RIGA TECHNICAL UNIVERSITY
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DESIGN AND OPTIMISATION OF BRUSHLESS SYNCHRONOUS MOTORS FOR USE IN LOW-POWER ELECTRICAL EQUIPMENT

Summary of Doctoral Thesis

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CONFIRMATION

Hereby I confirm that I have worked out the present Doctoral Thesis, which is submitted for consideration at Riga Technical University for the degree of Doctor of Engineering sciences. This work is not submitted in any other university for obtaining the doctor' degree.

Ludmila Lavrinovicha .... (Signature)

Date: ....

Doctoral thesis is written in the Latvian language. It contains introduction, 5 chapters, conclusions and main results of the work. Total volume of the thesis is 119 pages. Thesis consists of 64 figures and 19 tables. The number of references that is included in the thesis is 97.

CONTENTS

INTRODUCTION

Topicality of the thesis

Electrical motor is one of the major components of mechanical systems, which is used in many areas of technology. About 90 % of all electric motors are used in the low-power electrical equipment [1].

Mainly used low-power electric motors in household equipment, as well as in industrial and commercial enterprises are brushed motors, thanks to their simple and precise regulation of rotation speed [2, 3]. To reduce dimensions and weight of brushed motors, they are typically designed as high-speed and low-torque motors. Thus, the mechanical systems having such motors contain different transmission elements, often the belt transmission. In addition, mechanical systems with brushed motors have a low level of safety; they are expensive in the operation due to common servicing of brushes and collector, as well as transmission elements. Consequently, development and modernisation of such mechanical systems is a topical and important task.

One of the methods to improve features and safety of mechanical systems is the replacement of the brushed motors with brushless motors. This statement is well-founded for instance in the following sources [4, 5, 2, 6, 7].

Low-power brushless electric motors have high variety of constructive designs and functional significance. Depending on the application requirements brushless electric motors can be designed both with internal rotor and external rotor as well [8, 9, 10]. External rotor motors can be directly combined with operation element of the mechanical system that avoid transmission elements in different cases, and at the same time improve their reliability and overall dimensions.

The greatest interest in the development and modernisation of the mechanical systems cause brushless synchronous motors with electronic phase commutation, also known as alternating current electronic motors [11, 12].

Today, with the rapid development of brushless synchronous motors, there is an important issue of such motor energy performance, which is associated with a wide use of the high-energy permanent magnets. As the use of high-energy permanent magnet significantly raise the cost of such motors production, it is necessary to modernise the known designs for motors with permanent magnets or develop new ones, as well as develop new synchronous reluctance motors, which enable them to compete with those existing.

In view of the fact that the recently high using intensity of the active materials in electric motors causes the increase of the level of magnetic saturation, the study of new and existing electric motors is not possible without a detailed analysis of the magnetic field with consideration of the actual magnetic circuit saturation. Special computer programs, where magnetic field calculations are carried out by means of the finite element method (FEM), are widely used for such tasks solutions.

Development of the new motor designs, which is based on the magnetic field calculations, is associated with many magnetic field numerical calculations. In each task, the magnetic field calculation corresponds to the particular model of electrical machine with particular configurations of the magnetic circuit, current value and active material properties as well. For this reason, any changes of the geometry or characterising parameters of the studied motor require a new numerical experiment that further complicates the optimisation of the electric motor. To simplify such process, special metamodels are advised for the use being synthesised on the basis of the results of the magnetic field numerical calculations. Metamodels determine the relations between the results obtained in magnetic field calculations.

Subject under investigation, goal of the work and tasks

The low-power brushless synchronous motors (permanent-magnet synchronous motor and synchronous reluctance motor) capable of being run as alternating current electronic motor are the subjects of investigation in this work.

The goal of this work is to improve electromagnetic parameters of the low-power brushless synchronous motors by the development of new designs and synthesis of metamodels as well.

To achieve the set goal of the work the following main tasks have been defined:

1. to develop and provide a new designs of permanent-magnet synchronous motor and synchronous reluctance motor with improved electromagnetic parameters;
2. to develop a subprogram allowing significantly reduce labour-intensity in input data preparation during the magnetic field calculations;
3. based on the results of the magnetic field calculations to synthesise a metamodels, which can be used for analysis and optimisation of new designs of electric motor;
4. by the use of the synthesised metamodels to optimize the geometry of active area of the external-rotor permanent-magnet synchronous motor and synchronous reluctance motor;
5. to test the nominated theoretical regularity in the experimental studies.

Means and methods applied in the research

Numerical calculations of the magnetic field of the brushless synchronous motors under investigation are carried out in accordance with Maxwell's equations using the FEM with the help of software *QuickField* [13].

In order to simplify and accelerate the multiple calculation of the magnetic field subprogram in *Microsoft Excel* environment [15] is developed using *Visual Basic* programming language and *Active Field* Technology [14]. *Active Field* technology allows combining the developed subprogram with software *QuickField*, where using *Microsoft Excel* input data automatically takes the construction of the topological model and description of electromagnetic parameters of the object under investigation.

The method that has been developed by Latvian researcher V. Eglays and is described in the paper [16] is used for the synthesis of metamodels, which are used for analysis and optimisation of motors under investigation.

Scientific novelty of the work

1. Metamodels for external-rotor permanent-magnet motors and synchronous reluctance motors are synthesised.
2. Methodology based on numerical calculations of the magnetic field and metamodel synthesis for design optimisation of permanent-magnet synchronous motors and synchronous reluctance motors with external rotor is developed.
3. Developed the new designs of brushless synchronous motors.
4. The fact that the design of synchronous reluctance motor without rotor yoke can improve the motor efficiency is established.

Four received patents of Latvia and one filled international patent have confirmed the novelty of the developed motor designs.

Practical application of the work

1. Subprogram in *Microsoft Excel* environment is developed for automatic construction of the topological model and description of electromagnetic parameters of the motors under investigation in the software *QuickField*.
2. Two prototypes of permanent-magnet synchronous motors are designed and constructed, and one synchronous reluctance motor is designed with improved electromagnetic parameters in comparison with existing motors.
3. Developed brushless synchronous motors will be able to applied instead of the low-power brushed electric motors, for instance in the hand electric tools.

Work approbation

The main results of the research have been presented at the following international conferences:

1. „Analysis of a Permanent – Magnet Brushless DC Motor with Fixed Dimensions”, *51st* International Scientific Conference on Power and Electrical Engineering, Latvia, Riga, 14 October, 2010.
2. “VBA-Program for the Automatic Analysis of Brushless DC Motor Magnetic Field”, 6th International Conference on Electrical and Control Technologies (ECT-2011), Lithuania, Kaunas, 5–6 May, 2011.
3. “Metamodel for Permanent Magnet Synchronous Motor with Outer Rotor”, The 8th International Conference "Electric Power Quality and Supply Reliability" (PQ-2012), Estonia, Tartu, 11–13 June, 2012.
4. “The Influence of Permanent Magnet Parameters on the Effectiveness of Brushless DC Motor with Outer Rotor*”,* 21st Edition of the International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM 2012), Italy, Sorrento, 20–22 June, 2012.
5. „Magnetostatic Analysis of Surface-Mounted Permanent Magnet Motor with External Rotor for Use in Electric Hand Planer”, 14th International Scientific Conference Electric Power Engineering 2013 (EPE-2013), Chech Republic, Kouty nad Desnou, 28–30 May, 2013.
6. “Synchronous Reluctance Motor without Rotor Ferromagnetic Yoke”, IEEE Region 8 EUROCON 2013, Croatia, Zagreb, 1–4 July, 2013.
7. “Metamodeling of the Outer-Rotor Synchronous Reluctance Motor”, 54th International Scientific Conference on Power and Electrical Engineering, Latvia, Riga, 14–16 October, 2013.
8. “Comparison of Permanent Magnet Synchronous Motor and Synchronous Reluctance Motor Based on Their Torque per Unit Volume”, Electric Power Quality and Supply Reliability Conference (PQ2014), Estonia, Rakvere, 11–13 June, 2014.

Author’s publications

The main results of the research are presented in 14 publications, 9 of them included into database *SCOPUS* and 5 into database *IEEE Xplore Digital Library*:

1. Brakanskis U., Dirba J., Kukjane (Lavrinovicha) L., Drava V. Analysis of a Permanent – Magnet Brushless DC Motor with Fixed Dimensions. In: *Scientific Journal of RTU.* Power and Electrical Engineering. vol. 27. Riga: RTU, 2010, pp. 77–80.

