UDC 621.313.823.2

O. V. Makarchuk, Cand. Sc. (Tech.), Assoc. Prof. Lviv Polytechnic National University, Lviv, Ukraine, e-mail: oleksandr.v.makarchuk@lpnu.ua

ADDITIONAL LOSSES IN THE STATOR WINDINGS OF THE HIGH-SPEED BRUSHLESS ELECTRICAL MACHINE WITH PERMANENT MAGNETS

О. В. Макарчук, канд. техн. наук, доц. Національний університет „Львівська політехніка", м. Львів, Україна, e-mail: oleksandr.v.makarchuk@lpnu.ua

ДОДАТКОВІ ВТРАТИ У СТАТОРНИХ ОБМОТКАХ ВИСОКОШВИДКІСНИХ БЕЗКОНТАКТНИХ ЕЛЕКТРИЧНИХ МАШИН З ПОСТІЙНИМИ МАГНІТАМИ

Purpose. To propose a method for determining the additional losses in the stator windings of electrical machines, in which the current frequency is significantly higher than the mains frequency.

Methodology. The numerical methods for solving differential equations of mathematical physics are applied for the study. The Finite Element Method is used for algebraization of partial derivatives; an implicit method of backward differentiation formula is used for algebraization of time derivatives while the Newton-Raphson method is applied for solving nonlinear algebraic equations.

Findings. A mathematical model, which allows counting the total losses caused by skin effect in the slot of the stator winding of a high-speed electrical machine, was created. The model takes into account: its own slot leakage flux, the main magnetic flux, a saturation of the magnetic core, various slot forms and the method of electrical connection of conductor strands in the slot. The mathematical formulation and the boundary condition of this problem are offered.

The results of mathematical experiments of defining additional and total losses in the windings located in the half-closed and open slots for high-speed generator with permanent magnet excitation of 200 kW, 50000 rpm, are presented. The cause-and-effect relationships are analyzed. Findings can help while designing such machines.

Originality. The problem of calculating losses is formulated as a 2-dimensional boundary problem of electrodynamics, which allows us to take into account an interference of the above factors.

Practical value. The necessity for accurate determination of the losses in the phase windings of high-speed machines occurs not only when designing the windings, but also while assessing the thermal condition of such machines.

Keywords: *additional losses, current displacement, skin effect, FEM-analysis, boundary condition, high-speed electrical machine*

If high-speed electrical machines are considered as machines of ultimate power, they may be a sort of production indicators. Therefore, they have been the focus of attention for many researchers, and tasks, associated with their development, are still relevant.

Objectives of the article. The slot effect in stator windings of high-speed permanent magnet electrical machines (HSPMEM) is considerably stronger than that in machines, operating at industrial frequency. Factors, ignored by classical analytical theory for determination of this phenomenon that was developed by Edme in 1922, have become more critical and change entire picture of nonuniform distribution of current density in the cross section of embedded coil side not only quantitatively but also qualitatively. Increasing losses in the stator winding appear to be a negative consequence of this phenomenon that can challenge the implementation of the project for developing HSPMEM.

Analysis of the recent research. The review of available recent research studies in this field gives evi-

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dence of a small number of publications devoted to research of losses in machine stator windings that operate at frequencies that are considerably higher than industrial frequency [1]. Most research studies focus on improvement of the methods for calculation of additional losses in convenient machines of BLDC or PMSM types [2, 3] and asynchronous machines [4, 5]. Some interesting approaches were proposed for calculation of slot effect in transformers and choke coils [6, 7].

Analysis of literature sources allowed distinguishing study methods that are used most frequently for solution of similar tasks on calculation of additional losses in transformers and asynchronous machines. Nonlinearity of this task and the need to consider additional critical factors suggests the usefulness of applying numerical methods. The most suitable method for this purpose is the finite element method, used in combination with numerical time integration methods.

