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Calculation of electromagnetic component vibration of brushed direct current machines with structural units defects

Abstract. *The special features of taking into account the basic defects of brushed direct current machines influence on the vibration component of electromagnetic nature are scientifically substantiated. It is based on the use of the modern methods for magnetic field calculation. The efficiency of the use of the developed field model and the method for its parameters calculation in the analysis of the structural units typical breakages influence on the magnetic induction vector components distribution is confirmed. The dynamic eccentricity influence on the spectral distribution of forces of magnetic nature acting on the brushed direct current machine basic pole is analyzed. It enables identification of this defect in the future.*

Streszczenie. *Wzięcie pod uwagę wpływu efektów bazowych w szczotkowych silnikach prądu stałego na elektromagnetycznej natury składnik drgań jest naukowo uzasadniony. Opiera się to na użyciu nowoczesnych metod obliczania pola magnetycznego. Efektywność użycia rozwiniętego modelu polowego oraz metody obliczania parametrów w analizie uszkodzeń konstrukcyjnych wpływają na rozkład składowych wektora indukcji magnetycznej została potwierdzona. Przeanalizowano wpływ dynamicznej ekscentryczności na spektralny rozkład sił natury magnetycznej, działających na podstawowy biegun szczotkowej maszyny prądu stałego. Technika ta umożliwia identyfikację defektu w przyszłości.* ***(Obliczenie elektromagnetycznego składnika wibracji w szczotkowych maszynach prądu stałego z defektami konstrukcyjnymi)***

Keywords: brushed direct current machine, magnetic induction, vibro-exciting force, spectral characteristics.
Słowa kluczowe: szczotkowe maszyny prądu stałego. Indukcja magnetyczna, siły drganiowe, analiza spektralna

Introduction

The state of electric machines (EM) with long mean-time-between failures (LMTBF) significantly influences their reliability indices and energy efficiency during operation [1, 2]. Trustworthy and timely detection of this state and its variation due to occurrence and development of different types of structural defects directly determines the energy saving potential with regard to EM with LMTBF [3, 4]. In this respect, the determination of magnetic field parameters in EM air gap and their further analysis is the most promising trend. It provides the possibility to assess the state of the researched EM from the point of view of variation of both the general level of vibration of electromagnetic nature and its separate components.

The purpose of this paper consists in creation of a mathematical model on the basis of modern methods of field calculation. This model enables the assessment of the degree of the most common defect type influence on the value and spectral composition of vibration electromagnetic component.

Theory

On the whole, vibration in EM can be divided into four basic types as to its nature: electromagnetic vibration, mechanical vibration, aerodynamic vibration and vibration caused by operation of commutation equipment [5]. It is the research of vibration electromagnetic component that enables assessment of most defects due to their influence on the machine magnetic symmetry

Statistical data of EM failures demonstrate that a great number of them are caused by the influence of variation of the properties and parameters of the basic structural units such as electrical steel core, units of commutation and current pickup, winding, etc. This influence is manifested in the deterioration of EM reliability and accumulation of negative factors increasing the possibility of their failure [1].

This problem is especially topical for brushed direct current machines due to availability of a sliding contact characterized by naturally low reliability indices quickly changing in time.

A defect influence on the electromagnetic field distribution and variation of its parameters in EM active zone can be determined with sufficient accuracy by means of modern electromagnetic research [6]. In this case, the developed software widely used for electromagnetic field calculation allows obtaining results whose analysis makes it possible to assess the degree of structural defects influence.

When EM vibration parameters, most often its vibrovelocity ν are calculated, it is represented by the sum of components of mechanical ν_{meci} and electromagnetic ν_{emi} nature by the Cartesian coordinates $i = x,y,z$

(1) $$\nu_i = \nu_{meci} + \nu_{emi}\,.$$

For EM without structural defects values ν_{emi} is much lower than ν_{meci} and in a number of cases it is not taken into account at all. However, typical structural defects often occur locally and cause essential magnetic asymmetry with further increase of the level of vibration of electromagnetic nature. It can be additionally used as their diagnostic signs.

