RIGA TECHNICAL UNIVERSITY

Faculty of Power and Electrical Engineering

Institute of Power Engineering

Svetlana ORLOVA

Student of Electrical Machines and Apparatus Doctoral Program

OPTIMISATION OF THE INDUCTOR GENERATOR AS AN AUTONOMOUS SOURCE OF POWER SUPPLY

Summary of Doctoral Thesis

Scientific supervisor
Dr.habil.sc.ing.
V. PUGACHOV

Scientific adviser
Dr.habil.sc.ing., professor
N. LEVIN

RTU Publishing House

Riga 2011

UDK 621.313.32 (043.2)
Or 525 o

Orlova S. Optimisation of the inductor generator as an autonomous source of power supply.
Summary of Doctoral Thesis. – R.: RTU, 2011. – 25 p.

Printed according to the decision of RTU Institute of Power Engineering,
17 March 2011, protocol Nr. 41 (76).

This work has been partly supported by the European Social Fund within the project „Support for the implementation of doctoral studies at Riga Technical University".

This work has been partly supported by European Social Fund Project "Scientific Group Supporting Latvian Activities of the European Strategic Energy Technology Plan", No.1DP/1.1.1.2.0./09/APIA/VIAA/027.

DOCTORAL THESIS
PROPOSED FOR ACHIEVING DR. SC. ING. DEGREE AT
RIGA TECHNICAL UNIVERSITY

Doctoral Thesis is proposed for achieving Dr. Sc. Ing. Degree is publicly presented on the 18th of May, at Faculty of Power and Electrical Engineering, Riga Technical University, Kronvalda boulevard 1 – 117.

OFFICIAL REVIEWERS

Asoc. professor, Dr.sc.ing. Anastasija Zhiravetska
Riga Technical University

Head of centre for experimental investigation of electrical devices,
Dr. sc. ing. Aleksandr Mesnayev
Riga Electric Machine Building Works

Professors, Dr. habil. sc.ing, Zigurds Sika
Emeritus Scientist

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.

Svetlana Orlova.....................................(Signature)

Date:..................................

Work is written in Latvian language, it contains preface, 4 chapters, conclusions, 8 attachments, 63 pictures and 26 tables. Total amount of this work 127 pages. Bibliography includes 98 used literatures sources.

CONTENTS

GENERAL DESCRIPTION OF THE WORK

Topicality of the work

The ever increasing consumption of energy requires that its efficiency is growing steadily, and, therefore, the power systems and their elements are continuously optimised. Since the electric machines are the main converters of energy, their timely updating is needed. The conditions of growing energy market, development of new technologies and the toughened ecological requirements dictate that there should be new solutions as to the betterment of mass-and-dimension indices of electric machines, improvement of their reliability as well as safety and efficiency of their operation. Therefore, this work is devoted to the issues of optimisation of the axial inductor machines.

Goal of the work, subject of investigation and tasks

The goal of this work was to elaborate recommendations for raising the efficiency of axial inductor machines based on the analysis of a magnetic field possessing the radial tangentially-axial distribution.

The subject of investigation is a two-core under-van inductor generator 2ГВ.13.2У1 made in Latvia by the JSC "Latvo" (the Riga Electric Machine Building Works).

To achieve the set goal the following tasks were to be solved:

- substantiation of the optimum circuit for the armature winding;
- selection and substantiation of the methods for calculating a magnetic field taking into account its distribution in the axial inductor machine;
- validation of the objective function for analysing the results of magnetic field modelling and determination of a rational geometry of the tooth zone.
- experimental testing of new technical solutions;
- determination of the prospects for development of the axial inductor machine;
- evaluation of the research results.

Methods of investigation

For modelling the magnetic field of inductor machine the method of finite elements was employed. The results of calculation were compared with the experimental data obtained at the test complex of the Riga Electric Machine Building Works.

Scientific novelty of the work

The scientific novelty of the work consists in the following proposals:

- a technique for transforming the 3D field problem into a 2D one using the method of finite elements;
- the objective function which made it possible to take into account the generator's operation under the no-load and load conditions and to find an optimal geometry for its tooth zone;
- recommendations for rational geometry of the tooth zone of axial inductor machines;
- the design with a reduced (to Z_1=18) number of stator teeth in the under-van inductor generator 2ГВ.13.2У1, with the number of rotor teeth (Z_2=10) kept the same;
- the scientific novelty of the work has been confirmed by two patents.

Theoretical and practical significance of the work

<u>The theoretical significance of the work consists in the following:</u>

- the methods for calculation of the magnetic field in an axial inductor machine were supplemented by a new technique that allows taking account of the magnetic field distribution in an axial magnetic core;
- the objective function was proposed for finding an optimal geometry of the generator's tooth zone.