Unsolved aspects of the problem. Local saturation of tooth area is caused by the current of the conductor and magnetic field of dissipation as a prime cause of slot effect and the first harmonic field. The higher saturation level is, the larger share of magnetic flow penetrates from the tooth into the slot changing current density redistribution and increasing slot losses.

Considering this fact, we can speak of availability of additional influencing factors such as saturation of the magnetic core and the form of the slot, namely its “opening”. The factor of increasing armature resistance (Field’s factor) is conventionally determined by Edme’s functions obtained due to absence of saturation of tooth area and for open rectangular slots. Moreover, the influence of the first harmonic field is not taken into account.

It should be mentioned that classical approach provides for tandem coupling of coils, but phase coils of HSPMEM are similar as a rule. Therefore, one (for one-layer coils) or two (for two-layer coils) effective conductors, which consist of multiple strands connected in parallel, are located in the slot.

We state that additional losses in armature coils of HSPMEM exceed the main losses. Therefore, a special attention should be paid to their calculation while designing such machines.

Purpose of the study. The aim of this study is to develop methods for calculating additional losses that would consider the main factors influencing slot effect process in their interrelation.

Study object is phase coil, located in the slots of non-salient pole laminated stator of HSPMEM.

Presentation of the main research. We have developed a mathematical model for calculation of additional losses in HSPMEM coil that considers actual distribution of current density vector field in coil conductors, located in ferromagnetic slot of free form and penetrated by external magnetic field of set amplitude. The mode provides for the actual method for coupling of effective conductors and strands in a slot and saturation of the magnetic core. The task is defined in two planes.

The need in determination of the actual current density vector field, induced by this or that method, results in necessity for solving the dynamical problem in terms of field theory.

Poisson’s invariant equation in coulomb calibration for magnetic vector potential is $(\nabla\cdot\overline{A}=0)$

$$\nabla^2\overline{A}=\sigma\nabla U+\sigma\frac{\partial\overline{A}}{\partial t}-\overline{\upsilon}\times\sigma\ \nabla\times\overline{A}, \qquad (1)$$

where ∇ is a differential Hamiltonian operator; σ is a matrix of electrical conductivity of the medium; $\overline{\upsilon}$ is medium velocity vector; U is electrostatic scalar potential of external field.

Current density field will be determined by the following formula

$$\overline{J}=\sigma\left(-\nabla U-\frac{\partial\overline{A}}{\partial \mathrm{t}}+\left[\overline{\upsilon}\times\overline{B}\right]\right), \qquad (2)$$

on the basis of which it is possible to state that total current density vector specified in formula (2), consists of three components: the 1st component is conditioned by the external electrical field, the 2nd component is conditioned by the magnetic field that changes in time and the 3*d* element is conditioned by movement of the conductor at $\overline{\upsilon}$ speed in the magnetic field with $\overline{B}$ amplitude.

The equation (1) itself is used for further conversion. Together with boundary conditions, it forms the basis of mathematical formulation of the problem of calculating the dynamic magnetic field, considering electromagnetic and mechanic loads.

It is clear that solution of equation (1) requires integration on the basis of spatial and time coordinates.

The computational domain of this model is represented by tooth separation of the stator core (Fig. 1).

You can see symbols and dimensions of the figure, Boundary conditions are represented by expressions that allow configuring the external magnetic field (the inductor field) so that it corresponds to the vision of possible routes of the field passing through the stator core. The excitation field is determined by linear distribution of vector potential along the upper horizontal line

$$A_z[x,t]\Big|_{y=h_{sz}+\delta}=\frac{B_\delta}{\beta}\sin\left(\omega t+\beta x+\upsilon\right), \qquad (3)$$

where $\beta=\pi/\tau$ is a factor of proportionality between coordinates of the point, expressed in angular and linear measurement units; υ is phase shift between the current of the effective conductor and redial component of the vector $\overline{B_\delta}$.