Let us consider the specific features of the defects from the point of view of magnetic field variation. For an EM profile 2D model magnetic tension tensor T is calculated as:

(2) $$T = \begin{bmatrix} \left(B_x^2 - \frac{1}{2}|B|^2\right) & B_x B_y \\ B_y B_x & \left(B_y^2 - \frac{1}{2}|B|^2\right) \end{bmatrix},$$

where B_x, B_y – orthogonal components of the magnetic induction vector $\overline{B}$.

To obtain the distribution of power interactions occurring due to the electromagnetic field influence the dependence of electromagnetic force density in the analyzed magnetic system is used; it is presented as [1]:

(3) $$f = \nabla T\,,$$

where ∇ – Hamilton operator.

The total electromagnetic force in the analyzed area of volume V is determined by integration of its density distribution

(4) $$\vec{F} = \int_V f \; dV\,.$$

Using Gauss theorem, expression (3) is transformed as follows:

$$\vec{F} = \int_V f \, dV = \int_V \nabla \cdot T \, dV = \oint_S T \cdot \vec{n} \, dS, \tag{5}$$

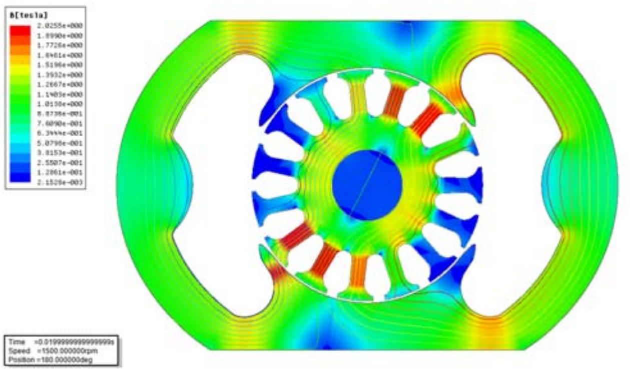
where $\vec{n}$ – a unit vector normal to contour S.

The presented expressions enable obtaining the required distributions and integral values of efforts.

Experimental research

A brushed direct current motor PL-072 was taken for the research. Its parameters are: rated voltage – 220 V; rated current – 1.3 A; rated rotational frequency – 1500 rev/min, power – 180 W; efficiency – 63%; armature winding resistance – 17.5 Ohm; parallel excitation winding resistance – 820 Ohm; commutator-brush transition resistance – 0.6 Ohm; operation mode – long (S1); number of the excitation winding turns – 2500; diameter of the excitation winding bare wire – 0.17 mm, number of conductors in the armature slot – 208; diameter of the armature winding bare wire – 0.4 mm

A mathematical model was developed on the basis of the nameplate data of the motor and its basic structural dimensions. This model enables the research of the influence of the basic types of structural defects by means of purposeful alteration of the geometry and local alteration of the electrical and magnetic properties of the materials [7, 8]. The overview of the model in the mode of electromagnetic parameters calculation and the results obtained during its application are shown in Figs. 1-3.



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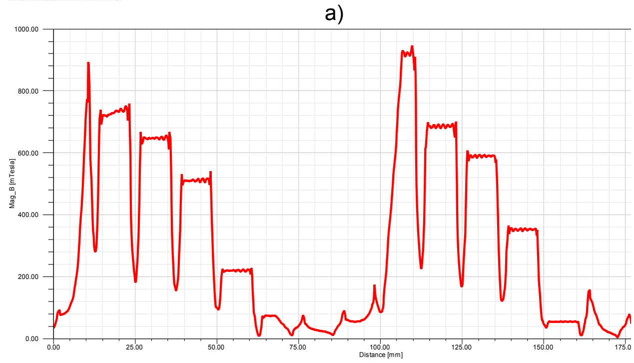

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Fig. 1. Motor model during the determination of the magnetic parameters: a – distribution of electromagnetic parameters across the transverse section; b – a curve showing magnetic induction variation in the air gap for the time moment t = 0.2 s.