<u>The practical significance of the work consists in the following:</u>

- recommendations are given with respect to the rational geometry of the generator's tooth zone;
- the new rotor for a 2ГВ.13.У1 generator made by the Riga Electric Machine Building Works has allowed for raising its power.

Approbation

The main results of the investigation are presented at following international conferences:

1.“Magnetic field in the tooth zone of an axial inductor machine (AIM) “, 5th annual Conference of Young Scientists on Energy Issues, Kaunas, Lithuania, May 2008;

2.“Magnetic field in the tooth zone of an axial inductor machine”, Problems of present-day electrotechnics, Kiev, Ukraine, June 2008;

3.“Research of magnetic field of an axial inductor machine“, Riga Technical University 49th international scientific conference, Riga, Latvia, October 2008;

4.”Rational geometry of a magnetic circuit of an axial inductor generator”, The 4TH International Conference on Electrical and Control Technologies ECT 2009, Kaunas, Lithuania, May 2009;

5.“Optimization of the circuit of an axial inductor machine based on the calculation and analysis of magnetic field”, 13th European Conference on Power Electronics and Applications EPE-2009, Barcelona, Spain, September 2009;

6.”Optimization of the magnetic circuit of an axial inductor machine”, Riga Technical University 50th international scientific conference, Riga, Latvia, October 2009;

7.“Non-overlapping concentrated windings in homopolar inductor machines”, 20th International Symposium on Power Electronics, Electrical Drives, Automation and Motion, Pisa, Italy, June 2010;

8.“Optimization of the magnetic circuit of the homopolar inductor machine with non-overlapping concentrated windings”, 14th International Power Electronics and Motion Control Conference, EPE-PEMC, Ohrid, Republic of Macedonia, September 2010.

Innovations

1. Inductor machine. Bezsmertnij A., Dirba J., Ketners K., Levins N., Orlova S., Pugachov V. // Patents Nr. 13947 no 20.08.09.

2. Axial inductor machine. Dirba J., Ketners K., Levins N., Orlova S., Pugachov V. // Patent Nr. 13971 no 08.04.09.

Structure of the work

CONTENT OF THE WORK

Introduction

Among electro-mechanical converters of energy the axial inductor generators have received wide application. The inductor generator is a synchronous electric machine in which the magnetic excitation flux passing through a stator tooth is pulsing due to change in the permeance of the air gap between this tooth and the rotor. A distinctive constructional feature of such a machine is the absence of rotating windings (all the windings are disposed in the stator and are immovable), whereas the rotor is made as a tooth-wise cylinder, at the rotation of which there occurs pulsation of the magnetic flux linked with the armature winding.

An axial inductor generator can have one, two and more cores of the stator and the rotor. In the work only two-core axial inductor generators are considered.

The axial inductor generator under consideration (Fig. I1) consists of a frame in which two stator cores with an armature winding are arranged, and of the shaft with two tooth-wise cores of the rotor (without winding). An annular excitation winding is placed between the stator cores.

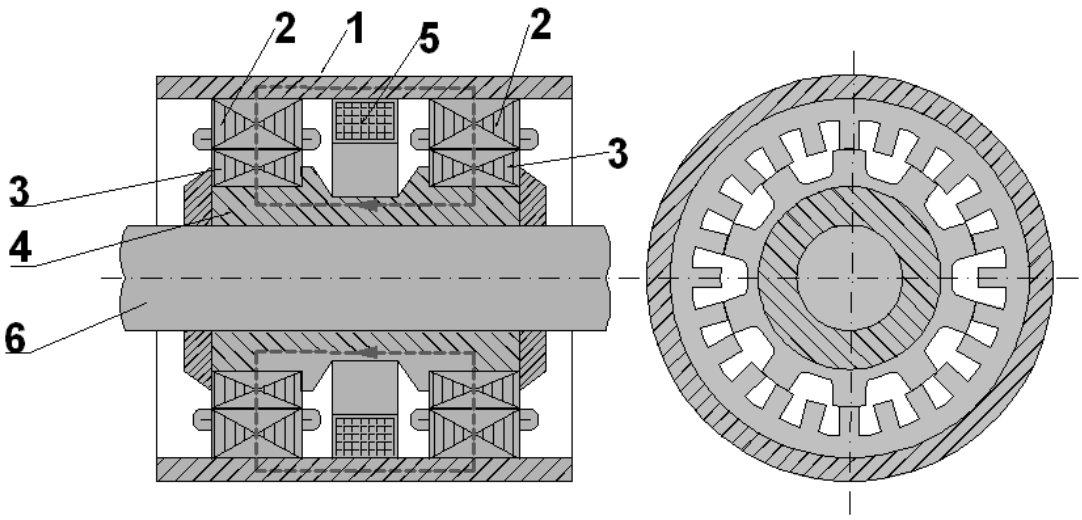


Fig. I1. The axial two-core inductor generator: 1- frame; 2- cores of stator with winding; 3- cores of rotor; 4 – rotor sleeve; 5- excitation winding; 6- shaft

