Calculation of Magnetic Losses with Non-Uniform Distribution of Magnetic Induction in the Stator Tooth of a Switched Reluctance Motor

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Abstract. The aim of this study is to investigate and determine the effect of accounting for the non-uniform distribution of magnetic induction (by detailing the stator tooth model) on the calculation results of magnetic losses in the stator teeth of a switched reluctance motor in quasi-steady-state modes. To achieve this goal, dependencies of phase flux linkage, electromagnetic torque of the motor, and additionally, dependencies of the root mean square values of magnetic inductions in stator tooth elements on the rotor angle and current have been determined using the finite element method. An investigation of dynamic modes of the switched reluctance motor based on an improved simulation model has been conducted at various values of constant load torque. Dependencies of magnetic inductions over time for each stator tooth element for the studied quasi-steady-state operating modes have been obtained. Magnetic losses have been calculated, taking into account the maxima of the temporal dependencies of root mean square values of magnetic induction in stator tooth elements. The most important outcome is a quantitative assessment of the influence of the non-uniform distribution of magnetic induction on the calculated value of magnetic losses based on the detailing of the stator tooth model in the operational modes of the switched reluctance motor compared to the traditional approach. The significance of the work lies in developing an approach to refining the calculation of magnetic losses by considering local saturation–in the magnetic circuit during the operation of the switched reluctance motor.

***Keywords*:** switched reluctance motor, magnetic losses, stator tooth detailing, magnetic induction, quasi-steady-state mode.

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Calculul pierderilor magnetice cu distribuția neuniformă a inducției magnetice în dintele statorului al unui motor cu reluctanță comutată

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Rezumat. Scopul acestei lucrări este de a cerceta și de a determina gradul de influență a distribuției inducției magnetice neuniforme (prin detalierea modelului întrefierului statorului) asupra rezultatelor calculării pierderilor magnetice în dinții statori ai unui motor cu reluctanță comutată (MRC) în moduri cvasi-statice. Pentru a atinge acest obiectiv, a fost realizată o modelare matematică de simulare a modurilor dinamice ale motorului cu reacție pe baza unui model rafinat, ai cărui parametri de intrare includ dependențe bidimensionale (pe lângă dependențele legăturii fluxului de faze și cuplul electromagnetic a motorului) de inducție magnetică în elementele întrefierului statorului pe unghi de rotație și curent, calculată prin metoda elementelor finite. Pierderile magnetice se determină ținând cont de dependențele maxime de timp ale valorilor rădăcină pătratică medie (rpm) ale inducției magnetice în elementele întrefierului statorului MRC, obținute prin analiza modurilor cvasistatice studiate. Cel mai semnificativ rezultat este determinarea unei evaluări cantitative a gradului de influență a distribuției inegale a inducției magnetice asupra valorii calculate a pierderilor magnetice pe baza utilizării detaliului modelului întrefierului statorului în modurile de funcționare ale MRC în comparație cu abordarea tradițională. Un rezultat important al acestei lucrări este dezvoltarea unei abordări de rafinare a calculului pierderilor magnetice la motoarele cu reluctanță comutată, ținând cont de saturațiile locale ale circuitului magnetic.

***Cuvinte-cheie*:** motor cu reluctanță comutată, pierderi magnetice, detalierea întrefierului statorului, inducție magnetică, mod cvasistatic.

Расчет магнитных потерь при неравномерном распределении магнитной индукции в зубце статора вентильно-реактивного двигателя