2. Kukjane (Lavrinovicha) L., Brakanskis U., Dirba J. VBA-Program for the Automatic Analysis of Brushless DC Motor Magnetic Field. In: *Electrical and Control Technologies 2011*: *Proceedings of the 6th International Conference on Electrical and Control Technologies (ECT-2011)*, Lithuania, Kaunas: Technologija, 2011, pp. 231–234. ISSN 1822-5934.
3. Dirba, J., Lavrinovicha, L., Levins, N., Pugachev, V. Application of Synchronous Brushless Motors in Electric Hand Tools. *Latvian Journal of Physics and Technical Sciences*, 2012, vol. 49, no. 1, pp. 29–34. ISSN 0868-8257. Available from: doi:10.2478/v10047-012-0003-7. (*SCOPUS*)
4. Dirba, J., Lavrinovicha, L., Jekabsons, G., Vitolina, S. Metamodel for Permanent Magnet Synchronous Motor with Outer Rotor. In: *The 8th International Conference "Electric Power Quality and Supply Reliability": Conference Proceedings*, Estonia, Tallinn: Tallinn University of Technology, 2012, pp. 9–12. ISBN 9781467319775. (*SCOPUS* un *IEEE Xplore Digital Library*)
5. Dirba, J., Lavrinovicha, L., Onzhevs, O., Vitolina, S. The Influence of Permanent Magnet Parameters on the Effectiveness of Brushless DC Motor with Outer Rotor. In: *21st Edition of the International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM 2012)*, Italy, Sorrento: IEEE, 2012, pp. 718–723. ISBN 9781467313001. (*SCOPUS* un *IEEE Xplore Digital Library*)
6. Lavrinovicha, L., Dirba, J., Brakanskis, U., Lavrinovich, N. Experimental Study of Synchronous Electronically Commutated Outer – Rotor Brushless Motor at Stalled Rotor. In: *Power and Electrical Engineering*. vol. 31. Latvia, Riga: RTU, 2013, pp. 112–116.
7. Lavrinovicha, L., Dirba, J., Lavrinovichs, N. Magnetostatic Analysis of Surface-Mounted Permanent Magnet Motor with External Rotor for Use in Electric Hand Planer. In: *EPE: Electric Power Engineering 2013 (EPE 2013)*, Czech Republic, Ostrava: Technical University of Ostrava, 2013, pp. 1–4. (*SCOPUS* un *IEEE Xplore Digital Library*
8. Lavrinovicha, L., Brakanskis, U., Dirba, J. Synchronous Reluctance Motor without Rotor Ferromagnetic Yoke. In: *IEEE Eurocon 2013: IEEE Region 8 EuroCon 2013 Conference*, Croatia, Zagreb: 2013, pp. 1020–1024. ISBN 9781467322317. Available from: doi:10.1109/EUROCON.2013.6625106. (*SCOPUS* un *IEEE Xplore Digital Library*)
9. Levins, N., Pugachev, V., Dirba, J., Lavrinovicha, L. Electric Machines with Non-Radially Mounted Rectangular Permanent Magnets. *Latvian Journal of Physics and Technical Sciences*, 2013, vol. 50, iss. 2, pp. 15–22. ISSN 0868-8257. Available from: doi:10.2478/lpts-2013-0008. (*SCOPUS*)
10. Levins, N., Pugachev, V., Dirba, J., Lavrinovicha, L. High-Reliability Brushless Synchronous Motors for Hand Tools and Household Appliances. *Latvian Journal of*

Physics and Technical Sciences, 2013, vol. 50, iss. 3, pp. 3–11. ISSN 0868-8257. Available from: doi:10.2478/lpts-2013-0015. (*SCOPUS*)

11. Lavrinoviča, L., Dobrijans, R., Onževs, O. Metamodeling of the Outer-Rotor Synchronous Reluctance Motor. In: *Electronic Proceedings of 54th International Scientific Conference of Riga Technical University: 54th International Scientific Conference of Riga Technical University*, Latvia, Riga: RTU, 2013, pp. P8.1–P8.6.
12. Dirba J., Lavrinovicha L., Metamodels for new designs of outer-rotor brushless synchronous electric motors. *Latvian Journal of Physics and Technical Sciences*, 2014, vol. 51, iss. 2, pp. 22–30. ISSN 0868-8257. (*SCOPUS*)
13. Lavrinovicha L., Dirba J. Comparison of Permanent Magnet Synchronous Motor and Synchronous Reluctance Motor Based on Their Torque per Unit Volume. In: *Electric Power Quality and Supply Reliability Conference (PQ2014)*, Estonia, 2014. Tallinn: Tallinn University of Technology, 2014, pp. 233–236. (*SCOPUS* un *IEEE Xplore Digital Library*)
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Innovations

1. Pugachevs V., Dirba J., Kukjane (Lavrinovicha) L., Levins N., Orlova S. *The synchronous reluctance motor*. Int. Cl.: H02K19/02. Filing date 2011-08-17. Patents and Trademark. LV Patent 14418 B. 2012-01-20.
2. Levins N., Dirba J., Lavrinovicha L., Pugachevs V. *High speed magnetoelectric synchronous motor*. Int. Cl.: H02K1/27. Filing date 2012-03-13. Patents and Trademark. LV Patent 14509 B. 2012-07-20.
3. Levins N., Dirba J., Lavrinovicha L., Orlova S., Pugačevs V. Synchronous motor with permanent magnets. Int. Cl.: H02K1/27. Filing date 2011-11-07. Patents and Trademark. LV Patent 14458 B. 2012-03-20.
4. Levins N., Dirba J., Lavrinovicha L., Pugachevs V. *High speed magnetoelectric synchronous motor*. Int. WO2013/135312 A. International filing date 2012-08-16.World Intellectual Property Organization. 2013-09-19.
5. Levins N., Pugachevs V., Dirba J., Lavrinovicha L., Brakanskis U. Synchronous reluctance motor. Int.Cl. H02K19/02. Filing date 2012-11-16. Patents and Trademark. LV Patent 14627 B. 2013-04-20.

1. LOW-POWER BRUSHLESS SYNCHRONOUS MOTORS – ALTERNATIVE FOR WIDELY USED BRUSHED MOTORS

The first chapter of the work focuses on the analysis of characteristics, advantages and disadvantages of the low-power electric motors. On this analysis results the brushless synchronous motors are chosen as a studied object. General description of the brushless synchronous motors is given in this section and considering the fact that they can be run as alternating current electronic motors, this section deals with the fundamental issues of alternating current electronic motors. Basic equations for brushless synchronous alternating current electronic motors are described. Using such equations the analysis of mechanical characteristics of the studied motors are made, and obtained characteristics are compared with known brushed motor characteristics.

Low-power electric motors differ from other motors types not only with mass productions and wind use, but also with constructive performance and diversity of functional opportunities. Low-power electric motors can be divided into asynchronous, synchronous and brushed motors (or collector motors).

Depending on construction of the rotor, asynchronous motors can be divided into cage rotor motors and motors with phase rotor. The main advantage of asynchronous motors with cage rotor is absence of sliding contacts. These motors have a fast running, they have a stable operation under the variable load conditions, and they have a simple production and servicing. However, they have high starting current, low power factor, relatively low starting torque, complex control of rotation speed, and they are sensitive to the changes of the power network parameters. Asynchronous motors with phase rotor in comparison with cage rotor asynchronous motors are able for providing a lower starting current, higher starting torque and rotation speed regulation in small range. However, they have a complex construction and sliding contacts. In addition, the asynchronous motors have significant reactive power consumption, especially in the operating modes with a small load. [17]

Low-power synchronous motors are divided into motors with electromagnetic excitation, motors with permanent magnets, reluctance and hysteresis motors [18]. Nowadays, application of the permanent magnets in synchronous motors allows to provide the following motor advantages: low energy losses, hence higher efficiency, smaller dimensions and weight, invariability of the magnetic flux (it does not depend on the variations of the supply voltage and frequency), and such motors have better cooling conditions as well. However, permanent-magnet motors have also disadvantages that are associated with the permanent magnet high cost and sensitivity to vibrations and high temperatures. In contrast, synchronous reluctance motors have no excitation winding and any permanent magnet; therefore, they are safer and less expensive in comparison to other motors. However, the most widely used synchronous reluctance motors have relatively low electromagnetic torque per unit volume in comparison with other brushless motors.

Brushed motors can have an electromagnetic excitation or permanent-magnet excitation. Motors with electromagnetic excitation have a series or parallel excitation. Usually small-size motors do not have compound excitation. Brushed motors with permanent-magnet excitation are widely used, especially in low-power electric drive. Brushed motors are widely used in household appliances, due to their small dimensions, high starting torque and easy and precise rotation speed regulation in a wide range [19]. However, such motors have low efficiency, low level of safety and insufficient operation time that is mainly due to the collector and brushes.