The principle of an inductor machine's operation has been known since the XIX century. The works by V. Apsit and L. Dombur consider in detail the history of development and practical use of this type machines. At the present time, thanks to the works by A.

Alekseev, V. Vologdin, M. Spicin, and Yu. Petrunkin, the axial inductor generators − as the most efficient − are successfully employed in the systems of energy supply for the air, railway, sea and road transport.

Worthy of mention are the most interesting works of a later period devoted to investigation into the basic properties of inductor machines − those of M. Alekseeva, N. Alper, V. Apsit, A. Bertinov, L. Dombur, R. Zhezherin, M. Krasnoshapka, N. Levin, V. Pugachov, A. Serebryakov, E. Skruzitis, A. Terzyan, V. Sharov, and G. Shturman. Owing to these works we have now a sufficiently complete notion of the most important physical processes in the inductor machines, which has made possible a sharp increase in the technical level of the latter and their production quality. In so doing, the in-depth analysis of the magnetic field in inductor machines is crucial for their upgrading.

In recent works carried out in the Latvian Republic (the authors: A. Zviedris, U. Brakansky, A. Zaitzev, A. Gasparyan, E. Kamolins, A. Podgornov) the problems are considered that arise at numerically modelling the magnetic field by the method of finite elements. The merit of this method is that it allows solving problems of the kind at a complicated geometry of the tooth zone, with the non-linearity of media taken properly into account.

At the same time, analysis of the magnetic field in an axial inductor machine has so far been performed ignoring the specifics of its axial distribution, which led to serious errors. Therefore, the purpose of this work is the improvement of such a machine's feasibility by optimisation of its parameters based on more accurate analysis of magnetic field with due consideration for the axial component.

1. The axial inductor machine as an economically advantageous source of autonomous energy supply of increased reliability

In Chapter 1 of the promotion work a comparative analysis is performed for the homopolar and heteropolar inductor machines, which shows that the homopolar inductor machine have higher efficiency, require less copper, and are better as to their maintainability.

In this chapter also the expedience of using concentrated windings in the axial inductor machine is substantiated. Thus, it is possible to reduce the number of stator slots with simultaneous reduction in the pulsations of the longitudinal flux (and without bevelling these slots) by choosing the number of stator teeth close to the doubled number of rotor teeth, i.e.

$$Z_1 = 2Z_2 \pm k, \tag{1.1}$$

where k=1,2,3..., is a small integer.

The application of concentrated windings in axial inductor generators with concurrent increase in the number of rotor teeth (Fig. 1.1) allows significant technological simplification of manufacturing the armature winding and the generator as a whole, considerable increase in the generator output power without enlarging the amount of active materials and improvement of mass-and-dimension indices of the machine.

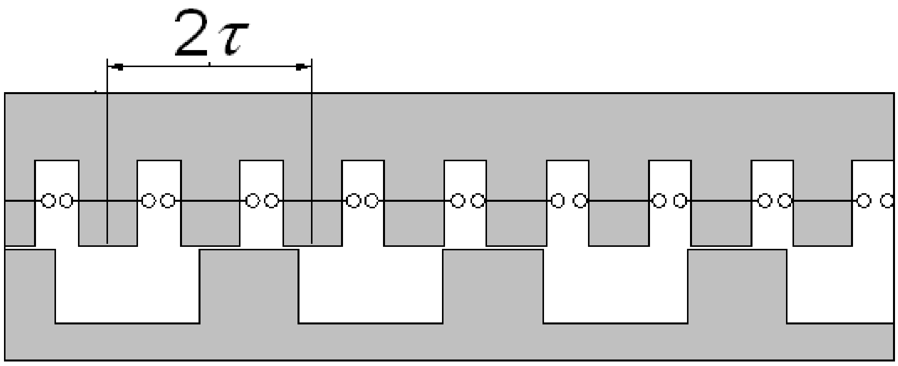


Fig. 1.1. A three-phase concentrated winding at $Z_1 = 2Z_2 \pm k$

2. Magnetic field calculation of the axial inductor machine as the basis for determination of its characteristics and optimisation of its parameters

Chapter 2 of the promotion work is dedicated to the magnetic field calculation. As known, the methods for calculation of electric machines and other electro-technical devices rely upon the results of investigation into their electro-magnetic fields. Therefore, analysis of the magnetic field in such an axial machine serves as the basis for determination of its characteristics with further optimisation of its parameters.