Lines that limit the left and the right edges of computational domain are determined by Dirichlet condition

$$\begin{aligned}A_z[t]\Big|_{x=-0,5t_z}&=\frac{B_\delta}{\beta}\sin\left(\omega t-0,5t_z\beta+\upsilon\right);\\ A_z[t]\Big|_{x=0,5t_z}&=\frac{B_\delta}{\beta}\sin\left(\omega t+0,5t_z\beta+\upsilon\right).\end{aligned} \qquad (4)$$

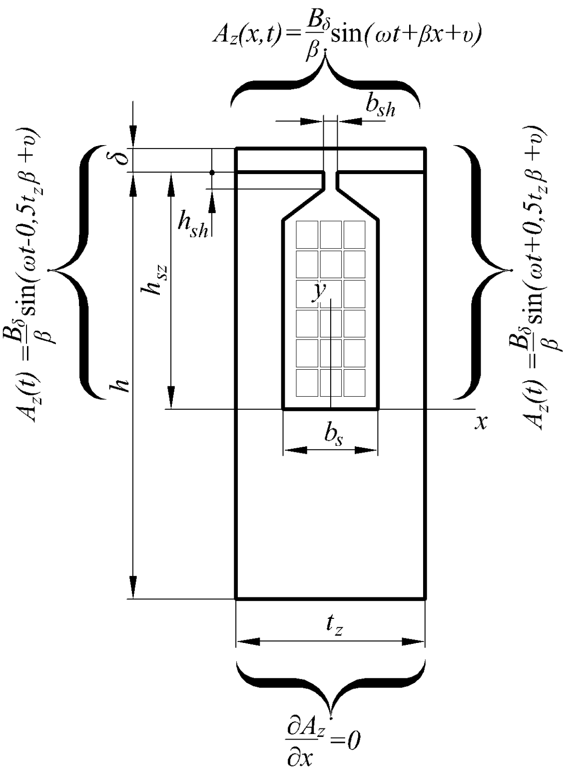


Fig. 1. Computational domain of the model and boundary condition

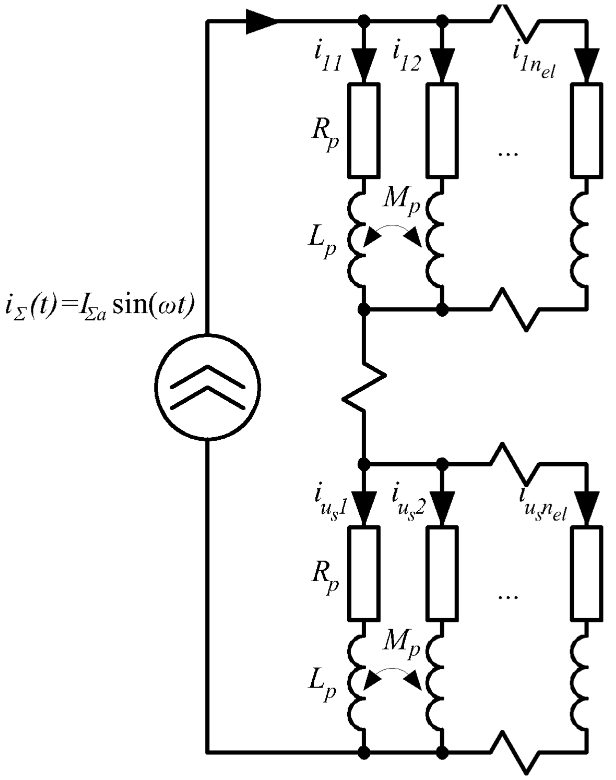


Fig. 2. Electrical diagram of connection of strands in a slot

Lines and outer generating lines of the stator are determined by Neumann condition

$$\left.\frac{\partial A_z}{\partial x}\right|_{y=h_{sz}-h}=0. \qquad (5)$$

Driving forces in this formulation are represented by current of the conductors that are located in the slot and the inductance amplitude is in the air gap.