To analyse a variety of different motors advantages and disadvantages two motor types could be highlighted, those which have the most interest in issues of motor parameters improvement. Such motors are permanent-magnet synchronous motors and synchronous reluctance motors, which are also able to run as alternating current electronic motor.

Alternating current electronic motor operates like the classic synchronous motor, as rotation frequency of stator magnetic field coincides with rotation frequency of rotor magnetic field. The difference between alternating current electronic motor and classic synchronous motor is that the rotational frequency of the first motor rotational field is determined by the feedback rotational frequency of the rotor [20].

Based on the synchronous machine theory fundamentals alternating current electronic motors as synchronous machines operate in special modes, which remain unchanged, for instance, such values as load angle θ between the supply voltage U_1 and the fundamental harmonic of no-load EMF, or angle ε between axes of excitation and armature MMFs.

Basic equations for permanent-magnet synchronous motor's electromagnetic parameters calculation, as armature current I_1, electromagnetic torque T_{em}, active power P_1, phase angle φ between the phase current I_1 and phase voltage U_1, follows. Such equations are derived from the vector diagram of the non-salient pole electric machine [21].

Equations for alternating current electronic motor that operates with control of an angle θ are the following

$$I_1 = \sqrt{\frac{U_1^2 - 2U_1 I_2 \omega L \cos\theta + \omega^2 I_2^2 L^2}{r_1^2 + \sigma^2 \omega^2 L^2}}\,; \tag{1.1}$$

$$P_{em} = \frac{m\omega L I_2 [U_1(\sigma\omega L \sin\theta + r_1 \cos\theta) - I_2 \omega L r_1]}{r_1^2 + \sigma^2\omega^2 L^2}; \tag{1.2}$$

$$P_1 = mU_1 \left[\frac{U_1 r_1 + I_2 \omega L (\omega L \sigma \sin\theta - r_1 \cos\theta)}{r_1^2 + \sigma^2\omega^2 L^2} \right]; \tag{1.3}$$

$$T_{em} = \frac{mpLI_2 [U_1(\sigma\omega L \sin\theta + r_1 \cos\theta) - I_2 \omega L r_1]}{r_1^2 + \sigma^2\omega^2 L^2}; \tag{1.4}$$

$$\mathrm{tg}\varphi = \frac{\omega L [\sigma U_1 - I_2(\sigma\omega L \cos\theta + r_1 \sin\theta)]}{U_1 r_1 + I_2 \omega L (\sigma\omega L \sin\theta - r_1 \cos\theta)}, \tag{1.5}$$

and with control of an angle ε are the following

$$I_1 = \frac{\sqrt{I_2^2\omega^2 L^2 (r_1 \sin\varepsilon + \omega L\sigma \cos\varepsilon)^2 + (r_1^2 + \sigma^2\omega^2 L^2)(U_1^2 - I_2^2\omega^2 L^2)}}{r_1^2 + \sigma^2\omega^2 L^2} -$$

$$- \frac{I_2 \omega L (\omega L \sigma \cos\varepsilon + r_1 \sin\varepsilon)}{r_1^2 + \sigma^2\omega^2 L^2}; \tag{1.6}$$

$$P_{em} = m\omega L I_1 I_2 \sin\varepsilon; \tag{1.7}$$

$$P_1 = mI_1(\omega L I_2 \sin\varepsilon + I_1 r_1); \tag{1.8}$$

$$T_{em} = mpLI_1 I_2 \sin\varepsilon; \tag{1.9}$$

$$\mathrm{tg}\varphi = \frac{\omega L (\sigma I_1 + I_2 \cos\varepsilon)}{I_2 \omega L \sin\varepsilon + I_1 r_1}, \tag{1.10}$$

where m – the number of phases;

ω – the angular frequency of armature current, rad/s;

p – the number of pole pairs;

σ – the distributed factor of the armature winding;

I_2 – the current of the excitation winding reduced to the armature winding, A;

r_1 – the active resistance of the armature winding, Ω;

L – the inductance correspondent to the flux of armature reaction, H.

Equations (1.1)–(1.10) allow obtaining of all necessary curves for alternating current electronic motor at changing rotation frequency.

It should be noted that during the use of equations (1.1)–(1.10) the permanent magnets in synchronous motors are replaced relatively with the equivalent winding current I_2. Current I_2 is calculated as equivalent, i. e. providing the same fundamental harmonic of magnetic flux density in the motor air gap as used permanent magnets [22].

Synchronous reluctance motors have no excitation winding (I_2 = 0) and any permanent magnets, so the basic equations for such motor's electromagnetic parameters calculation with control of angle θ are the following

$$I_1 = \frac{U_1\sqrt{(\omega L_{ad}\sigma\sin\theta + r_1\cos\theta)^2 + \left[\omega L_{ad}\left(\frac{k_q}{k_d}+\sigma-1\right)\cos\theta - r_1\sin\theta\right]^2}}{r_1^2 + \sigma\omega^2 L_{ad}^2\left(\frac{k_q}{k_d}+\sigma-1\right)}; \tag{1.11}$$

$$P_{em} = \frac{m\omega L_{ad}U_1^2\left[\omega L_{ad}\left(\frac{k_q}{k_d}+\sigma-1\right)\cos\theta - r_1\sin\theta\right](\sigma\omega L_{ad}\sin\theta + r_1\cos\theta)\left(1-\frac{k_q}{k_d}\right)}{\left[r_1^2 + \sigma\omega^2 L_{ad}^2\left(\frac{k_q}{k_d}+\sigma-1\right)\right]^2}; \tag{1.12}$$

$$P_1 = mU_1^2\left[\frac{r_1 + 0.5\omega L_{ad}\left(1-\frac{k_q}{k_d}\right)\sin 2\theta}{r_1^2 + \sigma\omega^2 L_{ad}^2\left(\frac{k_q}{k_d}+\sigma-1\right)}\right]; \tag{1.13}$$

$$T_{em} = \frac{mpL_{ad}U_1^2\left[\omega L_{ad}\left(\frac{k_q}{k_d}+\sigma-1\right)\cos\theta - r_1\sin\theta\right]}{\left[r_1^2 + \sigma\omega^2 L_{ad}^2\left(\frac{k_q}{k_d}+\sigma-1\right)\right]^2}\times$$

$$\times\frac{(\sigma\omega L_{ad}\sin\theta + r_1\cos\theta)\left(1-\frac{k_q}{k_d}\right)}{\left[r_1^2 + \sigma\omega^2 L_{ad}^2\left(\frac{k_q}{k_d}+\sigma-1\right)\right]^2}; \tag{1.14}$$

$$\mathrm{tg}\varphi = \frac{\omega L_{ad}\left[\sigma\sin^2\theta + \left(\frac{k_q}{k_d}+\sigma-1\right)\cos^2\theta\right]}{r_1 + 0.5\omega L_{ad}\left(1-\frac{k_q}{k_d}\right)\sin 2\theta}, \tag{1.15}$$

and with control of angle ε are the following

$$I_1 = \frac{U_1}{\sqrt{(\omega L_{ad}\sigma\cos\varepsilon + r_1\sin\varepsilon)^2 + \left[\omega L_{ad}\left(\sigma-1+\frac{k_q}{k_d}\right)\sin\varepsilon - r_1\cos\varepsilon\right]^2}}; \tag{1.16}$$

$$P_{em} = 0.5m\omega L_{ad}I_1^2\left(1-\frac{k_q}{k_d}\right)\sin 2\varepsilon; \tag{1.17}$$

$$P_1 = mI_1^{\ 2}\left[r_1 + 0.5\omega L_{ad}\left(1 - \frac{k_q}{k_d}\right)\sin 2\varepsilon\right]; \tag{1.18}$$

$$T_{em} = 0.5mpL_{ad}I_1^{\ 2}\left(1 - \frac{k_q}{k_d}\right)\sin 2\varepsilon; \tag{1.19}$$

$$\mathrm{tg}\varphi = \frac{\omega L_{ad}\left(\cos^2\varepsilon + \frac{k_q}{k_d}\sin^2\varepsilon + \sigma - 1\right)}{r_1 + 0.5\omega L_{ad}\left(1 - \frac{k_q}{k_d}\right)\sin 2\varepsilon}, \tag{1.20}$$

where L_{ad} – the inductance that corresponds to the armature magnetic flux along direct axis, H;

k_q and k_d – the armature reaction factors along direct and quadrature axes.

Based on the above equations (1.1)–(1.10), mechanical curves $n = f(T_{em})$ of the permanent - magnet alternating current electronic motor[1] at operating modes with different values of controlled angle θ (fig. 1.1.) and operating modes with different values of controlled angle ε (fig. 1.2.) are obtained.