In the work presented, for calculations of magnetic field in the axial inductor machine the method of finite elements was chosen.

Being simple in design, axial inductor machines fundamentally differ from other synchronous machines by the electro-magnetic system; the magnetic field in the former has a clearly expressed three-dimensional character.

Intricacy of modelling the magnetic field in the active zone of an axial inductor machine is caused by the necessity to model the absent source of excitation field, since the coaxial excitation winding is situated in the space between the stator cores (Fig. I.1).

The problem of magnetic field calculation can be solved by three ways:

- by solving the 3D magnetic field problem;
- by reducing the calculation to two 2D problems;
- by transformation of the 3D problem into a 2D one.

In the present work, the magnetic field calculation by solving a three-dimensional problem is not considered due to the absence of available programs.

The method of reducing the calculation to two 2D problems implies the presence of a field in the radial active zone of stator and rotor cores and in the main air gap (where the field is plane-parallel), and in the axial magnetic core (where this field is axially symmetric). In the work, this method of solution is complemented by the algorithm that allows taking account of the magnetomotive force (MMF) drop in the axial magnetic circuit at different geometry of the tooth zone − that is, solves the optimisation problem.

Before starting the field analysis by the third way proposed in the given work (Fig. 2.1) the axial sections of the magnetic circuit are transformed to radial ones, with the cross-section areas of its transformed elements kept constant.

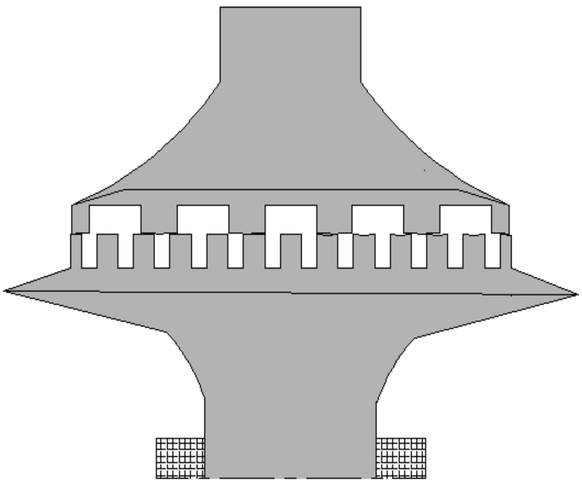


Fig. 2.1. Cross-section of the magnetic circuit after introduction of the transformed axial elements of magnetic core

Analysis of the results obtained by two methods for the magnetic field calculation validates each of them (Fig. 2.2). However, the calculation by transforming the 3D problem into a 2D one allows the solution process to be simplified, which saves time since it is not necessary to repeatedly solve one and the same problem at various randomly set values of the vectorial magnetic potential and to select an appropriate variant among a set of solutions.

a) b)

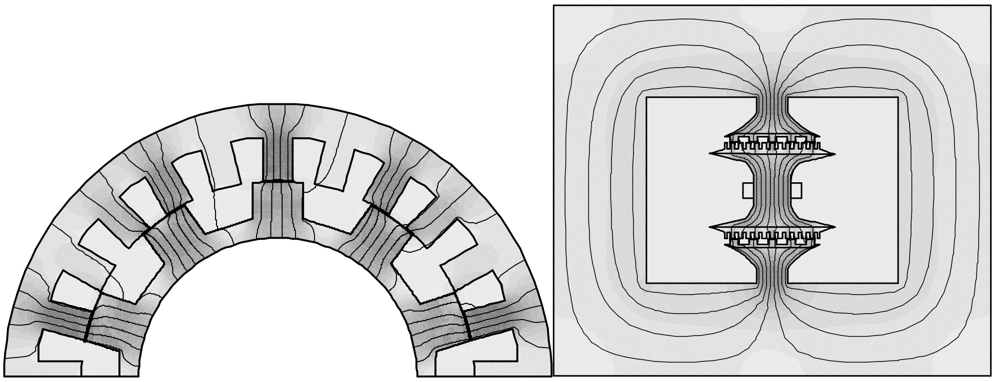


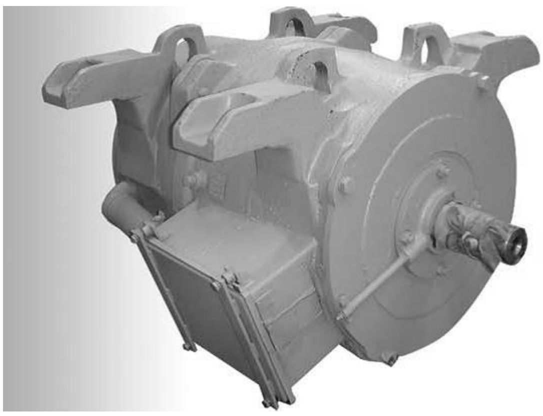
Fig. 2.2. The view of magnetic field:

a) in the machine's cross-section; b) after transforming the axial sections of magnetic core

3. Elaboration of recommendations for raising the efficiency of axial inductor machine

Chapter 3 is devoted to elaboration of the recommendations for raising the efficiency of axial inductor machines.

As the object of investigation, a 32 kW under-van inductor generator 2ГВ.13.2У1 was chosen (lot-produced by the JSC "Latvo" (Fig. 3.1). The given generator is employed for feeding the vans with conditioning and heating systems.



3.1. att. Under-van inductor generator 2ГВ.13.2У1

Designers of an axial inductor generator often come up against the problem of choosing the rational geometry of its tooth zone that would ensure efficient use of the magnetic flux. At poorly chosen geometrical parameters of the tooth zone the machine might not ensure the demanded power. Therefore, such geometry is determined through search for optimal relation between rotor and stator teeth as well as for proper relative width of rotor slot.

The inductor generator 2ГВ.13.2У1 under consideration has 24 teeth on the stator and 10 teeth on the rotor, with the relative slot width γ=1.45; at such relationship the teeth on the rotor turn out to be much wider than those on the stator. In this case the leakage fluxes are increasing, which means reduced loading capacity and elevated losses. In Table 3.1 the main parameters of the generator's tooth zone are given. Fig. 3.2 shows the tooth zone of the generator and its main sizes.

Table 3.1

The main parameters of the generator's tooth zone

Title	Parameter	Value	Unit
Number of stator teeth	Z_1	24	-
Number of rotor teeth	Z_2	10	-
Stator tooth pitch	b_1	0.043	m
Rotor tooth pitch	b_2	0.1029	m
Width of stator tooth	b_{z1}	0.025	m
Width of rotor tooth	b_{z2}	0.042	m
Width of stator slot	b_{r1}	0.018	m
Relative slot width	γ	1.45	-
Width of rotor slot	b_{r2}	0.0609	m
Air gap	δ	0.001	m
Length of stator/rotor core	l	0.115	m
Steel grade	Electrotechnical steel 2211, depth of sheets Δ= 0.5 mm		
Cross-section of stator tooth	$S_{z1} = b_{z1} \cdot l \cdot k_{Fe}$	0.002662	m^2
Cross-section of rotor tooth	$S_{z2} = b_{z2} \cdot l \cdot k_{Fe}$	0.004472	m^2
Height of stator teeth	h_{z1}	0.036	m
Height of rotor teeth	h_{z2}	0.03115	m
Stator bore diameter	D_S	0.3293	m
Rotor sleeve diameter	D_{ie}	0.233	m
Outer stator diameter	D_a	0.4583	m

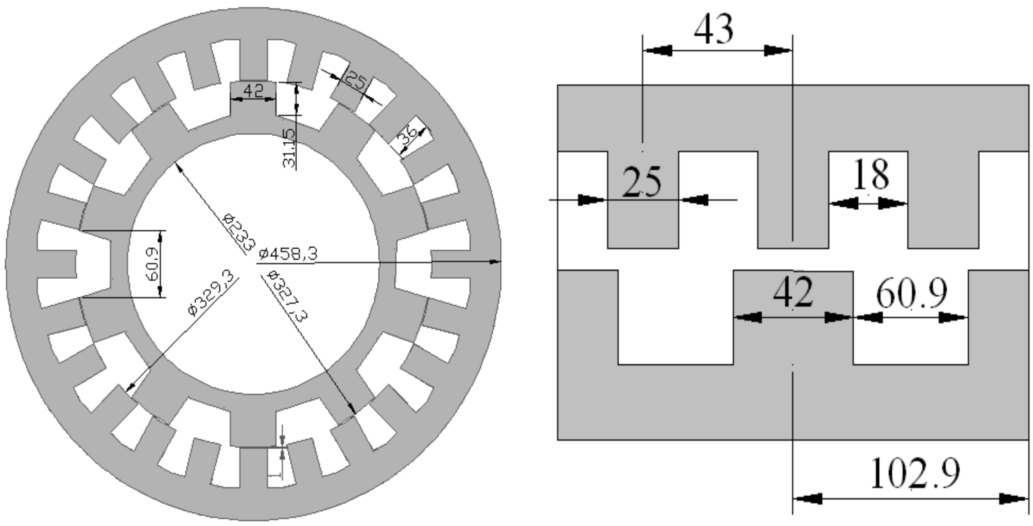


Fig. 3.2. The tooth zone of generator 2ГВ.13.2У1 (with the main sizes in mm)