The equation is written in accordance with the 1st Kirchhoff's law (Fig. 2) in order to determine a method for coupling of strands and effective conductors in the slot before formulating the problem (1)

$$i_\Sigma=\sum_{n=1}^{n_{el}} i_{jn}, \qquad (6)$$

where $n=\overline{1,n_{el}}$ is a current number of the strand (n_{el} is a number of strands in effective conductor); i_Σ, i_{jn} are current of effective conductor (set) and strand (initial) that relate to *j* effective conductor. Thus

$$i_{jn}=\int_S \bar{J}dS=\iint_S J_z[x,y]dxdy=\sum_{e=1}^{E}\frac{S^{[e]}}{K}\sum_{k=1}^{K}J_{zk}^{[e]}, \qquad (7)$$

where $e=\overline{1,E}$ is a consecutive number of the finite element (FE); $k=\overline{1,K}$ is a consecutive number of the FE node; $S^{[e]}$ is FE area with number [*e*]; $J_{zk}^{[e]}$ is a nodal value of z projection of the current density vector.

Expression (1) along with the circular equation (6) and boundary condition (3–5) expresses the nature of mathematical formulation of the problem of calculating the current density field in computational area.

We have carried out a series of topic experiments with use of this model. The purpose of these experiments was to study the effect of its own dispersion flux, the main magnetic flux, saturation of the magnetic core and slot shape on distribution of the current density vector in slot area of the coil considering the interrelation of all these factors.

Program-based realization of the algorithm of this model is made with package ANSYS Multiphysics by means of APDL programming.

Fragments of the grid of finite element models for slot elements of different shape are shown in Fig. 3. Total number of CE is 3010. Total number of nodes is 8670.

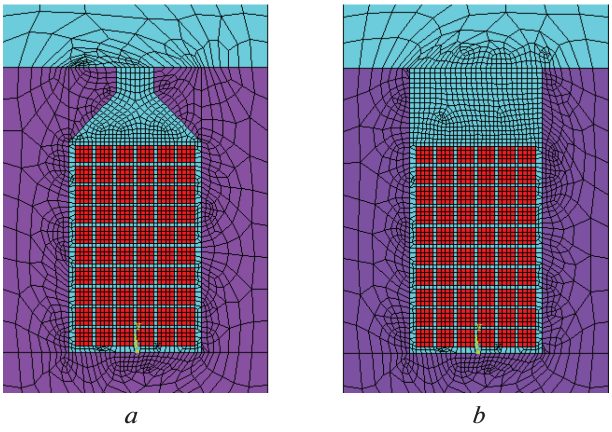

a *b*

Fig. 3. Fragment of FE grids:
a – for semiclosed slot; b – for opened slot

The output data for modeling were presented by dimensions, coil data and characteristics of magnetizing of the core of high-speed generator of 200 kW, operating at the speed of 50000 rpm ($2p = 2$).

The dimensions of computational domain are as follows:

- slot width $b_s = 7.8$ mm;
- full height of slot $h_{sz} = 16.8$ mm;
- area height $h = 63.8$;
- spline width $b_{sh} = 2.2$ mm;
- spline height $h_{sh} = 1.5$ mm;
- air gap $\delta = 6$ mm;
- area width (tooth separation) $t_z = 15.6$ mm;
- area length in z direction $l_p = 240.0$ mm;
- width of strand $b_p = 1.0$ mm;
- height of strand $h_p = 1.0$ mm;
- thickness of frame insulation $t_{kt} = 0.4$ mm;
- thickness of insulation between conductors $\Delta_{iz} = 0.2$ mm.

Winding data:

- the number of effective conductors in a slot $u_s = 2$;
- the number of strands in effective $n_{el} = 30$;
- the number of strands along the slot width $m_c = 6$;
- the number of strands along the slot height $m_r = 5$.