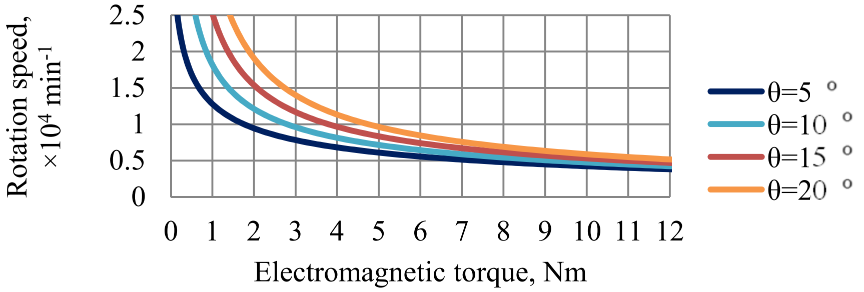

Fig. 1.1. Mechanical curves of alternating current electronic motor with permanent magnets at different angle θ values

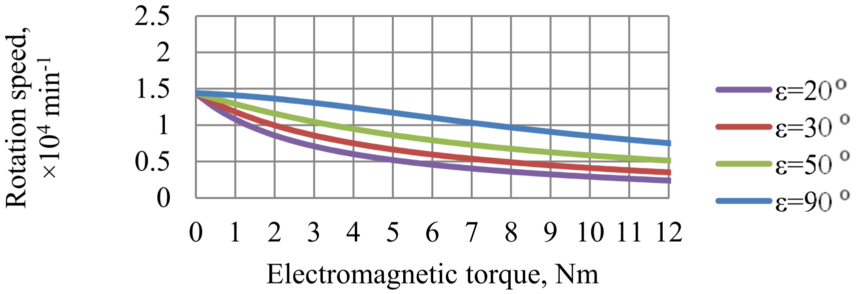

Fig. 1.2. Mechanical curves of alternating current electronic motor with permanent magnets at different angle ε values

[1] Parameters of permanent-magnet alternating current electronic motor: $p = 2$; $m = 3$; $U_1 = 92$ V; $L = 0.00061$ H; $r_1 = 0.25$ Ω; $\sigma = 1.04$; permanent magnet residual flux density 1.2 T and thickness 2 mm; pole overlap factor 0.8; $I_2 = 50$ A.

Mechanical curves of reluctance alternating current electronic motor[2] at responded operating modes, which are calculated using equations (1.11)–(1.20), are presented in figures 1.3 and 1.4.

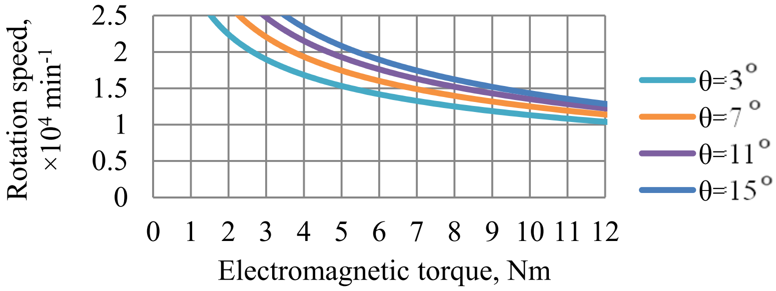

Fig. 1.3. Mechanical curves of reluctance alternating current electronic motor at different angle θ values

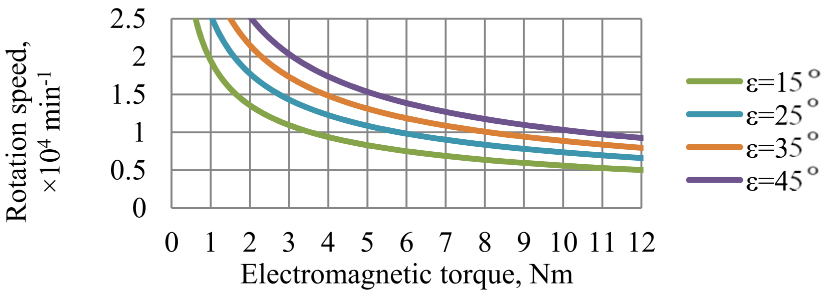

Fig. 1.4. Mechanical curves of reluctance alternating current electronic motor at different angle ε values

The analysis of alternating current electronic motor equations and obtained curves shows that they can provide a wide range of mechanical curves. Comparative analysis of the obtained mechanical curves of permanent-magnet and reluctance alternating current electronic motors shows that the permanent-magnet motors have a wider range of mechanical curves, which can be similar to those of brushed motors with parallel, series or compound excitation. On the other hand, reluctance alternating current electronic motors with operating in special modes can provide mechanical curves similar to the curves of brushed motors with series excitation.

The additional positive effects can be achieved during the choice of appropriate operating mode and curves, for instance such as limiting of no-load rotation frequency, which in many existing power tools creates known problems and require specialised solutions.

Generally, when load of alternating current electronic motor is changing, regulation of certain values (I_2, U_1, θ or ε) can provide any form of mechanical curve and high-energy performance as well.

[2] Parameters of reluctance alternating current motor: $p = 2$, $m = 3$, $U_1 = 92$ V, $L_{ad} = 0.00061$ H, $r_1 = 0.25$ Ω, $\sigma = 1.04$, $k_q/k_d = 0.15$.

2. NUMERICAL CALCULATIONS OF ELECTRIC MOTOR MAGNETIC FIELD – BASIS OF METAMODELS SYNTHESIS AND THEIR USE FOR OPTIMISATION OF MOTOR MAGNETIC SYSTEM

The second chapter of the thesis provides an overview of optimisation of electric motor magnetic system using a metamodels that are based on the results of magnetic field numerical calculations. Choice of the metamodels synthesis method is justified. Method of the metamodels synthesis is described.

In order to simplify the optimisation task solution, which contains labor-intensive calculations, nowadays the metamodels are often used. Metamodel is a simplified model of a mathematical model or an approximation of a complex model with a simple model [23, 24].

General idea of metamodeling is shown in fig. 2.1., where the first level defines the variables that significantly influence the optimisation criterion, the second level defines the numerical models of the object under investigation, and the third level defines the metamodel that describes the set of models of the previous level. The main objective of the metamodeling is establishment of the mathematical model that describes the input and output parameters interdependence.

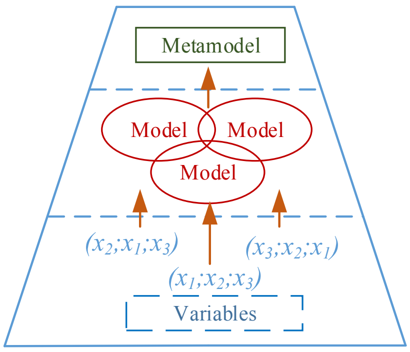

Fig. 2.1. General idea of metamodeling

Optimisation of the electric motor magnetic system using the metamodel can be divided into five following main stages:

1. Limitation of optimisation system;
2. Choosing of the optimisation criteria, variable factors, their changing diapason and optimisation restrictions;
3. Rational design of experiments;
4. Experiments realisation;
5. Synthesis of the metamodel and optimisation of the system under investigation.

All necessary information of electric motor magnetic field, considering real magnetic system saturation, for motor design and optimisation can be obtained by the numerical calculations according to Maxwell's equations [25] using finite element method and software *QuickField* [13].

Software *QuickField* provides fast, easy and precise numerical solution. However, in the case when the number of numerical experiments is large, their automatisation is necessary. For this purpose, a program [15] in *Microsoft Excel* environment is developed by the use of *Visual Basic for Application* (VBA) [26]. Moreover developed program in *Microsoft Excel* environment can be combined with software *QuickField* by using a special *Active Field* technology [14].

Algorithm of the developed program is shown in fig. 2.2.

