution for the selected position of the rotor and corresponding distribution of the temperature – Figure 3. Figure 4 shows the radial and tangent distribution in the air gap

Figure 4: Radial and tangential flux distribution in air gap $B(T)$.

Figure 5: Maxwell forces distribution $F(N)$ for selected position of the rotor.

components of the magnetic flux in the air gap between the stator and the rotor, and Figure 5 shows reluctance force distribution in the air gap.

4 Mechanical calculations

The static deformation of the stator is governed by equations [2,3]:

$$[K][U] = [F_M] + [F_T], \quad (12)$$

where $[K]$ – element stiffness matrix, $[U]$ – nodal displacement matrix, $[F_M]$ – Maxwell forces, and $[F_T]$ – thermal

Figure 6: Numerical finite element model for mechanic analysis for area of windings applied as composite material.

Figure 7: Displacement and deformation due to magnetostriction [μm].

Figure 9: Deformation and von Mises stress distribution [MPa] due to Maxwell and magnetostriction forces.

forces (thermal strain due to magnetostriction) acting on the stator for specific rotor position α .

For predicting the deformation response due to magnetic forces in rotating electrical machines, the magnetic field and mechanical numerical 2D analysis are performed. The magnetostriction is taken into account using the analogy to the phenomenon of thermal expansion, which induces the same strain in the material as the magnetostriction does. The distribution of temperature in the element of numerical mesh is based on magnetic flux density distribution in element. The magnetic field calculation are not covered in power loss estimation, and increases in temperature due power loss are not being analyzed. Base temperature was equal to zero Kelvin. Inverse magnetostriction effect was neglected. The calculated Maxwell forces and temperature distribution are auxiliary basis for determination of the stator deformation. The stator yoke

material is modeled as isotropic. The Young's modulus value stator yoke material is equal to $E = 2 \times 10^{11} \text{ N/m}^2$, Poisson modulus $\nu = 0.3$ and density $\rho = 7,800 \text{ kg/m}^3$.

The effect of magnetostriction has been studied by comparing the calculations with magnetostriction (by applying the temperature) and calculations without magnetostriction (without applying the temperature).

Numerical computation of BLDC motor was performed to establish the effect of applied boundary conditions and winding modeling on the deformation of the stator due to magnetic forces. Different kinds of calculations were performed to check the effect of applied boundary conditions and modeling of the windings on the results (Figure 6).

In order to compare the effects of different boundary conditions, two calculations are performed. First, the outer nodes on the foundation of the motor displacement in both directions applied equals to zero [4,5]. In the second case,

Figure 8: Displacement and deformation due to Maxwell forces and magnetostriction [μm].

Figure 10: Displacement and deformation due to Maxwell forces [μm].

Figure 11: Deformation and von Mises stress distribution [MPa] due to Maxwell and magnetostriction forces.

the nodes of the outer edge of the stator core are prohibited from moving in the tangential direction [1].

Two calculations are performed to compare the effects of taking into account the windings. In the first case, the effect of windings was neglected [1]; and in the second case, the windings are composite materials. The equations used for determining Young's modulus and the density of composite material are presented in [7].

4.1 Stator deformation for different boundary conditions in mechanical model

First, displacement boundary conditions are applied to the motor's foundation. The stator deformation for the

Figure 13: Deformation and von Mises stress [MPa] due to Maxwell and magnetostriction forces.

selected rotor position for zero displacement boundary condition on the foundation of the motor without windings is shown in Figures 7–11. Applying a boundary condition on motor's foundation causes a model to deform more unsymmetrically.

Maximum value of displacement due to magnetostriction is about 10–15% of the maximum value of displacement due to Maxwell forces (Figures 7 and 10).

Results of deformation due to Maxwell's forces only (Figure 10) and total Maxwell's forces and magnetostriction (Figure 8) show that the effect is not visible. The results of von Mises stress distribution are shown in Figures 9 and 11.

It is the interesting phenomenon that the Maxwell and magnetostriction forces may subtract or add to each other and final results of calculations depend on localization in the stator core.

Figure 12: Displacement and deformation due to Maxwell and magnetostriction forces [μm].

Figure 14: Displacement and deformation due to Maxwell forces [μm].

Figure 15: Deformation and von Mises stress [MPa] due to Maxwell forces.

Figure 17: Displacement and deformation due to Maxwell forces and magnetostriction [μm].

Second, the calculations were performed with displacement boundary condition applied on the outer points of stator core. For nodes on outer edge of the stator yoke, free radial displacement and zero tangential displacement are imposed [1]. In this case, maximum value of displacement due to magnetostriction is about 10–15% of the maximum value of displacement due to Maxwell forces (Figures 12 and 14). In Figures 12–15 (windings modeling as composite material) and Figures 20–21 (variant without windings), applying a boundary condition on outer nodes causes a model to deform more symmetrically. The differences between the stator deformation, calculated in the beginning with the first kind of boundary conditions and then determined with the second boundary conditions, are presented in Figures 8 and 10 in comparison with Figures 20 and 21 (models without windings). If windings in models are treated as the

composite material, the differences within the stator deformation, computed initially with the first kind of boundary conditions and then calculated with the second boundary conditions, are presented in Figures 16 and 17 compared with Figures 12 and 14. The effect of boundary conditions has been checked. The deformation of the stator core is shown for the identical rotor position in all presented earlier Figures.

4.2 Stator deformation for different modeling windings in mechanical model

The displacements due to Maxwell and magnetostriction forces calculated for the model consist of the core and

Figure 16: Displacement and deformation due to Maxwell forces [μm].

Figure 18: Deformation and von Mises stress [MPa] due to Maxwell forces.

Figure 19: Deformation and von Mises stress [MPa] due to Maxwell and magnetostriction forces.

the casing, and windings modeled as the composite material.

In the first case, the displacement boundary conditions were applied on the motor foundation. The obtained results show that the influence of taking into account the windings on deformation due to the magnetic forces is significant (Figures 16 and 17 – the variant of allowing for the windings as composite material and Figures 8 and 10 – the simplified case without winding).

In the second case, the displacement boundary conditions on outer points of stator were applied (Figures 12 and 14). The results of calculations show that the influence of taking into consideration windings on deformation due to magnetic forces is also essential (Figures 12 and 14 – windings within composite material and Figures 20 and 21 – the model structure without

Figure 21: Displacement and deformation due to Maxwell forces [μm].

windings). The effect of windings applied as composite structure material for two different boundary conditions can be seen by comparing Figures 8 and 20 for Maxwell forces and magnetostriction and by comparing Figures 10 and 21 where the deformation due to Maxwell forces was also reduced. The results have shown that in cases of the winding, applied as composite material structure, the overall deformation due to magnetic forces was reduced. The results of von Mises stress distribution are shown in Figures 18 and 19 when the displacement boundary conditions on outer points of the stator were employed. The case for displacement boundary conditions on motor foundations is presented in Figures 13 and 15.

5 Conclusions

In this article, the authors investigate the effect of various parameters of the numerical model on the results of magnetostriction deformation in BLDC motor. The effect of the selected parameters of numerical finite element model such as boundary conditions and the way of taking into account windings in mechanical finite element model on the deformation stator core due to magnetostriction in BLDC motor were examined. The contribution of the magnetostriction to stator deformation depends on the applied boundary condition and the manner in which the windings are applied in numerical model.

Acknowledgments: The computations were performed on PL-GRID.

Figure 20: Displacement and deformation due to Maxwell and magnetostriction forces [μm].

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