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Аннотация. Целью данной работы является исследование и определение степени влияния учета неравномерности распределения магнитной индукции (путем детализации модели зубца статора) на результаты расчета магнитных потерь в зубцах статора вентильно-реактивного двигателя в квазиустановившихся режимах. Для достижения поставленной цели: определены с помощью метода конечных элементов зависимости потокосцепления фазы, электромагнитного момента двигателя и дополнительно зависимости среднеквадратичных значений магнитных индукций в элементах зубца статора от угла поворота ротора и тока; проведено исследование динамических режимов вентильно-реактивного двигателя на основе уточненной имитационной модели при различных значениях постоянного момента нагрузки; получены для каждого элемента зубца статора зависимости магнитных индукций во времени для исследуемых квазиустановившихся режимов работы. Магнитные потери рассчитаны с учетом максимумов временных зависимостей среднеквадратичных значений магнитной индукции в элементах зубца статора и определены полные потери в зубце вентильно-реактивного двигателя. Анализ исследований выполнен с помощью сравнения относительных расхождений результатов расчета магнитных потерь при использовании детализированной модели и модели сплошного зубца (традиционный подход). Наиболее существенным результатом является количественная оценка степени влияния неравномерности распределения магнитной индукции на расчетную величину магнитных потерь на основе детализации модели зубца статора в рабочих режимах вентильно-реактивного двигателя по сравнению с традиционным подходом. Определен уровень увеличения расчетных значений магнитных потерь (до 80%) благодаря учету локальных насыщений в детализированной модели зубца статора по сравнению с их определением на основе расчетной схемы сплошного зубца. Значимость работы заключается в разработке подхода к уточнению расчета магнитных потерь при неравномерном распределении магнитного потока в магнитопроводе в режимах работы вентильно-реактивного двигателя. Результаты работы могут быть использованы для уточнения расчета потерь и энергетических показателей в методиках проектирования вентильно-реактивных двигателей.

Ключевые слова: вентильно-реактивный двигатель, магнитные потери, детализация зубца статора, магнитная индукция, квазиустановившийся режим.

INTRODUCTION

The issue of improving efficiency in the operation modes of adjustable electromechanical converters is of current significance. This emphasizes the importance of an adequate assessment of the efficiency coefficient of electric motors and, consequently, refining the results of magnetic loss calculations in steady-state modes.

Determining magnetic losses in Switched Reluctance Motors (SRMs), which consist of an inductor machine (toothed structure of the stator and rotor) with a reactive (non-wound) rotor and a semiconductor commutator with microprocessor control, is a sufficiently complex task. This complexity arises from the nonlinear characteristics of the machine's magnetic circuit, the distribution of magnetic flux in different parts of the magnetic circuit (stator yoke, stator teeth, rotor yoke, rotor teeth), which strongly depends on operating modes. Additionally, significantly non-harmonic processes in SRMs are dependent on the angular position of the rotor and the spatial distribution of magnetic induction. Moreover, the magnetic flux in the teeth and yokes of the stator and rotor changes at different frequencies. Based on the outlined challenges, mathematical models for calculating magnetic losses in SRMs must take into account the magnetic state and the branched system of the magnetic circuit (toothed structure of the stator and rotor), as well as the engine control strategy.

The operating modes of SRMs are characterized by continuous repeating transient processes, which are determined by phase commutation. These quasi-steady-state modes in SRMs occur due to variations in the motor torque depending on the rotor angle, even with a constant resistance torque.

The design process of switched reluctance motors is carried out in stages. In the first stage, the magnetic systems of the motors are developed in accordance with the technical specifications, and static two-dimensional dependencies of phase flux linkage and root mean square values of induction in the elements of the magnetic circuit model are formed based on the rotor angle and phase current. These dependencies are used as input data for the second stage, which includes the investigation of dynamic modes as well as the calculation of losses and efficiency indicators of SRMs in quasi-steady-state modes. At this stage, tasks related to the effective control of the rotational speed of SRMs are addressed, considering the patterns of changes in the torque of the working mechanism.

Typically, the calculation of magnetic losses in SRM operation modes is based on modeling transient processes, assuming a uniform distribution of magnetic induction in conventionally defined sections of the magnetic circuit. In operational SRM modes, significant local saturations of the magnetic circuit occur due to the changing mutual positions of the stator and rotor teeth conducting the magnetic flux. The maximum non-uniformity of the flux occurs in the region adjacent to the air gap. The issue of the significance of refining magnetic losses considering local saturations in the crowns of SRM teeth is relevant and qualitatively addressed in this work by initially dividing the tooth crown into a small number of elements.