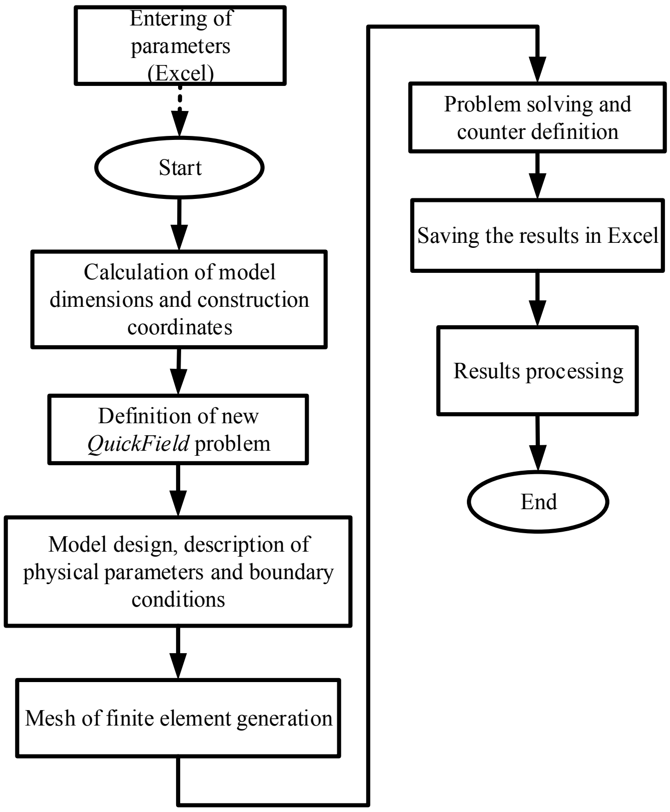

Fig. 2.2. Developed program algorithm

The developed programme provides precise description of the model according to the input data. This programme significantly simplifies realisation of numerical experiments.

Metamodels, which are used for optimisation of brushless synchronous motors under investigation in this research, are synthesised with the help of method of Latvian researcher V. Eglays [16]. This method is based on polynomial approximation of tabular data. Such method is simple, sufficiently precise and efficient.

3. DEVELOPMENT OF NEW DESIGNS OF BRUSHLESS SYNCHRONOUS MOTORS

The third chapter deals with improvement opportunities of widely used designs of brushless synchronous motors. That also describes the new designs of brushless synchronous motors that developed in this research. Such new designs could compete with known motor designs.

The most often applied four-pole design of permanent-magnet synchronous motor with external rotor is presented in fig. 3.1. [27, 28, 29]. Pole overlapping factor of this motor is usually chosen within the range from 0.7 to 0.85. Such motor has relatively low value of electromagnetic torque per unit volume and intensive electromagnetic torque ripples that cause significant vibration, which in their turn worsens motor performance.

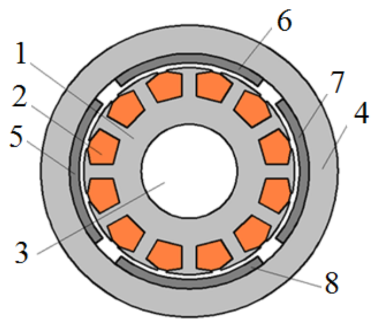

Fig. 3.1. Permanent-magnet synchronous motor:

1 – stator; 2 – armature winding; 3 – shaft; 4 – rotor yoke; 5–8 – permanent magnets

A new design of permanent-magnet synchronous motor, which is presented in fig. 3.2., is developed on the basis of analysis of the results of magnetic field and electromagnetic parameters calculations. Here the reduction of electromagnetic torque ripples for permanent magnet motor is achievement with special permanent magnet 1–4 form. This motor has permanent magnets created so that separated magnets sides at motor air gap are facing, but on the opposite surface, where the magnets touches to inner surface of the rotor yoke, their sides moving away along the arc l_{lok} (Patent of Latvia [30]).

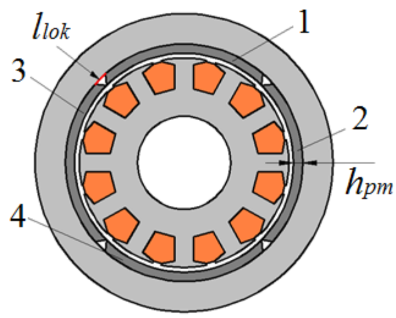

Fig. 3.2. Proposed design of permanent-magnet synchronous motor with external rotor:

1–4 – permanent magnets; h_{pm} – thickness of permanent magnet; l_{lok} – length of an arc

Length of the arc l_{lok} along that permanent magnets moving away in the new design of permanent-magnet synchronous motor is calculated according to the equation

$$l_{lok} = \frac{\pi h_{pm}}{p}, \tag{3.1}$$

where h_{pm} – thickness of permanent magnets.

Surface-mounted permanent-magnet synchronous motors have such disadvantage as insufficiently reliable permanent magnets mounting on rotor surface. Therefore, for increasing of synchronous motor reliability and reduce their production cost, another design of synchronous motor with bevelling buried permanent magnets in the rotor core is developed (Patent of Latvia [31]). The design of this permanent-magnet synchronous motor is presented in figure 3.3.

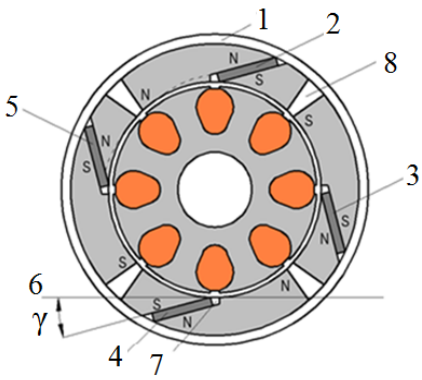

Fig. 3.3. New design of synchronous motor with bevelling buried permanent magnets:
1 – non-magnetic housing; 2–5 permanent magnets; 6 – tangent plane; 7 – rotor inner surface; 8 – non-magnetic gap

According to the invention [31] prismatic permanent magnets 2–5 are placed bevelling in the rectangular gaps between rotor poles. The magnets are placed at a 10–25 degrees angle against the tangent planes 6 of places on the rotor inner surface 7, where gaps between poles come into the air gap. Magnetisation direction of the magnets is perpendicular to the sides of rectangular gaps between rotor poles.

Permanent magnet placement in the rotor core provides a safe their strengthening. The non-magnetic gaps 8 in the centre of each pole provide reducing of magnetic field along quadrature axis of the developed motor. For reducing of electromagnetic torque ripples in the developed motor an uneven air gap varying from pole centre to this sides has been proposed to create. The uneven air gap approximates distribution of the magnetic flux density in air gap to a sine function. Possible uneven air gap of developed motor is shown with dashed line in fig. 3.3.

Often used design for synchronous reluctance motor with salient poles (fig. 3.4.) has a small value of electromagnetic torque per unit volume and massive ferromagnetic yoke by that the rotor poles are magnetically linked. Ferromagnetic yoke in such motors increases the overall motor weight.

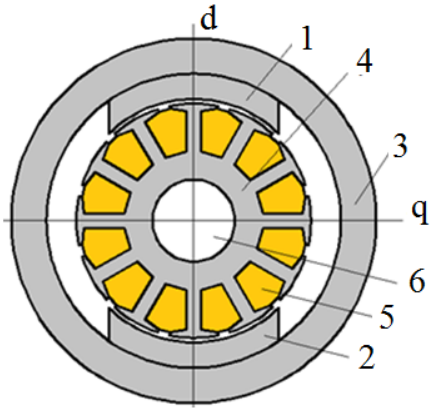

Fig. 3.4. Salient-pole synchronous reluctance motor:

1, 2 – salient poles of the rotor; 3 – ferromagnetic yoke; 4 – stator; 5 – armature winding; 6 – shaft

In order to improve electromagnetic torque per unit volume of synchronous reluctance motor the heavy and large ferromagnetic yoke is refused and an external rotor of the motor from the ferromagnetic segments 1, 2 (fig. 3.5.) is created. Ferromagnetic segments are created to be separated by non-magnetic space (Patent of Latvia [32]). In this case, the pole overlapping factor should be chosen from 0.8 to 0.98.

Refusing of the ferromagnetic yoke allows reduce the outer diameter of the motor, and increase of the pole overlapping allows increasing of motor electromagnetic torque.

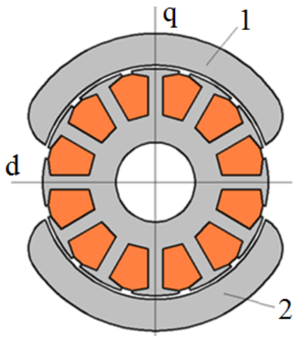

Fig. 3.5. New design of synchronous reluctance motor:

1, 2 – ferromagnetic segment-shaped packages

The new design of synchronous reluctance motor constructively is simple and cheap in production. However, small non-magnetic spaces between poles retain significant magnetic flux along transverse axis of the motor and electromagnetic torque ripples, which cause significant motor vibration during operation.

In order to reduce the electromagnetic torque ripples in such motor the skewing segments relative to the stator slots by value of stator tooth pitch (Patent of Latvia [33]) are proposed in this design.

