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FEATURES OF MODELING OF ELECTROMAGNETIC FIELD OF ELECTRIC MACHINES WHEN MAGNETIC SYSTEM PROPERTIES CHANGE

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ОСОБЛИВОСТІ МОДЕЛЮВАННЯ ЕЛЕКТРОМАГНІТНОГО ПОЛЯ ЕЛЕКТРИЧНИХ МАШИН ПРИ ЗМІНІ ВЛАСТИВОСТЕЙ МАГНІТНОЇ СИСТЕМИ

Purpose. Determination of particular features of electric machines electromagnetic field modeling when the change of magnetic system properties is caused by the presence of damages of the main types occurring during electric machines long-term operation and repairs.

Methodology. The comparative experimental analysis of changes of the properties of electric machine magnetic systems during their repair and long-term operation is substantiated. Mathematical grounds for influence of magnetic system main faults on electromagnetic field described by Maxwell's equations. Numerical modeling of magnetic field in electric machines with damaged magnetic systems with the finite-element method.

Findings. The principles of modeling electromagnetic field in electric machines with magnetic system damages characterized by considerable error-free running time and subjected to a number of overhauls have been grounded. As a result, the necessity of the use of models of various types for calculation of electromagnetic field, depending on the presence and localization of the main types of magnetic system damages, has been proved. The adequacy of the proposed approach to modeling core defects of DC motors has been confirmed.

Originality. The peculiarities of different types of damages in laminated cores and the ways to take them into account while simulating electric machine electromagnetic field are studied. The ways of solving the mentioned task using the finite element method by the example of computation of the change of vibroexcitation forces caused by the electromagnetic nature in direct current machines are developed.

Practical value. The obtained results make it possible to predict the change of an electromagnetic component of vibration and irregularity of torque distribution of DC motor, caused by laminated core defects. There is also a possibility of estimating the rate of laminated core damage influence on the main IM operating characteristics.

Keywords: *DC motor, defects, laminated core, electromagnetic field*

Introduction. The properties of electric machine (EM) magnetic system change in the process of their repair and long-term operation [1]. It results in increase in losses, deterioration of EM performance characteristics, variation of thermal and vibration operating conditions [2]. A similar problem occurs when improper magnetic materials are used in EM designs, which has been typical of the electric machine industry in the recent years. The analysis of processes in EM as a rule is based on the electric circuit theory and implies the use of equivalent circuits. Equivalent circuit parameters contain implicit information about the design and the connecting circuit of the machine windings, configuration of magnetic system, etc. However, these methods are based on a number of simplifications, which considerably affects the calculation accuracy. The calculation of EM parameters using electromagnetic field analysis is an alternative for such methods [3].

Magnetic field research is the most informative approach to taking magnetic system properties variation into consideration. However, estimation of influence of EM magnetic system condition on electromagnetic field is a complicated scientific and practical problem. Taking into account the nonlinearity of magnetic parameters dependences and nonuniformity of their distribution, as well as magnetic material saturation rate for existing geometry of magnetic systems is only possible when numerical methods are used. The performed analysis resulted in the substantiation of the possibility of determining EM main parameters and characteristics in the process of their modeling by creating models based on the finite element method (FEM).

The purpose of the paper consists in determining particular features of EM electromagnetic field modeling when the change of magnetic system properties is caused by the presence of damages of the main types occurring during EM long-term operation and repairs.

Presentation of the main research and explanation of the results. Laminated cores of stator, rotor, armature, poles, etc. are magnetic system components of most EMs. The earlier research revealed the necessity of taking into account the variation of their properties both for the whole cores and locally for their different sections.

Variations of core properties on the whole can be explained by their heating and reversal magnetization influence on the main electric and magnetic parameters during operation. As a rule, these parameters deteriorate when the operation time increases, which can be explained by electrical steel ageing. Admissible parameter variations are usually normalized by corresponding standards. Ageing processes are considerably intensified during repairs of electric machines. This is mainly explained by the repair technology itself. So, when windings are removed during an overhaul, the cores are annealed in a furnace at the temperature of 400 °C for 4 hours.