The electromotive force (EMF) of the generator at the no-load condition is determined by the following formula:

$$E_0 = 2 \cdot 4.44 \cdot f_1 \cdot \frac{N_S}{a} \cdot w_k \cdot k_{w1} \cdot \frac{\Phi_{max} - \Phi_{min}}{2}, \tag{3.1}$$

where $f_1 = \frac{Z_2 \cdot n_N}{60}$ is the current frequency, Hz;

n_N is the rotational speed;

N_S is the number of coils in a phase of generator;

a is the number of parallel branches in each phase of the armature winding;

Φ_{max}, Φ_{min} are, respectively, the maximum and minimum magnetic fluxes in a stator tooth when it is against a rotor tooth or against a rotor slot;

$w_к$ is the number of turns in one coil of the armature winding;

k_{w1} is the winding coefficient in the first harmonic.

The main parameters influencing the EMF values are (Fig. 3.3): the maximum magnetic flux Φ_{max} (i. e. the flux in a stator tooth when it is against a rotor tooth), the minimum flux Φ_{min} (i. e. the flux in a stator tooth when it is against a rotor slot), and the current frequency. It should be noted that these parameters are dependent in full measure on the tooth zone geometry.

Figure 3.4 presents the results of magnetic field investigation in the form of dependences of the flux half-difference multiplied by the number of rotor teeth on this number at different relative width of the slot. As seen from the data obtained, the maximum is reached when there are 16 teeth on the rotor and the relative slot width equal to 1.4. However, the results obtained in analysis of the no-load condition of the axial inductor machine are not sufficient, since in the search for optimal geometry of the tooth zone it is necessary to take into account the specifics of a machine's operation under load.

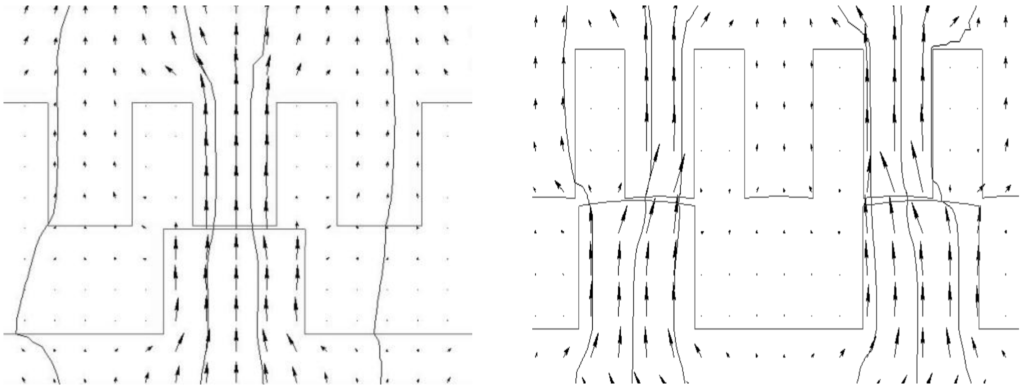


Fig.3.3. Magnetic field distribution in a stator tooth when it is against a rotor tooth (the maximum magnetic flux Φ_{max}) and in a stator tooth when it is against a rotor slot (the minimum magnetic flux Φ_{min})