4. ANALYSIS AND OPTIMISATION OF NEW DESIGNS OF BRUSHLESS SYNCHRONOUS MOTORS

This chapter contains analysis and optimisation of high-speed low-power brushless synchronous motors (permanent-magnet synchronous motor and synchronous reluctance motor) with external rotor using the magnetic field numerical calculations and synthesised metamodels. Synchronous motors with different materials of permanent magnets and synchronous reluctance motor are compared from the point of view of value of electromagnetic torque per unit volume of the motor.

The optimisation of the proposed motors with the method using synthesised metamodels is illustrated below with real examples. The chapter deals with optimisation of the four-pole permanent-magnet synchronous motor with external rotor. This motor is designed for direct drive high-speed hand power tools, such as electrical plane, where the outer dimensions of the motor under investigation are limited by its installation place. The objective of optimisation is to maximise the main magnetic flux of the motor under investigation that is generated by permanent magnets in limited dimensions of the motor and considering the restrictions of magnetic circuit saturation.

A cross section of four-pole permanent-magnet synchronous motor with external rotor under investigation is presented in fig. 4.1.

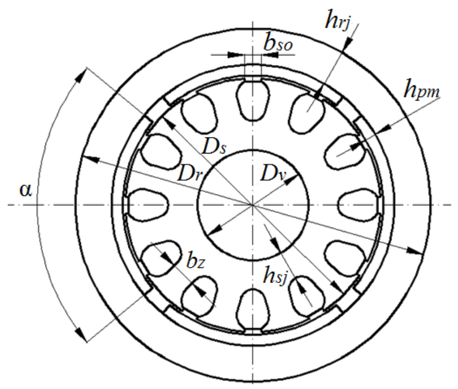

Fig. 4.1. Cross section of permanent magnet synchronous motor

As changing parameters for solution of optimisation task the five variables are selected, which mainly affects the main magnetic flux of the motor under investigation that in its turn affects the power and electromagnetic torque of the motor:

- the pole overlapping angle α;
- the residual flux density of the permanent magnets B_r;
- the relative permeability of the permanent magnets μ_r;
- the thickness of the permanent magnets h_{pm};
- the height of the rotor yoke h_{rj}.

Numerical experiments are carried out after choosing range of variables variation and design of experiments. Experiments are based on numerical calculations of the magnetic field using Maxwell's equations. Calculations of magnetic field are carried out by FEM using the software *QuickField* and specially developed program in *Microsoft Excel* environment.

Using a method based on polynomial approximation of tabular data on the basis of numerical calculation results of magnetic field the following metamodels are synthesised

$$\Phi = (-0.3168 - 0.0.3175\,\mu_r{}^{*} - 0.8246\,B_r^{*2} + 0.677\,B_r^{*}h_{pm}^{*} + 0.1363\,\alpha^{*}h_{pm}^{*} - \\ -1.583\,B_r^{*} + 0.235\,h_{rj}^{*} - 0.1394\,h_{rj}^{*}\,B_r^{*} - 0.0274\,h_{rj}^{*2})\cdot 10^{-3}; \quad (4.1)$$

$$B_{rj} = 1.127 - 0.6525\,h_{rj}^{*} - 0.265\,B_r^{*2} + 0.8705\alpha^{*}B_r^{*} + 0.2748\,\alpha^{*}h_{rj}^{*} - \\ -1.939\alpha^{*}h_{pm}^{*} + 2.158\,B_r^{*} + 2.425h_{pm}^{*} - 0.1979\,B_r^{*}h_{rj}^{*} - 1.124B_r^{*}h_{pm}^{*} + \\ +0.3878h_{pm}^{*}h_{rj}^{*} - 0.228\alpha^{*}\mu_r{}^{*}; \quad (4.2)$$

$$B_{sj} = -0.9987 - 0.2308\,\mu_r^{*} - 1.311\,B_r^{*2} - 0.0144\,h_{rj}^{*2} + 0.8229\,\alpha^{*}h_{pm}^{*} + \\ +3.101\,B_r^{*} + 0.2155\,h_{rj}^{*} + 0.0583\,B_r{}^{*}h_{rj}^{*} - 0.1283\,h_{pm}{}^{*}h_{rj}^{*}; \quad (4.3)$$

$$B_{sz} = 0.2918 + 1.226h_{pm}^{*} - 0.7185\alpha^{*} + 0.0571B_r^{*}h_{rj}{}^{*} - 0.0157h_{rj}^{*2} + \\ +2.867B_r^{*} - 0.2891\mu_r^{*2} - 0.9883B_r{}^{*2} - 0.5952B_r^{*}h_{pm}^{*} + 0.1017\alpha^{*}h_{rj}^{*}, \quad (4.4)$$

where $\alpha^{*} = 0.01\alpha, B_r^{*} = 1B_r, \mu_r^{*} = 1\mu_r, h_{pm}^{*} = 0.2h_{pm}, h_{rj}^{*} = 1h_{ry};$

Φ – the magnetic flux in the motor air gap, Wb;

B_{rj} – flux density in the rotor yoke, T;

B_{sj} – flux density in the stator yoke, T;

B_{sz} – flux density in the stator teeth, T.

Testing of the synthesised metamodels (4.1)–(4.4) using software *QuickField* showed that the relative error of them does not exceed 8 % in the plan points and intermediate points as well.

The optimal values of variable parameters, which provide the maximum value of magnetic flux in the motor under investigation with outer diameter D_r = 63 mm, are calculated maximising function (4.1) and assuming restrictions of magnetic system saturation. The restrictions of magnetic system saturation are assumed so that the calculated values of magnetic flux density according to equations (4.2)–(4.4) does not exceed 1.9 T in the stator teeth, 1.65 T in the stator and rotor yoke. The optimal values of calculated variable parameters are shown in table 4.1.

Table 4.1.

The optimal values of variable parameters for permanent-magnet synchronous motor

Label	Value	Unit
α	133	el.deg.
h_{pm}	3	mm
h_{rj}	5	mm
B_r	0.831	T
μ_r	1.02	-
Φ	0.00163	Wb

To assess the efficiency of the use of synchronous reluctance motor in the low-power electrical drives, this chapter contains also the optimisation of new design two-pole (p = 1) synchronous reluctance motor with segment-shaped rotor using specially synthesised metamodels. The task of optimisation is to find the maximum value of electromagnetic torque per unit volume T_{em}/V of the studied motor with fixed values of the nominal power and the nominal rotation speed. A cross section of the synchronous reluctance motor under investigation is presented in figure 4.2.

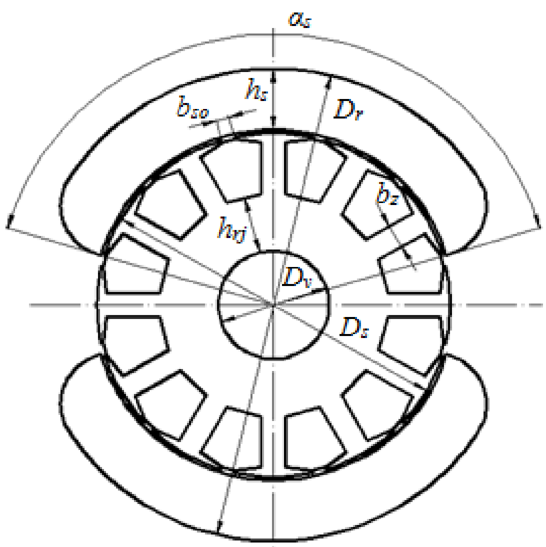

Fig. 4.2. A cross section of the synchronous reluctance motor

Three variable parameters are carried out for optimisation of the synchronous reluctance motor under investigation:

- pole overlapping angle α;
- thickness of the rotor segment h_s;
- outer diameter of the stator D_s.

Width of the stator teeth and height of the stator yoke depend on the variable stator diameter assuming that the stator slot area is constant.