Evident irregularity of magnetic induction distribution both about the geometric axis of symmetry and about the pole edges in the researched direct current machine, as is seen in Fig. 1, explains the type of dependence of force distribution in the orthogonal coordinates shown in Fig. 2.

During the analysis of magnetic field parameters the induction in the air gap is usually decomposed into a tangential and radial component with a simultaneous analysis of their frequency spectra. For the modeled motor it is shown in Fig. 3.

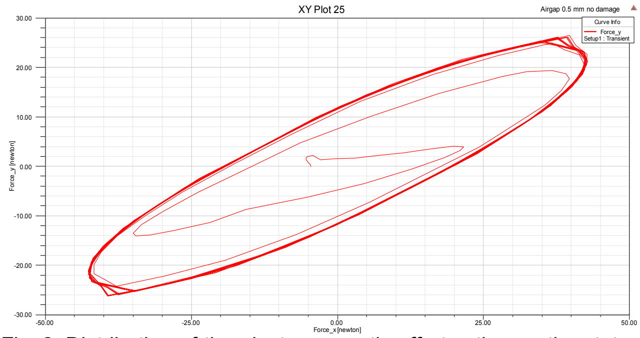
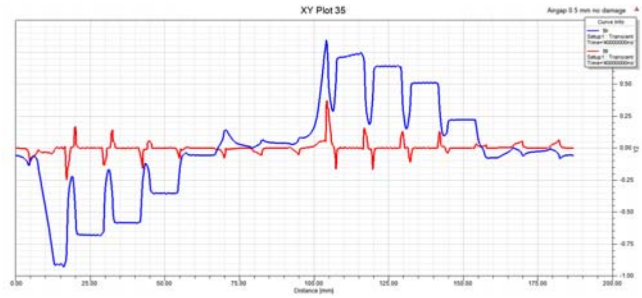


Fig. 2. Distribution of the electromagnetic effort acting on the stator according to the axes of the orthogonal coordinate system



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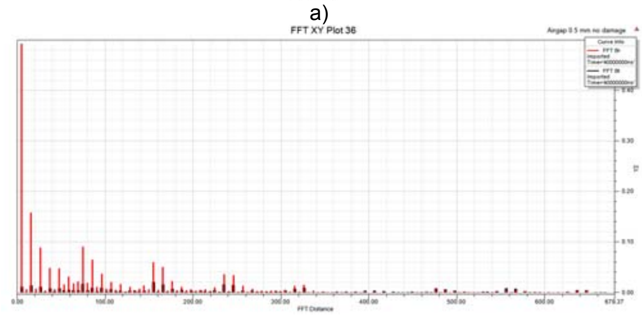


b)

Fig. 3. Results of the determination of magnetic induction components: a – curves showing variations of the radial and tangential components of magnetic induction; b – frequency spectrum of magnetic induction components

The results shown in Fig. 3 make it possible to come to a preliminary conclusion about the tangential component minimal influence on the brushed direct current electric machine vibration characteristics of electromagnetic nature.

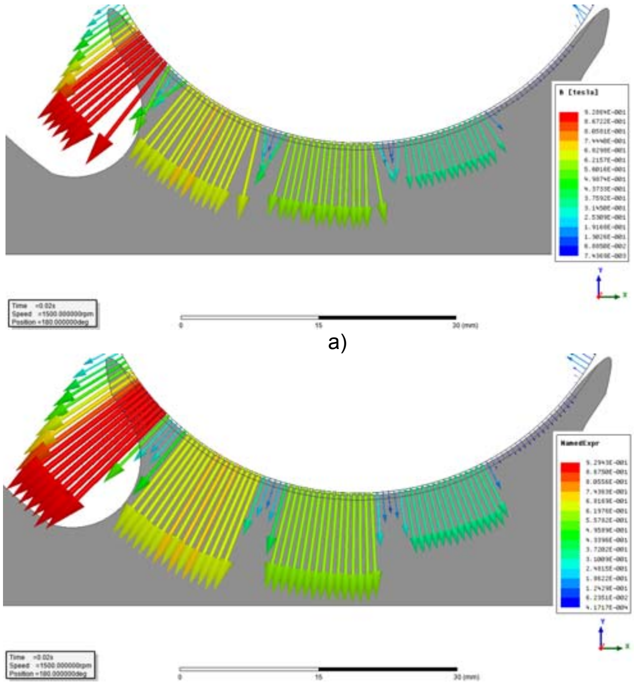
Let us assess the possibility for neglect of this component by comparison of the values of the magnetic induction vector and its radial component and their distribution along the air gap.