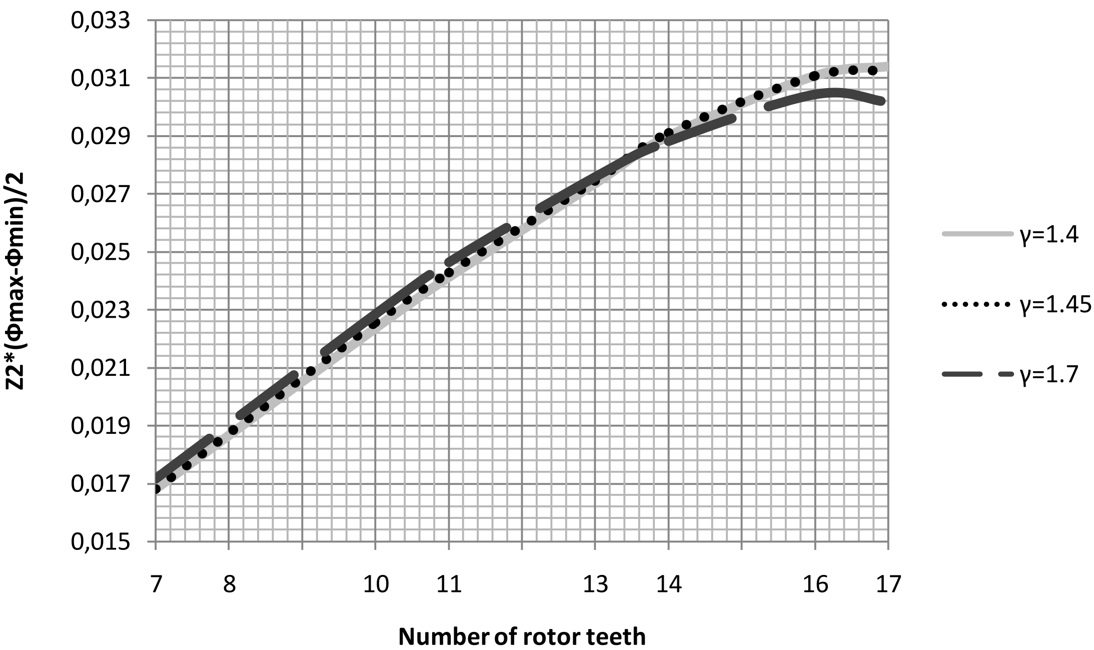


Fig.3.4. $\frac{\Phi_{max} - \Phi_{min}}{2} \cdot Z_2$ *vs.* the number of rotor teeth at relative width of the slot γ=1.4; 1.45; 1.7

To find out the optimal geometry of the tooth zone for a two-core inductor generator with axial excitation and tooth coils it was proposed to apply an objective function

$$C_g = \frac{\pi}{120} k_{w1}^2 n_N Z_1 Z_2 \frac{(\Phi_{\max} - \Phi_{min})^2}{\frac{(\Phi_{\max(k)} + \Phi_{\min(k)})}{F_k}}, \tag{3.2}$$

where $\Phi_{max(k)}, \Phi_{min(k)}$ are the maximum and minimum values of the magnetic flux that determines the no-load EMF and the short-circuit current I_k;

$F_k = \sqrt{2} w_k I_k$ is the short-circuit MMF.

Figure 3.5 shows the dependences of the objective function on the number of rotor teeth at different γ ratios. As could be seen from the presented curves, the objective function values are increasing with the number of rotor teeth up to a definite level; further increase in this number leads to decrease in the objective function value. It should be noted that for each number of rotor teeth an optimal ratio should be found for the ratio γ between the slot and rotor tooth widths; for example, for 10 teeth on the rotor the objective function maximum is reached at γ=1.7, while for 14 teeth − at 1.45.