LITERATURE REVIEW

In the design of electric machines, the calculation of magnetic losses is carried out based on the classical approach using the expression [1], expressed in watts

$$P_c = p_{1,0/50} \cdot \sum_{i}^{n} \left(\frac{f}{50} \right)^{\alpha} \cdot k_{di} \cdot B_i^2 \cdot m_i, \qquad (1)$$

where $p_{1.0/50}$ are the losses in 1 kg of steel at an induction of 1 T and a current frequency of 50 Hz; n is the total number of sections in the magnetic circuit (teeth and yokes of the stator and rotor); f is the frequency of remagnetization; α is the exponent, dependent on the steel grade and the thickness of the magnetic circuit's steel sheets; B_i, T, m_i, kg are the magnetic induction and mass of the i-th section of the magnetic circuit, respectively; k_{di} is the coefficient taking into account the increase in magnetic losses due to incline during stamping and assembly technology.

Traditionally, in electric machines, magnetic induction is determined based on the theory of magnetic circuits for sections of the magnetic circuit [1], assuming a uniform distribution of magnetic flux. This approach does not account for significant non-uniformity in the distribution of magnetic induction in the sections of the magnetic circuit.

Well-known methods for calculating magnetic losses in SRMs are based on describing the waveforms of magnetic flux in each part of the machine's magnetic circuit, using an idealized form of magnetic induction in the stator teeth [2-14]. In study [3], these inductions are determined graphically, and Fourier analysis is employed to assess the frequency and amplitude of each harmonic component of the flux. Article [4] presents relationships of the flux in different parts of the SRM magnetic circuit in the form of matrix equations.

In [6], a simulation of magnetic losses in SRMs is proposed based on an energy approach [7]. When investigating dynamic modes, loss calculation blocks in the stator and rotor are incorporated into the SRM mathematical model in [8, 9].

Magnetic losses are calculated using various methods based on the classical Steinmetz equation or its modifications [9-12, 15-18]. In the yokes of the stator and rotor of SRMs, zones subject to different remagnetization frequencies are identified [10-12, 15, 17, 18].

In the cited works, the models of stator and rotor teeth are considered homogeneous (solid), and the calculation of magnetic losses is based on the spatially averaged and temporally maximum values of magnetic induction.

The consideration of local saturation in the teeth of the SRM stator and rotor is addressed in [19], where this investigation is conducted using a simplified analytical mathematical model.

In [20], a method for calculating magnetic losses in SRMs is presented, utilizing network analysis of resistances for calculating magnetic inductions. The model comprises multiple nonlinear resistances and inductances that account for the variation in the distribution of magnetic flux in the stator and rotor poles depending on their positions in dynamic modes.

The article [21] introduces a method for calculating losses in the steel of SRMs based on determining static dependencies of magnetic induction in the yoke and teeth zones with the finite element method, considering the phase current and rotor position of the SRM. Magnetic induction in the stator and rotor teeth is determined in three homogeneous elements: at the base of the tooth, its middle part, and the tooth crown. The obtained results are stored in 2D reference tables of the simulation model created in Matlab/Simulink. Based on these data, magnetic inductions are analytically calculated in operating modes at different angles of SRM activation and deactivation, as well as load torques.

To calculate and analyze magnetic losses in a direct current motor, the authors of [22] addressed the task of dividing the core into a significantly larger number of sectors, determining for each (based on the results of field analysis using the FEMM program) the root mean square values of the maximum magnetic inductions. This approach enables a more precise calculation of losses in electric machines.

The calculation of losses in quasi-steady-state operating modes of SRMs is based on modeling transient processes [15, 16] using a mathematical model presented as a system of differential equations of electrical and mechanical equilibrium:

$$\left.\begin{aligned} u(t) &= R\cdot i(t)+\frac{d\psi(\theta,i)}{dt} \\ \frac{d\omega_r}{dt} &= \frac{1}{J}(M-M_c) \end{aligned}\right\}, \qquad (2)$$

where R, u, i are the active resistance, instantaneous values of stator phase voltage and current; $\psi(\theta,i)$ is the flux linkage of the stator phase depending on the rotor angle θ and phase current; ω_r is the angular rotation frequency of the motor rotor $\omega_r=d\theta/dt$; J is the moment of inertia of the SRM rotor and the masses associated with it; M_c is the load torque on the motor shaft; M is the electromagnetic torque, calculated as the partial derivative of the coenergy W' with respect to displacement [23-25]:

$$M=\sum_{1}^{m}\left[\frac{\partial W'(\theta,i)}{\partial\theta}\right]_{i=const}, \qquad (3)$$

$$W'(\theta,i)=\int_{i_1}^{i_2}\psi(\theta,i)\cdot di, \qquad (4)$$

where m is the number of stator phases.