The values of the radial component of magnetic induction in the scalar and vector forms were determined from the corresponding orthogonal components for the Cartesian coordinate system as:

$$\begin{aligned} B_r &= \overline{B} \cdot \bar{i}_r = \left(B_x \bar{i}_x + B_y \bar{i}_y\right)\left(\cos(\phi)\bar{i}_x + \sin(\phi)\bar{i}_y\right) \\ \overline{B}_r &= B_r \cdot \bar{i}_r = B_r\left(\cos(\phi)\bar{i}_x + \sin(\phi)\bar{i}_y\right) \end{aligned}, \tag{6}$$

where $\overline{i_x}, \overline{i_y}, \overline{i_r}$ – unit vectors on corresponding axes; ϕ – calculation angle at the transition between different coordinate systems.

The researched parameters were obtained on the basis of system (5), determined from the basic calculation parameters of the model with the use of the inherent possibilities of a postprocessor and are shown in Fig. 4.



a)

b)

Fig. 4. Distribution of magnetic induction along the centerline of the air gap: a – magnetic induction vector; b – radial component of the magnetic induction vector

The character of the distribution, including the value and directions of vectors shown in Fig. 4, confirms the initial supposition about the possibility for neglect of the magnetic induction vector tangential component, which results in an error of the calculation of about 1.5 %. That is why in the further analysis of efforts of electromagnetic nature it is sufficient to use only the radial component of the Maxwell's magnetic tension tensor. In this case the resultant efforts acting at the definite section of the magnetic system are calculated by means of integration.

It should be noted that the calculation of the vibration rated indices implies determination of the resonance frequency and mode shape vibrations of the mechanical system. So, the given mass and resilience of the oscillation system basic elements do not essentially change in the presence of defects, with a high-quality assessment of the vibration processes of electromagnetic nature it is sufficient to take into account the efforts and their frequency distribution.

On the grounds of the made assumption the possibility for the use of the expression for the calculation of the radial and tangential components of the Maxwell's magnetic tension tensor according [9] was substantiated:

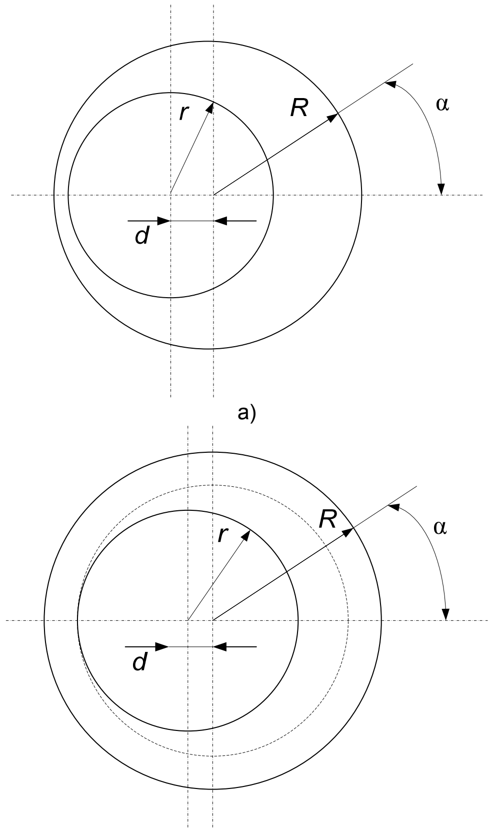
(7)
$$f_r = \frac{1}{2\mu_0}\left(B_r^2 - B_\tau^2\right),$$
$$f_\tau = \frac{1}{\mu_0} B_r B_\tau .$$

As a result, the calculation relations for the effort integral components will be of the form:

(8)
$$F_r = L_d \int\limits_L f_r dl,$$
$$F_\tau = L_d \int\limits_L f_\tau dl,$$

where L_d – axial length of the model, L – contour along which integration is performed , l – elementary section of the contour length.