Driving forces of the problem:

- RMS current of the effective conductor $I_\Sigma = 175.4$ A;
- current frequency $f_n = 833.3$ Hz;
- amplitude of radial component of induction of the main field $B_\delta = 0.72$ T;
- phase shift between current and the radial element of induction $\upsilon = \pi/2$ rad;
- proportionality factor between angular and metrical coordinates $\beta = 14.54$ rad/m.

Specific resistance of the conductor material was $\rho_{Cu} = 1.75 \cdot 10^{-8}$ Oh · m. This value corresponds to specific resistance of copper at temperature of 20 °C. Magnetization characteristics of the magnetic core correspond to properties of electric steel of 2411 type (GOST21427.2-83).

The calculation is performed within 6 periods of feed current, time increment was 1/80 of the period.

Fig. 4 shows the results of calculations of vector magnetic potential fields, magnetic field induction and current density at the time $t = 7.05$ ms.

Fig. 5 shows dependence of the voltage on the time, calculated by (7) at the last computational period.

The diagrams, shown in Figure 5 *a, c,* correspond to the currents of strands in the 3*d* left column of the effective conductor, located near the spline.

Valid values of these currents, losses and Field's factors K_R for two conducted studies are recorded in Table.

It should be mentioned that Field's factor, calculated by classical method for opened rectangular slot of specified dimensions is equal to $K_R = 3.8$, and its value, calculated upon the absence of external field and in linear arrangement, is $K_R = 6.3$.

Table

The influence of the slot shape on the skin effect

Index name	Semiclosed slot	Opened slot
Effective conductor at the bottom of the slot		
$I_{1,3}$, A	4.001	3.948
$I_{1,9}$, A	4.306	4.212
$I_{1,15}$, A	5.327	5.322
$I_{1,21}$, A	7.602	7.878
$I_{1,27}$, A	11.602	12.259
Main losses (DC), W	4.318	4.318
Full losses (AC), W	9.417	9.695
Effective conductor near the spline		
$I_{2,3}$, A	14.948	16.666
$I_{2,9}$, A	7.471	8.960
$I_{2,15}$, A	5.434	5.656
$I_{2,21}$, A	14.141	10.830
$I_{2,27}$, A	26.889	19.815
Main losses (DC), W	4.318	4.318
Full losses (AC), W	37.367	64.346
For all conductors in the slot		
Main losses (DC), W	8.636	8.636
Full losses (AC), W	46.785	74.041
Field's factor	5.418	8.574

Conclusions. Mathematical model for calculation of additional losses in slot area of the stator winding of a permanent magnet electrical machine is developed on the basis of Poisson's numerical solution for quasi-steady approximation of electromagnetic field within 2-dimentional formulations. The model considers the actual shape of stator slot, the influence of the excitation field and saturation of the magnetic core.

Analysis of the obtained results suggests the following conclusions that can help in developing high-speed permanent magnet electrical machines:

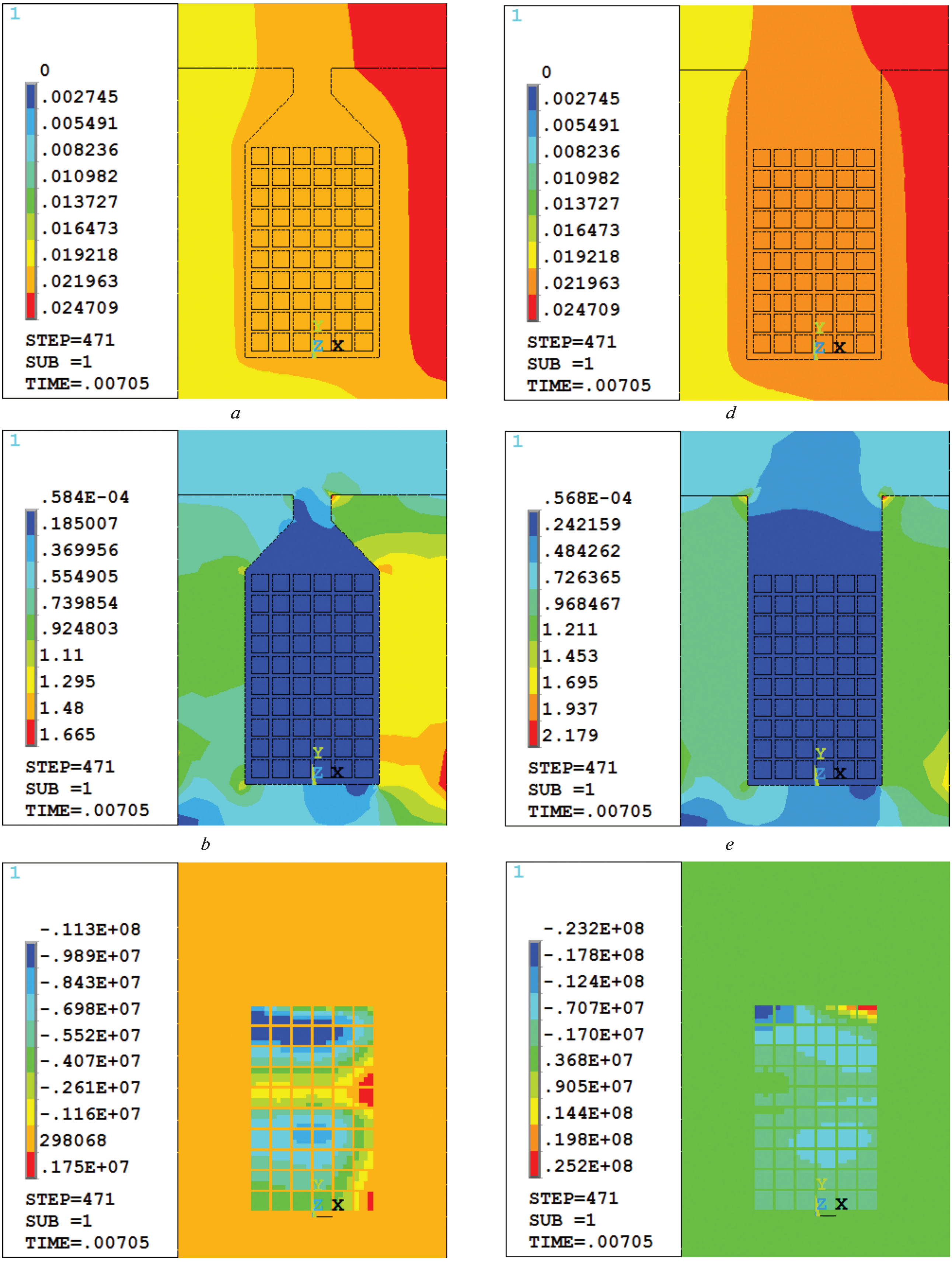
Classical method for calculation of additional losses in the slot area of machine stators, operating at frequencies that are considerably higher than industrial frequency, on the basis of Edme's functions is in significant error.

The first harmonic field induces eddy currents in upper layers of the stator winding while saturating tooth area. This results in increasing losses in it.

Opening of the slot considerably increases penetration of the excitation field into the slot and the value of additional losses in the stator winding.

The excitation filed in semiclosed slots does not affect redistribution of the current density vector field and currents in electromagnetic conductors of the coil.