Fig. 1 shows technical magnetization curves $B_m = f(H)$ for electrical steel of 1211 type before and after a number of annealings, Fig. 2 contains curves of steel losses $P_{st} = f(B_m)$ (the curve before annealing is designated by number 1, the curves after the 1st – 3d annealings – by numbers 2–4 correspondingly). The results were obtained for rectangular laminated samples with the use of Epstein's device.

It can be seen in Figs. 1–2 that steel thermal annealing results in: first, the magnetic induction value at which steel saturation takes place reduces; second, steel losses increase.

Steel properties deteriorate uniformly after the first and the second annealing. So, if the initial magnetization curve for unannealed steel (curve *1*, Fig. 1) is considered to be the reference, for the saturation point, when intensity is H = 741.861 A/m, magnetic induction decreases by 2.57 and 5.21 %, respectively. After the third annealing there occurs a sudden change in properties deterioration (induction decreases by 9.35 % in relation to the initial curve). In this case steel losses growth occurs in the following way. After the first and the second annealing normal condition steel losses (magnetization curve operating point H = = 741.861 A/m, B_m = 0.824 T) increase by 4.14 and 7.81 %, respectively, and after the third annealing – only by 5.94 % in relation to the initial value, which is difficult to provide a logical explanation for.

If supply voltage is constant, in case of annealed steel, increased current consumption is observed, which results in the shift of operating point at the magnetization curve into the saturation zone. So, for rated voltage, at which the operating point for unannealed steel is located on the bend of the magnetization curve (point *A*, Fig. 1), due to current growth and, consequently, magnetic intensity, by 4.01, 8.41 and 21.59 %, respectively, the values of induction, less than the initial rated one by 1.59, 3.35 and 4.7 %, respectively, (points *B*, *C* and *D* in Fig. 1) correspond to operating points for annealed steel. When the values of losses were corrected in relation to new operating points, their values exceeding the value of losses in point A by 7.29, 14.72 and 24.86 %, respectively, were obtained (Fig. 2).

These results can be explained by comparing them with variation of properties of sheet electrical steel, which is known from literature. On this ground the mentioned variations can be accounted for by the growth of eddy currents in the cores steel due to deterioration of the properties of intersheet insulation covering under thermal action. Besides, the variation of magnetic circuit saturation rate is evident, which is to be properly taken into account in calculation models.

Alongside with this, in particular cases, there can be observed general slackening of core pressing caused by both destruction of intersheet insulation and worsening of the core fit on the body or on the shaft. The mentioned variations result in the growth of the core

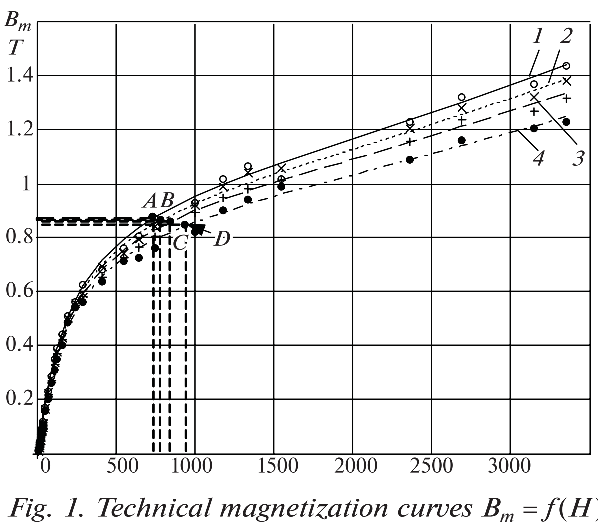


Fig. 1. Technical magnetization curves $B_m = f(H)$ of 1211 type steel

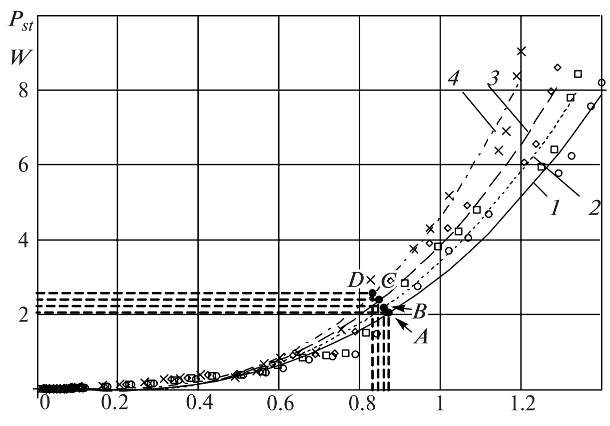


Fig. 2. Curves of losses $P_{st} = f(B_m)$ in 1211 type steel at successive annealings at the temperature of 400 °C

magnetic reluctance, thereby reducing the main flux. It causes decrease in the moment on IM shaft.