The considered approach is applicable to the calculation of vibro-exciting efforts in electromagnetic systems with violation of magnetic symmetry. Let us analyze the use of the proposed method for the solution to the problem of the assessment of the influence of the direct current machine armature dynamic eccentricity caused by its slump due to broken bearings in the field of action of centrifugal forces and adhesion on the values of vibro-exciting efforts (Fig. 5).



a)

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Fig. 5. Special features of taking into consideration the eccentricity caused by broken bearings: a – static variant; b – dynamic variant

The solution to this problem implies a comparative analysis of the total radial effort at one of the basic poles of the electric machine in the presence and absence of the considered defect.

Under the condition that R is the stator internal radius, r is the external radius of the rotating part, air gap δ value variation dependence on angle α at the shift of the armature rotation axis in relation to the stator axis by distance d will be of the form [10]:

(9) $$\delta(\alpha) = R - r - d\cos\alpha = \delta_0 - d\cos\alpha ,$$

where $\delta_0 = R - r$ – basic air gap.

Accordingly, the relative permeance at the static eccentricity is determined as

(10) $$\lambda(\alpha) = \frac{\mu_0}{\delta(\alpha)} = \frac{\mu_0}{\delta_0 - d\cos\alpha} .$$

In the case of dynamic eccentricity it is necessary to take into account the change of the angle of the minimal (maximal) air gap position:

(11) $$\alpha_d = \alpha - \omega t ,$$

where α_d – angle of the change of the rotating part position in the presence of dynamic eccentricity; ω – angular rotation velocity of the armature; t – time moment to which the armature position corresponds.

As a result, the expression for the relative permeance will take the following form

$$\lambda(\alpha,t)=\frac{\mu_0}{\delta_0 - d\cos(\alpha-\omega t)}. \quad (12)$$

During the research a comparative analysis of the total radial effort at one of the basic poles of the brushed direct current machine without defects and a machine with 60% dynamic eccentricity was carried out.

The solution to the posed problem with the use of the developed method resulted in obtaining the distribution of the vibro-exciting effort acting on the machine basic pole (Fig. 6).

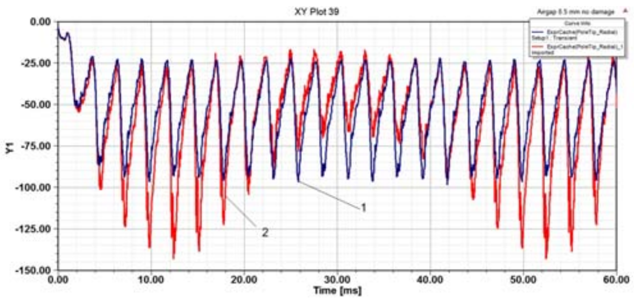

Fig. 6. Variation of the effort of electromagnetic nature: 1 – a healthy motor; 2 – a motor with a defect

Modeling was performed at the time interval of 60 ms during which the researched motor makes one and a half turns. In this case it is sufficient to determine the character of alteration of the curves of the radial efforts of electromagnetic nature. To provide the high accuracy of spectral decomposition at the set time interval 1200 calculation iterations were realized, which corresponds to the time discretization period of 0.00005 s. The obtained spectra of the radial components of the vibro-exciting effort of electromagnetic nature in the frequency domain are shown in Fig. 7.