The solution to the task of designing a SRM as a whole, and specifically determining magnetic losses, is accomplished through the analysis of operational modes [23, 24, 26]. The authors of the papers [17, 18, 21] employ a method for calculating magnetic losses in the SRM magnetic circuit, which includes:

1) Modeling the SRM based on the finite element method to determine static dependencies $\psi(\theta,i)$, relying on the geometric dimensions and material of the SRM magnetic circuit.
2) Modeling transient processes in the SRM based on the system of equations (2), (3), and (4) considering the control algorithm of the semiconductor converter.
3) Determining dependencies of magnetic induction over time in various parts of the SRM magnetic circuit.
4) Determining the demagnetization frequency and the value of magnetic induction for each section of the stator and rotor core in the operational modes of the SRM.
5) Calculating the total magnetic losses, which are divided into three parts: eddy current losses, hysteresis losses, and additional losses.

The authors of this article conducted theoretical and experimental studies on the operational modes of a SRM from 2016 to 2021, where magnetic losses were calculated based on engineering design methods or determined experimentally [23, 24, 27].

In this work, research was carried out to determine the degree of influence of considering the non-uniform distribution of magnetic induction (by detailing the stator tooth model) on the results of calculating magnetic losses in the stator teeth of the Switched Reluctance Motor. Magnetic losses were calculated, taking into account the peaks of the temporal dependencies of the root mean square values of magnetic induction in the SRM stator tooth elements, obtained through the analysis of the investigated quasi-steady-state modes.

The aim of this study is to investigate and comparatively analyze the influence of detailing the stator tooth model on the results of calculating magnetic losses in quasi-steady-state modes of a Switched Reluctance Motor.

I. RESEARCH METHODOLOGY

As the object of study, a switched reluctance motor with a configuration of 6/4 (6 - the number of stator teeth, 4 - rotor teeth) was chosen. The stator core is laminated and made of electrical steel grade 2013, with a sheet thickness of 0.5 mm, steel filling factor k_c=0,95, specific magnetic losses of 2.5 W/kg for an induction of 1 T and a frequency of 50 Hz. The outer diameter of the stator is 89 mm, the inner diameter is 55 mm, the width of the stator tooth is 14.4 mm, the height of the stator tooth is 11.3 mm, and the stator yoke is 6.0 mm. The width of the rotor tooth is 8 mm, the height of the rotor tooth is 10 mm, and the rotor yoke is 9 mm. The air gap is 0.25 mm, and the active length is 60 mm.

Mathematical modeling was performed using MATLAB-Simulink with the SymPowerSystems library. The mathematical model is described by a system of differential equations of electrical and mechanical equilibrium (2). The electromagnetic torque is determined through the force of magnetic tension by Maxwell's equation:

$$M = \oint_S \left[\overline{r T_n} \right] dS, \qquad (5)$$

where S is the surface encompassing the volume of the active zone of the SRM rotor; $\bar{r}$ is the radius vector from the origin of the coordinate system to an element dS of the surface S; $\overline{T_n}$ is the force of magnetic tension acting externally on one unit of the surface S in the direction of the normal vector $\bar{n}$.

A simulation model was used, implementing control modes of the SRM with a semiconductor commutator with a current limitation. To investigate and analyze different methods of calculating magnetic losses in dynamic modes, this model is implemented with blocks approximating static dependencies of the root mean square $B_{kv}(\theta,i)$ and mean $B(\theta,i)$ values of magnetic induction on the rotor angle and phase current. These values are obtained from preliminary field analysis. The task of determining the root mean square values of magnetic induction in the sections of the SRM magnetic circuit was solved in this article using the COMSOL Multiphysics program.