Using results of the numerical experiments the following metamodels are synthesised

$$T_{em}/V = -16.670 - 1.601(\alpha_s^*)^{-1} + 5.749(h_s^*)^{-1} + 6.25\alpha_s^* + 5.068h_s^* + 1.073D_s^* - \\ - 0.1004D_s^* - 2.183(\alpha_s^*)^2 - 0.6578D_s^*(h_s^*)^{-1} - 0.01136(\alpha_s^*)^{-1} - \\ - 0.04832(h_s^*)^{-5}; \qquad (4.5)$$

$$B_r = -5.53 + 0.5351(\alpha_s^*)^{-1} + 2.928(h_s^*)^{-1} + 1.961h_s^* + 0.3122D_s^*\alpha_s^* - \\ - 0.3738D_s^*(h_s^*)^{-1} + 1.002h_s^*D_s^* - 0.1416(\alpha_s^*)^{-2} - 0.00993(D_s^*)^{-2}(\alpha_s^*)^{-3}; \qquad (4.6)$$

$$B_{sj} = -1.26 + 1.87D_s^* - 5.118(\alpha_s^*)^{-1} + 3.263(h_s^*)^{-1} + 8.497\alpha_s^* + \\ + 0.3937(\alpha_s^*)^{-3} + 0.8932\alpha_s^{*3} - 2.299\alpha_s^*D_s^*(h_s^*)^{-1} + \\ + 0.7807(\alpha_s^*)^2 D_s^* - 5.541(\alpha_s^*h_s^*)^2 - 0.132(D_s^*)^3(h_s^*)^{-1} - \\ - 0.2957\alpha_s^*(D_s^*)^{-1}(h_s^*)^2 + 0.2881\alpha_s^*(D_s^*)^3; \qquad (4.7)$$

$$B_{sz} = -1.71 - 0.3719D_s^* - 1.835(\alpha_s^*)^{-1} + 11.19(h_s^*)^{-1} + 9.988h_s^* - \\ - 1.404h_s^*(D_s^*)^{-1} + 0.4016(D_s^*h_s^*)^{-1} + 0.8739(\alpha_s^*h_s^*)^{-1} - 1.069(h_s^*)^{-3}, \qquad (4.8)$$

where $\alpha_s^* = -1.667 + 0.01852\alpha$, $D_s^* = -6.167 + 0.167D_s$, $h_s^* = 0.4196 + 0.01787h_s$;

T_{em}/V – electromagnetic torque per unit volume, Nm/l;

B_r – flux density in the rotor segments, T.

Testing of the synthesised metamodels (4.5)–(4.8) by the use of the software *QuickField* showed that the relative error of them does not exceed 5 % in the plan points and intermediate points as well. Synthesised metamodels (4.5)–(4.8) are used to maximise the value of the electromagnetic torque per unit volume of the new design synchronous reluctance motor under investigation. Assuming the restriction of the magnetic flux density ($B_{rs} \leq 1.65$ T, $B_{sj} \leq 1.65$ T, $B_{sz} \leq 2$ T) the optimal values of the variable parameters are calculated. The optimal parameters provide the maximum value of the electromagnetic torque per unit volume when the current density is equal to j = 6 A/mm^2. The values of the optimal variable parameters are shown in table 4.2.

Table 4.2.

The optimal values of variable parameters for synchronous reluctance motor

Label	**Value**	**Unit**
α_s	143	el.deg.
h_s	6	mm
D_s	46	mm
T_{em}/V	1.74	Nm/l

This chapter focuses also on the comparative analysis of the synchronous motors with different permanent magnet materials and new design synchronous reluctance motor with the same number of pole pairs (p = 1) and power from 1 kW to 2.5 kW based on the electromagnetic torque per unit volume.

Comparative analysis of the studied brushless synchronous motor with power 1 kW shows that electromagnetic torque per unit volume of synchronous motor with NdFeB permanent magnets is 1.4 times higher, and electromagnetic torque per unit volume of synchronous motor with ferrite permanent magnets is 1.36 times higher than torque per unit volume of synchronous reluctance motor with segment-shaped rotor. Moreover, values of the torque per unit volume of the studied motor are increasing with the power. However, the value of electromagnetic torque per unit volume of the permanent-magnet motor increases faster than that of synchronous reluctance motor. Torque per unit volume of synchronous motor with NdFeB permanent magnets is 1.55 times higher, and torque per unit volume of synchronous motor with ferrite permanent magnets is 1.52 times higher than the torque per unit volume of the synchronous reluctance motor with segment-shaped rotor at power 2.5 kW.

Analysing the comparative results of the examined motors, one can conclude that in several cases, when conditions of the weight and sizes are not a priority, the novel design of synchronous reluctance motor can successfully complete with permanent-magnet synchronous motor due to its high reliability and relatively low cost.

5. EXPERIMENTAL STUDY OF BRUSHLESS SYNCHRONOUS MOTORS

This chapter summarises the results of experimental studies of brushless synchronous motors with rotating and braking rotor.

Two permanent – magnet synchronous motors are designed and produced an the result of doctoral work, as well as synchronous reluctance motor with segment-shaped rotor has been designed. Synchronous motors with permanent magnets are produced with electronic commutation as alternating current electronic motors. A rated power of the first permanent-magnet synchronous motors is equal to P_N = 1.2 kW, and of the second permanent-magnet motor is equal to P_N = 0.8 kW. Synchronous reluctance motor, in its turn, is designed with a rated power P_N = 1 KW for operation with supply with frequency equal to 50 Hz.

The obtained curves under the load of the permanent-magnet synchronous motor with rated power 1.2 kW in the experiments with rotating rotor are compared with calculated curves according to the equations given in the first chapter. Such curves are presented in figure 5.1.

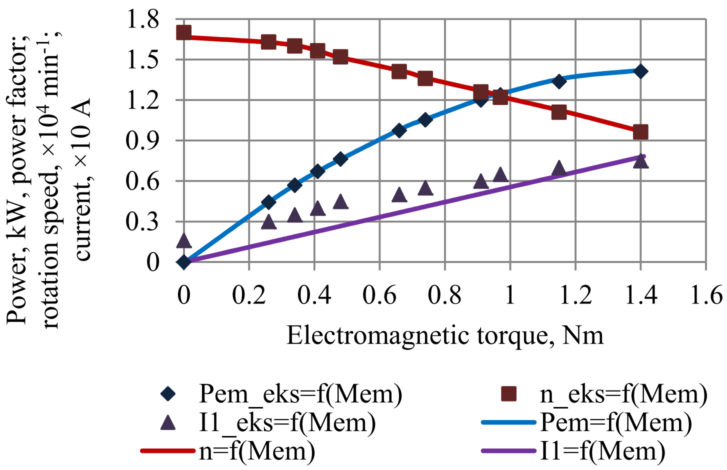

Fig. 5.1. Experimental and calculated curves of alternating current synchronous electronic motor with permanent magnets and rated power P_N = 1.2 kW

Experimental curves of the studied alternating current electronic motor show a good coincidence with the calculated curves.

Angle curves of the synchronous motor can be experimentally determined also in the static operating mode with the known armature current and braking rotor of the motor [34]. In this case, armature winding is provided directly from a direct current power supply according to the scheme presented in figure 5.2. (a) or (b).

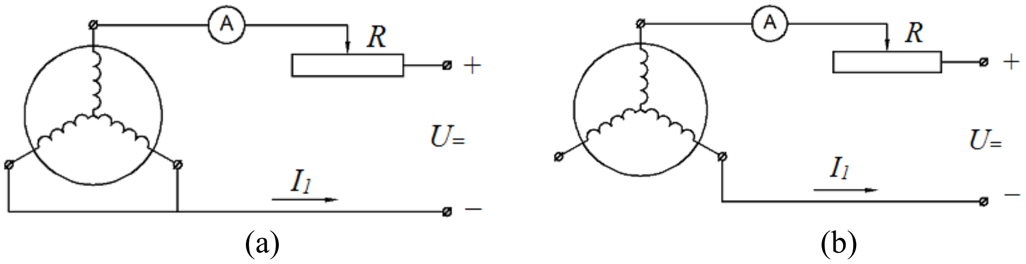

Fig. 5.2. Schemes of the three-phase armature winding for experimental studies of synchronous motor with braking rotor:

(a) – direct current flows through three phases; (b) – direct current flows through two phases

According to the method of experimental determination of motor static electromagnetic torque a fundamental harmonic of magnetisation force, which is generated by the direct current $I_{1=}$ at braking rotor, must be equal to the magnetisation force that is generated by alternating current I_1, which flows through armature winding then rotor rotates. Value of the direct current for connection scheme of three-phase armature winding shown in figure 5.2 (a) is equal to $I_{1=} = \sqrt{2} I_1$, and for the scheme of three-phase armature winding that is shown in figure 5.2. (b) the current is equal to $I_{1=} = \sqrt{\frac{3}{2}} I_1$. The value of direct current is set with the help of resistor by changing the resistance R.

The method for determination of the electromagnetic torque of the motor with braking rotor allows easy and quickly obtain the experimental results without special loading devices. The second permanent-magnet motor with the rated power 0.8 kW is tested in the experimental studies with braking rotor. The developed experimental stand for determination of static electromagnetic torque-angle curves for studied motor is shown in figure 5.3.