The considered local core damages include crushing of top part of the teeth zone and shorting of electrical steel sheets [4]. All these damages mainly influence the variation of magnetic and electric parameters of magnetic system sections in the axial and radial directions.

Decrease in magnetic induction at such sections may reach 7–10 %, increase in magnetic intensity – 60–70 %, growth of steel losses – up to 50 %.

The results of EM research by field methods confirm the efficiency of the use of application packages based on the finite element method [5, 6] for solution of such problems.

To choose the type of the created field model rationally it is necessary to analyze the kind and location of core damages. For the case of uniform variation of magnetic parameters along the EM core, sufficient accuracy of the analysis results is provided by a 2D model of calculation of the electromagnetic field in the cross section of the active zone. Variation of parameters in the axial direction is caused by damages along the core (pressing slackening, lengthwise teeth shortening).

To determine integral values of a torque moment, research of the influence of axial redistribution of vibroexitating forces, when vibroparameters are calculated, as well as winding temperature ununiform distribution caused by local exceed of steel losses, it is necessary to use 3D models.

Modeling was performed on the basis of Maxwell equations supplemented with material properties coupling equations describing its behavior in electromagnetic field [7]. Simplified coupling equations are of the form

$$\vec{\delta}_{con} = \gamma\vec{E};$$

$$\vec{H} = \vec{v}_a\left(\vec{B} - \vec{B}_r\right) + q_1\frac{\partial}{\partial t}\left(\vec{B} - \vec{B}_r\right) - q_2\frac{\partial^2}{\partial t^2}\left(\vec{B} - \vec{B}_r\right),$$

where $\vec{\delta}_{con}$ is conduction current density; γ is material electric conductivity; $\vec{E}$ is a vector of electric field strength; $\vec{H}$ is a vector of magnetic intensity; $\vec{v}_a$ is velocity vector field; $\vec{B}$ is a vector of magnetic induction; $\vec{B}_r$ is a vector of residual magnetic induction; q_1, q_2 are dynamic indices of laminated material electrophysical parameters, that are determined from equations

$$q_1 = (1/12)\Delta^2\gamma_{el}; \quad (1)$$

$$q_2 = (1/720)\Delta^4\mu_{max}\gamma_{el}^2. \quad (2)$$

In (1–2) Δ is steel sheet thickness in cores; μ_{max} is absolute magnetic permeability; γ_{el} is sheet material conductivity.

The features of modeling include, first of all, the necessity of taking into consideration all the above considered phenomena: decrease in magnetic induction B, growth of magnetic intensity H, increase in steel losses P_{st}, rise of magnetic system saturation rate.

As a first approximation, it is rather simple to solve this problem. With this purpose in view, it is necessary to take into account the fact that the considered variations of magnetic system properties will cause the decrease in active resistance r_μ and reactance x_μ of magnetization circuit. It will result in the increase in IM consumed current. Thus, current cannot be the main invariable parameter in calculations, the value of IM supply voltage is to be used instead, which is easily done in [6].

Then it is necessary to single out the damaged sections in the volume of laminated cores and determine their geometry in the form of closed figures. Variations of magnetic properties are assigned for these sections through real magnetization curves corresponding to the form and rate of damage.

When electric steel sheets of EM laminated cores are short-circuited, the calculation of eddy currents circuits was made on the basis of the analysis of vector magnetic potential distribution

$$\sigma\frac{\partial\vec{A}}{\partial t} + \nabla\times(\mu_0^{-1}\mu_r^{-1}\times\vec{A}) = \vec{J}.$$

Here σ is electric conductivity of the analyzed area; μ_0 – permeability of free space; μ_r is core steel relative permeability; $\vec{A}$ is vector magnetic potential; $\vec{J}$ is external source current density.