Saturation of the magnetic core reduces the value of additional losses in the stator winding and makes current distribution more even due to reduction of magnetic conductivity of the slot dissipation flux path. It is necessary to remember that excessive saturation of tooth area increases the main losses in the magnetic core of the stator core.



a *d*

b *e*

c *f*

Fig. 4. Results of calculation:

a, b and c — for semiclosed slot; d, e, f — for opened slot; a, d — field of vector magnetic potential, Vs/m; b, e — magnetic induction vector field, T; c, d — current density vector field, A/m^2

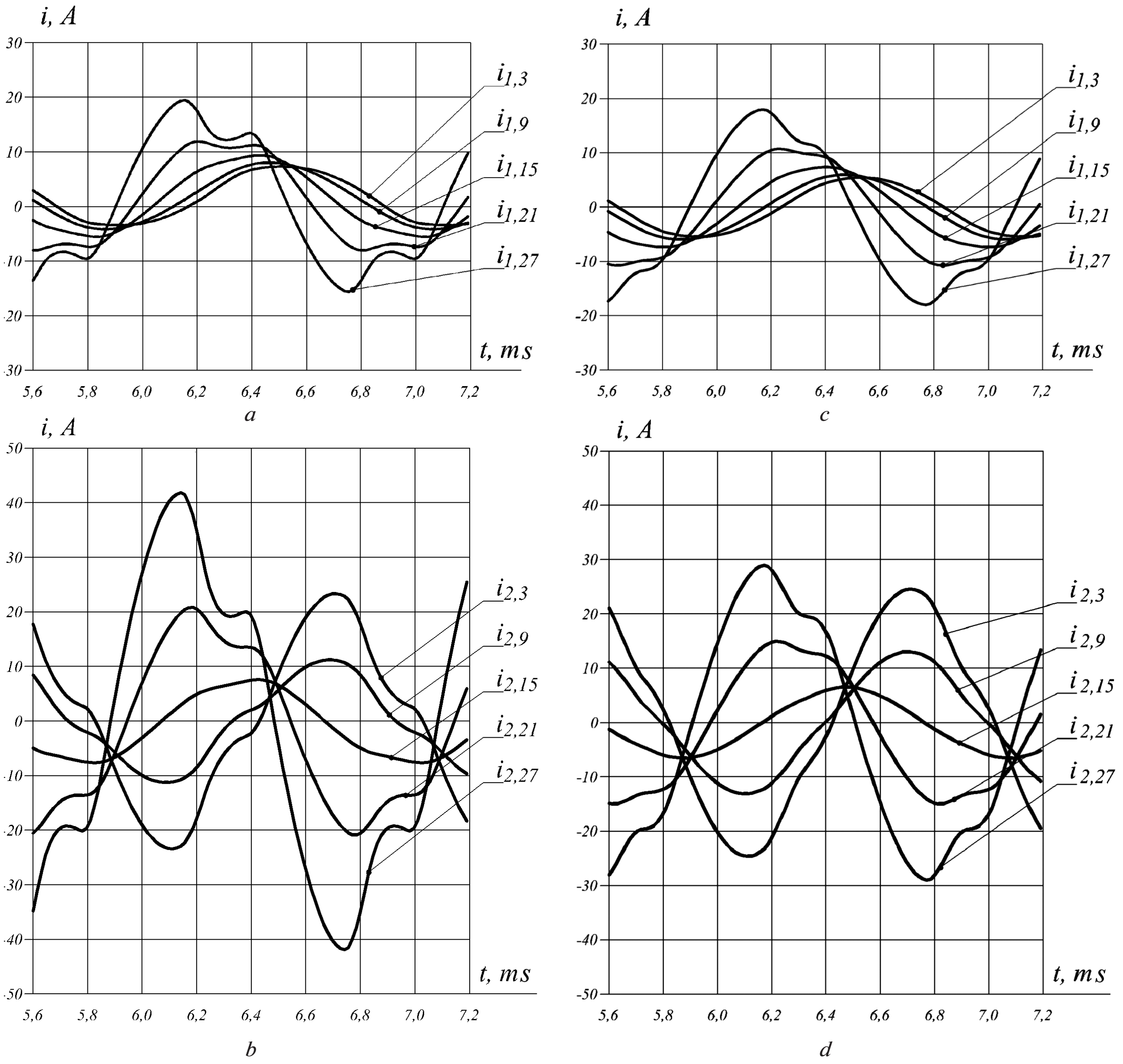


Fig. 5. Dependency of currents of electromagnetic conductors on time, A:

a, b — for semiclosed slot; c, d — for opened slot; a, c — effective conductor at the bottom of the slot; c, d — effective conductor near the spline

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Мета. Запропонувати спосіб визначення додаткових втрат в обмотках статорів електричних машин, частота струму в яких значно перевищує промислову.