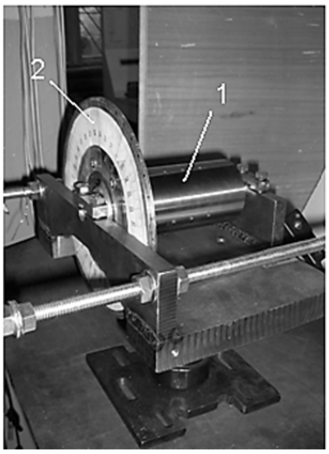

Fig. 5.3. Synchronous motor with outer rotor (1) and experimental stand with a graduated disc (2) for static torque-angle curve determination

For the creation of the static torque, the weight W is suspended to the motor rotor that value can be changed. Depending on the size of the suspended weight, the rotor rotates at a certain angle and in the case then suspended weight is equal to the magnetisation force of the permanent magnets the rotor is maintained at this position. Knowing the value of the suspended weight, the static electromagnetic torque can be calculated as

$$T_{em} = 9.81 \cdot W \cdot R_r, \tag{5.1}$$

where W – value of the suspended weight, kg;
R_r – surface radius, where the weight is suspended, m.

For determination of rotor rotation angle the disk with a graduated scale is fixed to the frontal part of the rotor.

Figure 5.4 presents experimentally obtained static electromagnetic torque – angle curves in comparison with the curves calculated by numerical calculation of magnetic field. Such curves obtained for the case when magnetic field of the motor is generated by permanent magnets.

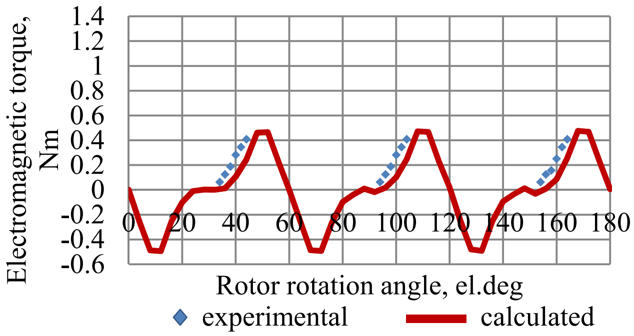

Fig. 5.4. Electromagnetic torque-angle curves when I_1 = 0 A

In order to restrict the heating of the motor during the experiments with direct current the electromagnetic torque-angle curves are obtained with reduced current of armature winding that is equal to I_1 = 3.5 A. A value of direct current, which flows in the armature winding, is equal to $I_{1=} = \sqrt{2} I_1 = \sqrt{2} \cdot 3.5 = 5$ A in the first experiment with braking rotor, when the armature winding is connected to the supply according to scheme (a) in figure 5.2., and in the second experiment, when the armature winding is connected to the supply according to scheme (b) in figure 5.2., a value of direct current is equal to $I_{1=} = \sqrt{\frac{3}{2}} I_1 = \sqrt{\frac{3}{2}} \cdot 3.5 = 4.3$ A. The results obtained in the first experiment are compared with numerically calculated and presented in figure 5.5, while the results obtained in the second experiment in comparison with numerically calculated are presented in figure 5.6.

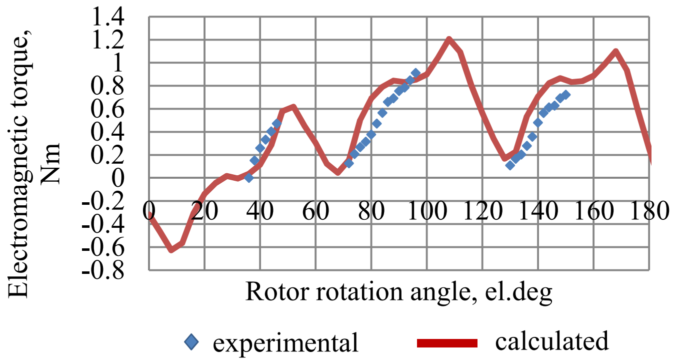

Fig. 5.5. Electromagnetic torque-angle curves, when I_1 = 3.5 A and scheme (a)

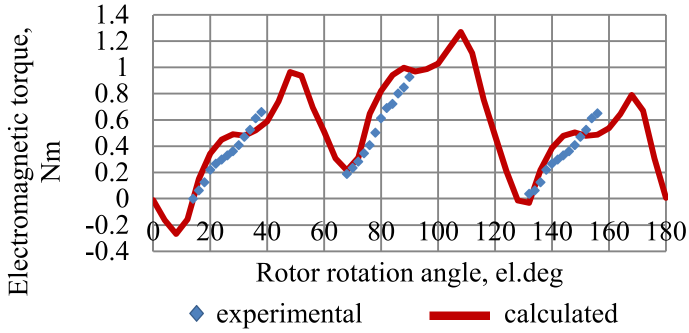

Fig. 5.6. Electromagnetic torque-angle curves, when I_1 = 3.5 A and scheme (b)

As it can be seen from figures 5.4–5.6 the numerically calculated electromagnetic torque-angle curves are slightly higher than those experimentally obtained that is obviously explained with the fact that the real motor has permanent magnets with lower energy than it was designed. Overall, the evaluation results show a satisfactory coincidence of experimental and numerically calculated results. The results suggest that the experimental studies can also be realised in the modes with braking rotor.

An improved design of synchronous reluctance motor with rated power P_N = 1 kW and rated rotation speed n_N = 3000 min^{-1} is developed in the dissertation work. A cross section of such motor with main dimensions is presented in figure 5.7.

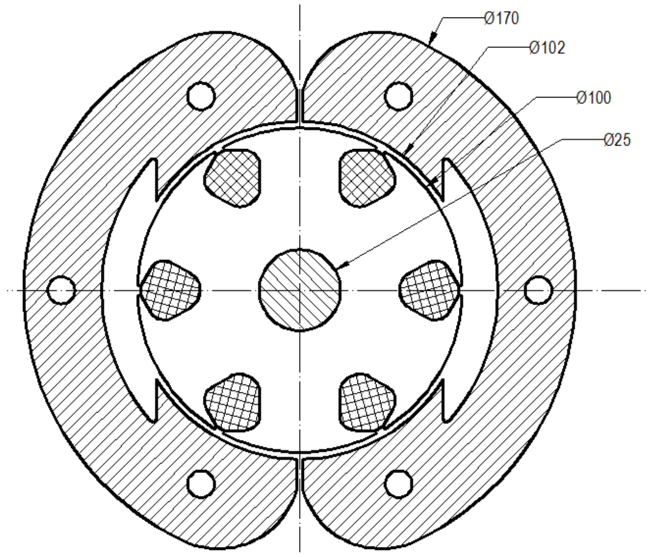

Fig. 5.7. A cross section of developed improved design of synchronous reluctance motor with dimensions (l_δ = 100 mm)

Additionally the non-magnetic spaces (“windows”) are created in each segment-shaped rotor packages of the developed improved design of synchronous reluctance motor. It is made in order to reduce the magnetic flux along quadrature axis.

THE MAIN RESULTS OF THE RESEARCH AND CONCLUSIONS

1. The metamodels for synchronous motor with permanent magnets and synchronous reluctance motor with external rotor are synthesised. Such metamodels can be used for motor analysis and optimisation with sufficient precision.
2. Methodology, which is based on numerical calculations of the magnetic field and metamodel synthesis, for design optimisation of permanent-magnet synchronous motors and synchronous reluctance motors with external rotor is developed.
3. New designs of synchronous motors with permanent magnets and synchronous reluctance motors are proposed. In the case of permanent-magnet motors the value of electromagnetic torque per unit volume for new designs is for about 10–15 % higher than for the well-known prototypes, and in the case of reluctance motors the value of electromagnetic torque per unit volume for new designs is for about 30–40 % higher than for the well-known prototypes.
4. The fact is proven that average electromagnetic torque per unit volume of the permanent-magnet synchronous motors with NdFeB magnets is 32 % higher and average electromagnetic torque per unit volume of the permanent-magnet synchronous motors with ferrite magnets is 30 % higher than electromagnetic torque per unit volume of synchronous reluctance motor with segment-shaped rotor under investigation in the power range from 1 kW to 2.5 kW.
5. In several cases when conditions of the mass and sizes of the motor are not in a priority, the synchronous reluctance motors of new design can successfully compete with permanent-magnet synchronous motors, as they are significantly cheaper and they have safer operation.
6. The special program for *Microsoft Excel* is developed using *Visual Basic* programming language. The program allows substantial saving in labour and time resources during preparation of input data for numerical experiments in software *QuickField* and analysis of magnetic field results.
7. Two alternating current electronic synchronous motors with permanent magnets are designed and produced, and the new design synchronous reluctance motor is designed for the future possible production.
8. Experimental studies of the produced motors are realised in the modes with operating rotor and in the modes with braking rotor as well. Experimentally obtained curves have a well coincidence with theoretically calculated curves.

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