Variation of cores electric properties due to eddy currents growth was taken into consideration by steel electric conduction reduction equivalent to eddy EMF growth. Steel losses P_{st} at magnetic circuit sections were determined according to modified Steinmetz equations [6]

$$P_{st} = P_h + P_c + P_e = K_1B_m^2 + K_2B_m^{1.5};$$

$$K_1 = k_hf + k_cf^2; \quad K_2 = k_ef^{1.5},$$

where P_h, P_c, P_e are hysteresis, eddy currents and additional losses components, respectively; B_m is amplitude value of magnetic induction component at the alternating current; f is frequency; k_h is coefficient of hysteresis losses; k_c is coefficient of eddy currents losses; k_e is coefficient of additional losses in the core.

Coefficients K_1 and K_2 were calculated according to the losses curve $P_{st} = f(B_m)$ using quadratic minimization function

$$err(K_1, K_2) = \sum_i\left[P_{sti} - (K_1B_{mi}^2 + K_2B_{mi}^{1.5})\right]^2 = \min,$$

where P_{sti} stands for losses in the i-th point of the curve; B_{mi} – magnetic induction in this point.

With the aim of experimental verification of the above stated provisions, a P–31U4 type direct current motor (DCM) with nominal power of P_n = 700 W and nominal rotation frequency of n_n = 1000 rpm was taken as the object of modeling.

The influence of four contiguous partially shortened armature teeth was investigated. The teeth were shortened in their upper part along the height of the top from the external end of the core along its full length. The area of shortening across the external surface of the teeth was changed from 25 to 100 % of their total area with 25 % pitch (Fig. 3).

Variation of steel properties was assigned in accordance with the results obtained during local testing of laminated cores in the course of repairs [4] with the help of corrected material magnetization curves and for the whole core – in accordance with the data in Figs. 1–2.

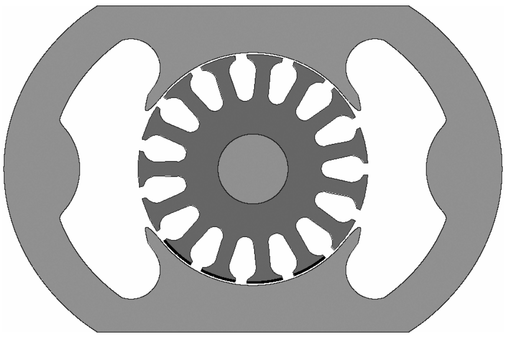
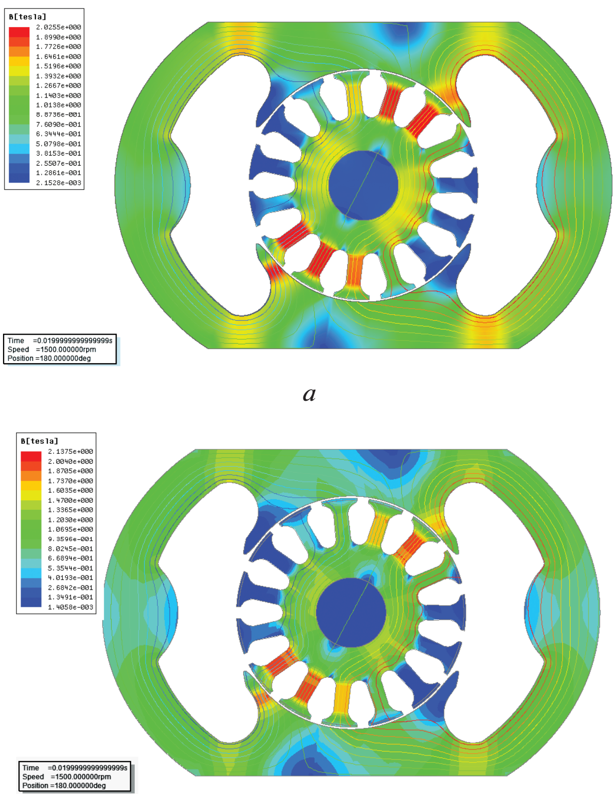


Fig. 3. Model of direct current motor with damaged armature tooth steel



a

b

Fig. 4. Distribution of magnetic induction vector $\vec{B}$,T in DCM with an armature core in normal condition (a) and when 25 % of the upper part of a four armature tooth area is shortened (b)

Modeling results shown in Fig. 4, *a, b* demonstrated that even insignificant (as to its depth and area) shortening of the armature tooth zone causes reduction of magnetic induction value in the area of damaged teeth by 17–23 %.