The calculation of losses was carried out through a differentiated computational scheme for determining magnetic losses in the SRM magnetic circuit, in this case, with the detailing of the stator tooth model (on element #1 and elements #2 – #5 in the crown area of the tooth), as shown in Fig. 1.

The algorithm of computational studies included: 1) detailing the stator tooth by dividing it into individual elements; 2) determining, for each element, based on the results of preliminary field analysis, the dependence of the root mean square value of magnetic induction on the rotor angle and current; 3) using this information to calculate the dynamic modes of the SRM and obtaining dependencies of magnetic induction on time; 4) determining, for each element, the maximum in-time root mean square value of magnetic induction; 5) calculating magnetic losses for each element of the stator tooth, followed by their summation.

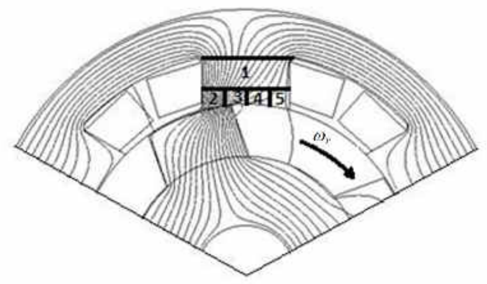


Fig. 1. Fragment of the cross-sectional view of the SRM electromagnetic system with stator tooth detailing.^{1}

Magnetic losses, when detailing the stator tooth, were calculated based on formula (1) for each element, taking into account the maximum values of magnetic inductions according to the formula:

$$P_{zs1} = k_{dz} \cdot p_{1,0/50} \cdot \left(\frac{f}{50} \right)^{\alpha} \cdot \sum_{j=1}^{n} \left(m_{zsj} \cdot B_{mkvj}^{2} \right), \qquad (6)$$

where n and j are the total number and the number of the stator tooth element according to Fig. 1; m_{zsj} is the mass of the j-th element of the stator tooth, and k_{dz}=2.

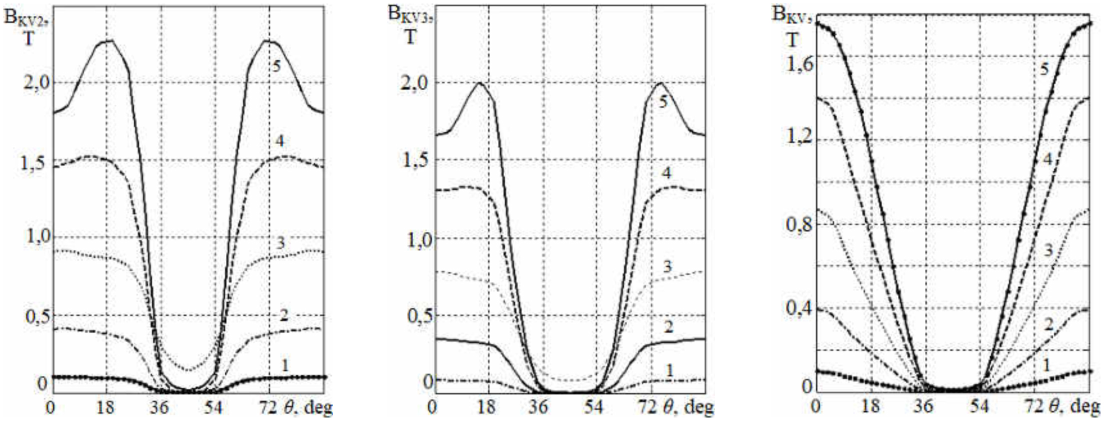
II. RESULTS AND DISCUSSION

Static dependencies of the root-mean-square values of magnetic inductions on the rotor angle and current were calculated with a uniform step from the minimum current density value j=1·10^{-6} A/mm^2 (Curve 1) to j=5·10^{-6} A/mm^2 (Curve 5). The graphs of these dependencies for elements #2 – $B_{kv2}(\theta,i)$ and #3 – $B_{kv3}(\theta,i)$ and the solid stator tooth $B_{kvz}(\theta,i)$ are shown in Fig. 2 *a*, Fig. 2 *b*, and Fig. 2 *c*, respectively.