Методика. Для дослідження використовуються чисельні методи розв'язування рівнянь математичної фізики, а саме: для алгебризації частинних похідних – метод скінченних елементів, для алгебризації похідних за часом – метод формул диференціювання назад, для розв'язування нелінійних систем алгебричних рівнянь – метод Ньютона-Рафсона.

Результати. Створена математична модель, що дозволяє розраховувати повні втрати в пазовій частині обмотки статора високошвидкісної електричної машини, обумовлені ефектом витіснення струму, та з урахуванням чинників, що здійснюють визначальний вплив на перебіг цього явища: власного потоку пазового розсіювання, основного магнітного потоку, насичення магнітопроводу, форми паза та способу електричного сполучення елементарних провідників котушки. Подане математичне формулювання та крайова умова даної задачі.

Для високошвидкісного генератора зі збудженням від постійних магнітів 200 кВт, 50 000 об/хв, наведені результати математичних експериментів із визначення додаткових та повних втрат в обмотках, що лежать у напівзакритих та відкритих пазах. Аналізуються причинно-наслідкові зв'язки, наведені висновки, що можуть допомогти у створенні таких машин.

Наукова новизна. Проблема розрахунку втрат формулюється як 2-вимірна крайова задача електродинаміки, що дозволяє врахувати вплив усіх вищезгаданих чинників у взаємозв'язку.

Практична значимість. Потреба в точному визначенні втрат у фазних обмотках високошвидкісних машин виникає не лише під час проектування обмоток, але й за оцінки теплового стану таких машин.

Ключові слова: *додаткові втрати, витіснення струму, скін-ефект, FEM-аналіз, крайова умова, високошвидкісна електрична машина*

Цель. Предложить способ определения добавочных потерь в обмотках статоров электрических машин, частота тока в которых существенно выше промышленной частоты.

Методика. Для исследования применяются численные методы решения дифференциальных уравнений математической физики, а именно: для алгебраизации частных производных – метод конечных элементов, для алгебраизации производных по времени – неявный метод формул дифференцирования назад, для решения нелинейных систем алгебраических уравнений – метод Ньютона-Рафсона.

Результаты. Создана математическая модель, позволяющая рассчитывать полные потери в пазовой части обмотки статора высокоскоростной электрической машины, вызванные эффектом вытеснения тока и с учетом причин, оказывающих определяющее влияние: собственного потока пазового рассеивания, основного магнитного потока, насыщения магнитопровода, формы паза и способа электрического соединения элементарных проводников в пазу. Приведены математическая формулировка и краевое условие данной задачи.

Для высокоскоростного генератора с возбуждением от постоянных магнитов 200 кВт, 50 000 об/мин, приводятся результаты математических экспериментов по определению дополнительных и полных потерь в обмотках, расположенных в полузакрытых и открытых пазах. Анализируются причинно-следственные связи. Сделанные выводы могут помочь при создании таких машин.

Научная новизна. Проблема расчета потерь формулируется как 2-мерная краевая задача электродинамики, что и позволяет учесть все вышеупомянутые факторы в их взаимосвязи.

Практическая значимость. Необходимость в точном определении потерь в фазных обмотках высокоскоростных машин возникает не только во время проектирования обмоток, но и при оценке теплового состояния таких машин.

Ключевые слова: *добавочные потери, вытеснение тока, скин-эффект, FEM-анализ, краевое условие, высокоскоростная электрическая машина*

Рекомендовано до публікації докт. техн. наук І. З. Щуром. Дата надходження рукопису 18.12.15.