This range of magnetic induction variation practically corresponds to the one obtained experimentally for a stalled armature of the investigated DCM (Fig. 5).

The value of magnetic induction was calculated according to the EMF level of the magnetic-test coils put on the investigated armature teeth. The teeth were shortened artificially by grinding. Difference between experimental and calculated data was from 5 to 8 % depending on the area of teeth shortening across the external surface, which confirms the adequacy of the proposed approach to modeling EM core defects.

In addition, the considered armature defects, mainly due to eddy currents from rotary magnetization, cause decrease in torque mean value and its fluctuation at the level of 5–12 % depending on the armature tooth damage rate. Such irregularity of torque distribution may result in deterioration of loaded DCM operation stability, especially in transient conditions.

Distribution of normal component of electromagnetic force (Fig. 6) and variation of torque instantaneous value (Fig. 7), obtained in a different position of the defect area in relation to the main poles of DCM, were investigated on the basis of the developed DCM model with damaged armature core steel.

The obtained results point out a considerable variation (from 20 to 45 %) of the value of electromagnetic force normal component in the area of laminated core defects, which will result in nonuniformity of efforts distribution and growth of vibration electromagnetic component.

Taking into account the calculation features according to [6], similar results can be obtained for the main parameters of any type IM in static and dynamic conditions. There is also a possibility to estimate the

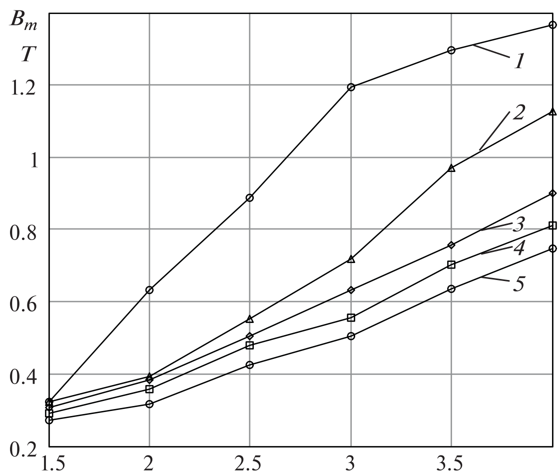


Fig. 5. Magnetic induction B_m, T experimental dependences on the armature current I_a, A:

1 – normal condition of the core; 2–5 – shortening of 25, 50, 75 and 100 % of the tooth surface

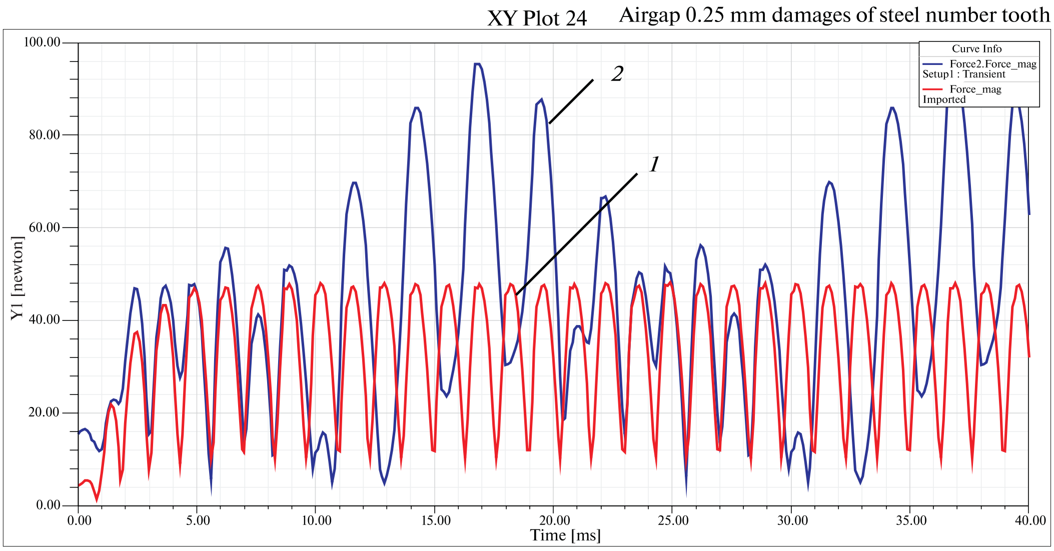


Fig. 6. Distribution of the normal component F_n, N of electromagnetic force in DCM in the function of time t, ms:

1 — with normal condition of the core; 2 — when the upper part of four teeth is shortened

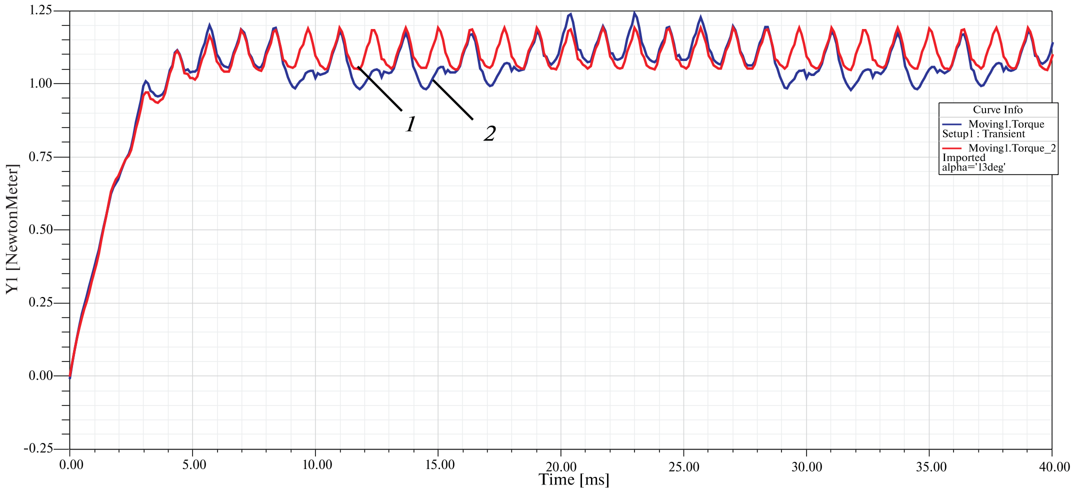


Fig. 7. Variation of the instantaneous value M, Nm of the torque in the function of time t, ms when the armature turns:

1 — with normal condition of the core; 2 — when the upper part of four teeth is shortened

rate of laminated core damage influence on the main IM operating characteristics.

Conclusions. The particular features of modeling electromagnetic field in EMs with magnetic system damages characterized by considerable error-free running time and subjected to a number of overhauls have been determined. As a result, the necessity of the use of models of various types for calculating electromagnetic field, depending on the presence and localization of the main types of magnetic system damages, has been substantiated. The adequacy of the proposed approach to modeling EM cores defects has been confirmed.

References / Список літератури

1. Zagirnyak, M., Prus, V., Kolotilo, I. and Miljavec, D., 2012. Determination of power indices for a three-phase induction motor with a phase-wound rotor through particular losses components. *Przeglad Elektrotechniczny (Electrical Review)*, No. 12b, pp. 80–82.

2. Hadziselimovec, M., Marcic, T., Stumberger, B. and Zagradicnik, I., 2011. Winding type influence on efficiency of an induction motor. *Przeglad Elektrotechniczny (Electrical Review)*, Vol. 87, Iss. 3, pp. 61–64.

3. Vaskovskii, Yu. M., 2007. *Poliovyi analiz elektrychnykh mashyn* [Electric machines field analysis]. Kyiv: NTU “KPI”.

Васьковський Ю. М. Польовий аналіз електричних машин / Васьковський Ю. М. – К.: НТУ „КПІ“, 2007. – 190 с.

4. Prus, V. V., Zagirnyak, M. V. and Nikitina, A. V., 2006. Grounds for Efficiency and Prospect of the Use of Instantaneous Power Components in Electric Systems Diagnostics. *Przeglad Elektrotechniczny (Electrical Review)*, No. 12, pp. 123–125.

5. COMSOL, 2008. *Multiphysics Reference Guide*, Version 3.5a. COMSOL AB.
6. Ansoft Corporation, 2011. *Ansoft Maxwell 3D User's Guide*, Rev 3.0. Pittsburgh: Ansoft Corporation
7. Shmelev, V. E., 2010. *Prostranstvenno-fazovoie modelirovaniie elektromekhanicheskoho preobrazovaniia energii v apparatahk i mashynakh vrashchatelnogo dvixheniia* [Space-phase modeling of energy electromechanical transformation in rotational motion units and machines] Vladimir: Publishing house of Vladimir State University.