Operational modes of the SRM were investigated for a range of resistance torque values M_c (0.6, 0.65, 0.725 N·m), a voltage of 150 V, and an inertia moment J=6,6·10^{-5} kg·m^2. The results of the analysis of quasi-steady-state modes of the SRM for M_c=0,6 N·m, turn-on angle $\theta_{вм}$=42° and turn-off angle $\theta_{вим}$=72° of the stator phase are illustrated in Fig. 3.

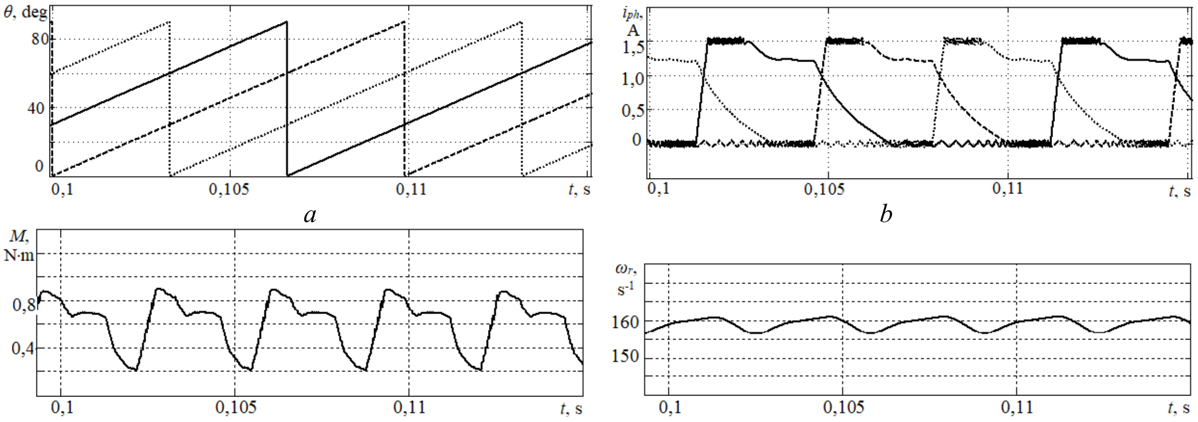
The period of rotor angle variation in geometric degrees, which determines the angular shift between interacting stator and rotor teeth, for the SRM configuration 6/4 is 90°. The angle changes from the initial value (unmatched position when the rotor tooth axis coincides with the stator slot axis) to the maximum value (matched position when the axes of the stator and rotor teeth coincide). Figure 3 *a* shows the temporal dependencies: rotor rotation angles relative to stator teeth $\theta=f(t)$; in Fig. 3 *b* – phase currents $i_{ф}=f(t)$; in Fig. 3 *c* – electromagnetic torque $M=f(t)$; in Fig. 3 *d* – angular rotation frequency of the motor rotor $\omega_r=f(t)$.

The temporal dependencies of inductions in the solid stator tooth $B_{kvz}(t)$ and its elements $B_{kvj}(t)$ are presented in Fig. 4. For each dependency, the maximum of the root mean square values of magnetic induction B_{mkv} was determined for further loss calculation using expression (6).



a *b* *c*

Fig. 2. Dependencies of magnetic induction on rotor angle and phase currents for elements #2 (*a*), #3 (*b*), and continuous (*c*) stator tooth.[2]



a *b* *c* *d*

Fig. 3. Temporal dependencies of rotor angle (*a*), phase currents (*b*), electromagnetic torque (*c*), and angular speed of the SRM rotor (*d*).[3]

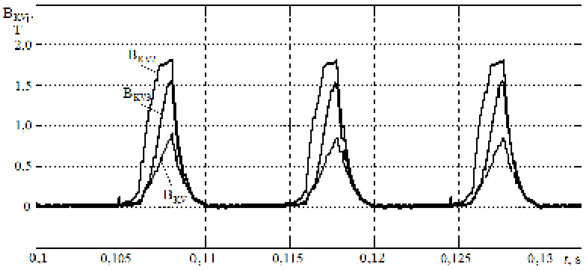


Fig. 4. Temporal dependencies of magnetic induction for elements #2, #3, and continuous stator tooth.[4]

The results of magnetic loss calculations in the stator tooth for the considered methods are presented in Tables 1 and 2, and a comparative analysis of these results is provided in Table 3. Losses in the solid tooth (based on the traditional approach) are calculated using formula (1) for the temporal maxima of the root mean square B_{mkv} and average B_m values of magnetic induction in space, denoted as P_{ZS2} and P_{ZS3} respectively in Table 2.