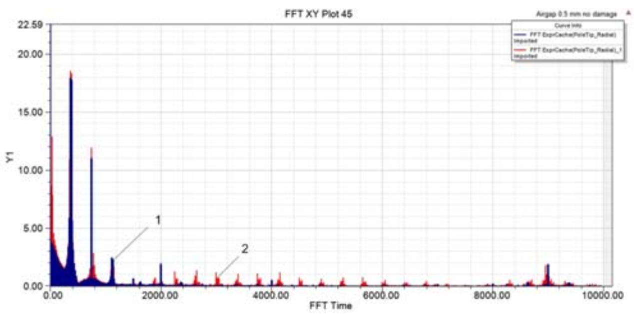

Fig. 7. Frequency spectra of the vibro-exciting effort of electromagnetic nature: 1 – a healthy motor; 2 – a motor with a defect

In Fig. 7 it is seen that the machine with the researched defect is characterized by occurrence of high-frequency components of electromagnetic efforts.

Also, during the research it was proved that variation of the spectral composition of both magnetic induction radial component and the vibration spectrum, to a certain extent, depends on the type of the existing breakage and its localization. It makes it possible to discern the type and degree of breakages of basic structural units of EM with LMTBF.

Conclusions

1. On the basis of the developed field model the peculiar features of the magnetic field in the active zone of the brushed direct current machine have been analyzed during determination of the components of vibro-exciting effort of electromagnetic nature.

2. The expediency of the use of the developed model and the method of its parameters calculation during the analysis of the influence of breakages and faults of electric machine design has been proved.

3. The dynamic eccentricity influence on the spectral distribution of the efforts of magnetic nature, acting on the basic pole of the brushed direct current machine, has been researched.

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REFERENCES

[1] Kotelenets N.F., Kuznetsov N.L.. Testing and reliability of electric machines, Moscow, Vysshaia shkola, (1988), (in Russian).
[2] Zagirnyak M.V., Mamchur D.G., Kalinov A.P., Elimination of the influence of supply mains low-quality parameters on the results of induction motor diagnostics, Proceedings of XIX International Conference on Electrical Machines, ICEM 2010, Rome, Italy, (2010), Paper RF-009474, IEEE Catalog Number CFP1090B-CDR, ISBN 978-1-4244-4175-4, Library of Congress Number 2009901651.
[3] Hamid A. Toliyat, Subhasis Nandi, Seungdeog Choi, Homayoun Meshgin-Kelk. Electric Machines: Modeling, Condition Monitoring and Fault Diagnosis, CRC Press, October 30, (2012).
[4] Maga D., Zagirnyak M., Miljavec D., Additional losses in permanent magnet brushless machines, Proceedings of 14th International Power Electronics and Motion Control Conference, EPE-PEMC 2010, Ohrid, Macedonia, (2010), Paper RF-009474, IEEE Catalog Number CFP1034A-DVD, ISBN 978-1-4244-7854-5.
[5] Vigayraghavan P., Krishnan R., Noise in Electric Machines: A Review, IEEE, (1998).
[6] Bianchi Nicola, Electrical Machine Analysis Using Finite Elements (Copyrighted Material), CRC Press, Taylor & Francis Group, University of West Florida, (2005).
[7] Prus V.V., Zagirnyak M.V., Nikitina A.V., Grounds for Efficiency and Prospect of the Use of Instantaneous Power Components in Electric Systems Diagnostics, *Przeglad Elektrotechniczny* (*Electrical Review*), (2006), No 12, 123–125.
[8] M. Zagirnyak, V. Prus, I. Kolotylo, D. Miljavec, Taking stator cores into account when induction motors vibration parameters are calculated. *Przeglad Elektrotechniczny* (*Electrical Review*), (2013), No 12, 192–195.
[9] Pragasen Pillay, William (Wei) Cai, An Investigation into Vibration in Switched Reluctance Motors, *IEEE Transactions on Industry Applications*, Vol. 35, No. 3, May/June, (1999).
[10] Ali Rezig, Mohammed Rachid Mekideche and Abdesslem Djerdir, Impact of Eccentricity and Demagnetization Faults on Magnetic Noise Generation in Brushless Permanent Magnet DC Motors, *Journal of Electrical Engineering & Technology,* Vol. 6, No. 3, 356–363.