Шмелев В. Е. Пространственно-фазовое моделирование электромеханического преобразования энергии в аппаратах и машинах вращательного движения / Шмелев В. Е. // Владим. гос. ун-т. – Владимир: Изд-во Владим. гос. ун-та, 2010. – 172 с.

Мета. Визначення особливостей моделювання електромагнітного поля електричних машин при зміні властивостей магнітної системи, обумовленому наявністю основних видів пошкоджень, що виникають при тривалій експлуатації та ремонтах електричних машин.

Методика. Порівняльний експериментальний аналіз змін властивостей магнітних систем електричних машин, що виникають у процесі їх ремонту й тривалої експлуатації. Математичне обґрунтування впливу основних видів дефектів магнітної системи на електромагнітне поле, що описується рівняннями Максвела. Чисельне моделювання електромагнітного поля в електричних машинах із пошкодженнями магнітних систем методом скінчених елементів.

Результати. Обгрунтовані принципи моделювання електромагнітного поля в електричних машинах з пошкодженнями магнітних систем, що характеризуються значним часом наробітку на відмову та рядом проведених капітальних ремонтів. У результаті доведена необхідність використання різних типів моделей для розрахунків електромагнітного поля залежно від наявності й локалізації основних видів пошкоджень магнітної системи. Підтверджена адекватність запропонованого підходу до моделювання дефектів осердь двигунів постійного струму.

Наукова новизна. Розглянуті особливості й запропоновані способи урахування різних видів пошкоджень шихтованих осердь при моделюванні електромагнітного поля електричних машин. Розкриті підходи до розв'язку такого завдання методом скінченних елементів на прикладі розрахунків зміни віброзбуджуючих сил електромагнітного характеру в електричних машинах постійного струму.

Практична значимість. Отримані результати дозволяють прогнозувати зміну електромагнітної складової вібрації та нерівномірність розподілу обертового моменту двигуна постійного струму, викликані ушкодженнями шихтованих осердь. Також існує можливість оцінки ступеня впливу пошкоджень шихтованих осердь на основні робочі характеристики електричних машин.

Ключові слова: *двигун постійного струму, пошкодження, шихтоване осердя, електромагнітне поле*

Цель. Определение особенностей моделирования электромагнитного поля электрических машин при изменении свойств магнитной системы, обусловленном наличием основных видов повреждений, возникающих при продолжительной эксплуатации и ремонтах электрических машин.

Методика. Сравнительный экспериментальный анализ изменений свойств магнитных систем электрических машин, возникающих в процессе их ремонта и продолжительной эксплуатации. Математическое обоснование влияния основных видов дефектов магнитной системы на электромагнитное поле, описываемое уравнениями Максвелла. Численное моделирование электромагнитного поля в электрических машинах с повреждениями магнитных систем методом конечных элементов.

Результаты. Обоснованы принципы моделирования электромагнитного поля в электрических машинах с повреждениями магнитных систем, характеризующихся значительным временем наработки на отказ и прошедших ряд капитальных ремонтов. В результате доказана необходимость использования различных типов моделей для расчета электромагнитного поля в зависимости от наличия и локализации основных видов повреждений магнитной системы. Подтверждена адекватность предложенного подхода к моделированию дефектов сердечников двигателей постоянного тока.

Научная новизна. Рассмотрены особенности и предложены способы учета различных видов повреждений шихтованных сердечников при моделировании электромагнитного поля электрических машин. Раскрыты подходы к решению такой задачи методом конечных элементов на примере расчета изменения вибровозбуждающих сил электромагнитного характера в электрических машинах постоянного тока.

Практическая значимость. Полученные результаты позволяют прогнозировать изменение электромагнитной составляющей вибрации и неравномерность распределения вращающего момента двигателя постоянного тока, вызванные повреждениями шихтованных сердечников. Также существует возможность оценки степени влияния повреждений шихтованных сердечников на основные рабочие характеристики электрических машин.

Ключевые слова: *двигатель постоянного тока, повреждения, шихтованный сердечник, электромагнитное поле*

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