The relative discrepancies in the results of magnetic loss calculations with tooth detailing (Table 1) compared to the solid tooth (Table 2) were determined using expressions (7) and (8) respectively:

$$\Delta_1 = \frac{P_{zs1} - P_{zs2}}{P_{zs2}} \cdot 100\%. \qquad (7)$$

$$\Delta_2 = \frac{P_{zs1} - P_{zs3}}{P_{zs3}} \cdot 100\%. \qquad (8)$$

The degree of discrepancy in the results of magnetic loss calculations in the solid stator tooth when using B_{mkv} or B_m is calculated:

$$\Delta_3 = \frac{P_{zs2} - P_{zs3}}{P_{zs3}} \cdot 100\%. \qquad (9)$$

As a result of the analysis, it was determined that with an increase in the resisting torque from M_{c1}=0,6 N·m to M_{c3}=0,725 N·m, the discrepancies in the calculation results Δ_1, based on the root mean square values of magnetic induction, do not exceed 24%. Discrepancies in results Δ_2 and Δ_3 increase from 35.76% to 83.22% and from 9.6% to 49.83%, respectively.

Considering that the research was conducted through mathematical modeling, further development of the work involves comparing the results of magnetic loss calculations for a specific machine with experimental data.

Table 1[5].

Results of magnetic loss calculation based on the detailed model of the stator tooth[6].

Load Torque, N·m	Magnetic Inductions and Magnetic Losses in Elements and Stator Tooth	Tooth Element Numbers of Stator Tooth				
		1	2	3	4	5
0,6	B_{mkvj}, T	0,79	1,81	1,53	0,78	0,16
	P_{zsj}, W	0,358	0,254	0,149	0,039	0,002
	P_{zs1}, W	0,82				
0,65	B_{mkvj}, T	0,91	2,07	1,76	0,9	0.19
	P_{zsj}, W	0,423	0,296	0,176	0,046	0,002
	P_{zs1}, W	0,943				
0,725	B_{mkvj}, T	1,08	2,48	2,11	1,07	0,23
	P_{zsj}, W	0,49	0,349	0,208	0,053	0,003
	P_{zs1}, W	1,103				

Table 2[7].

Results of magnetic loss calculation based on the solid stator tooth model[8].

Load Torque, N·m	Operating Parameters, Magnetic Losses					
	ω_r, rad/s	f, Hz	B_{mkvj}, T	P_{ZS2}, W	B_m, T	P_{ZS3}, W
0,6	158,8	101,1	0,88	0,662	0,84	0,604
0,65	144,6	92,06	1,01	0,778	0,89	0,604
0,725	125	79,58	1,2	0,902	0,98	0,602

Table 3[9].

Comparative results of magnetic loss calculation in the stator tooth[10].

Relative discrepancies of calculation results	Load Torque, N·m		
	M_{c1}=0,6	M_{c2}=0,65	M_{c3}=0,725
Δ_1, %	23,87	21,21	22,28
Δ_2, %	35,76	56,13	83,22
Δ_3, %	9,6	28,8	49,83

III. CONCLUSIONS

The effect of detailing the stator tooth model on the results of magnetic loss calculations in the switched-reluctance motor, obtained through the analysis of quasi-steady-state modes, has been investigated.

An increase of up to 80% in the calculated values of magnetic losses was identified by considering local saturations in the stator tooth compared to their determination based on the continuous-tooth calculation scheme.

This approach can be utilized to refine loss calculations and energy performance assessments in the design methodologies of switched-reluctance motors.

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