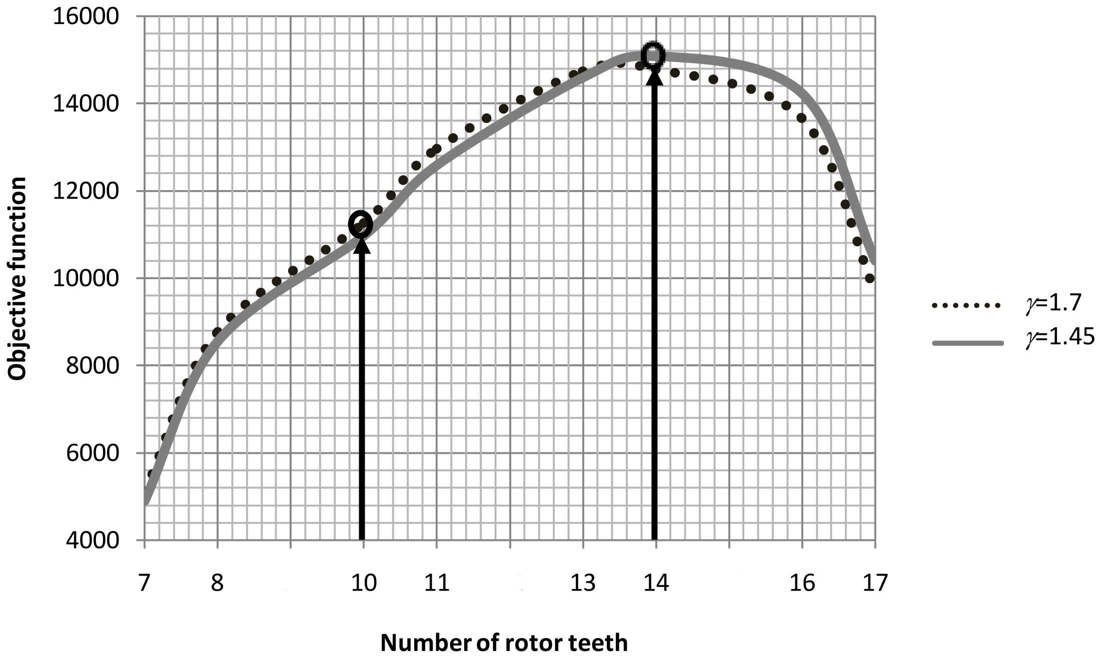


Fig. 3.5. The objective function *vs.* the number of rotor teeth at relative slot width γ=1.45; 1.7

From the results of objective function calculations it was found that the change in geometry − at the number of rotor teeth and slot width being 14 and 1.45, respectively, instead of 10 and 1.45 the generator power increases by 37%.

Based on the results of calculation and analysis of the magnetic field in the cross-section of an inductor generator the following recommendations can be given concerning the optimal geometry for the tooth zone of inductor machines:

- the number of stator teeth should be multiple of the doubled number of phases, i.e.

$$Z_1 = 2k_1 m \tag{3.3}$$

where k_1 is an integer;

- the number of rotor teeth should be determined by the expression:

$$Z_2 = \frac{Z_1}{2} + k, \tag{3.4}$$

- the number of rotor teeth should not be multiple of the number of phases, i.e.

$$Z_2 \neq k_2 m; \tag{3.5}$$

where k_2 is an integer;

- the ratio of the rotor tooth width to the stator tooth width should be in the limits:

$$\gamma_{1-2} = \frac{b_{z2}}{b_{z1}} = 1.02 \div 1.1; \tag{3.6}$$

- the ratio of the stator (rotor) tooth width to the air gap should not be less than 20, i.e.

$$\frac{b_{Z1}}{\delta} \geq 20;\ \frac{b_{Z2}}{\delta} \geq 20; \tag{3.7}$$

- the ratio of the rotor slot width to the rotor tooth width:

$$\gamma = \frac{b_{r2}}{b_{z2}} = 1.4 \div 1.7; \tag{3.8}$$

- the height of a rotor tooth should not be smaller than its width:

$$h_{Z2} \geq b_{r2}. \tag{3.9}$$

4. Experimental investigation of the axial inductor machine and possibilities of its further perfection

Chapter 4 of the promotion work concerns the experimental investigation carried out in order to validate the utility of the proposed mathematical model for optimising the design of the axial inductor machine and to check the effectiveness of concrete proposals as to the improvement of technically-economic indices of the generator. As the model for investigation, a under-van inductor generator was chosen (applied on the railway transport). In Table 4.1 its nominal data are presented.

Table 4.1

Nominal data of generator 2ГВ.13.2У1

Title	Value	Unit
Nominal power	32	kW
Nominal voltage	116	V
Nominal current	170	A
Nominal rotational speed	1000	min^{-1}
Number of phases	3	-
Phase connection	Y	-
Nominal current frequency	167	Hz
Steel grade	2211	-
Number of turns in the armature coil	13	-
Excitation winding current	3	A
Number of turns in the excitation winding	1520	-
Number of stator (rotor) core	2	-

As follows from calculations of the objective function, the optimal design for this type generator is with 24 teeth on the stator and 14 teeth on the rotor, which makes it possible to employ in testing a production stator without changing the circuit of armature winding and other significant modifications.

Experimental investigation of the generators with 10 and 14 teeth on the rotor was carried out at the test complex of the the Riga Electric Machine Building Works.

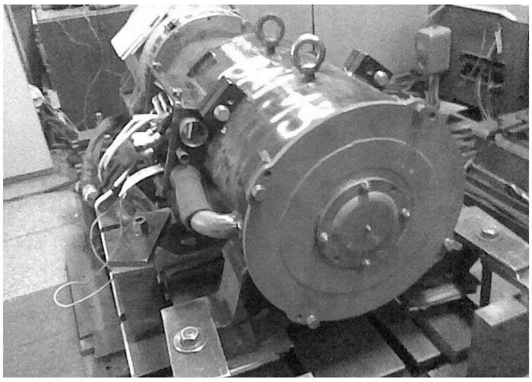


Fig. 4.1. The test bed for experimental investigation of generators

In Fig. 4.2, sectorial sketches are presented for the stator and rotor sheets of a lot-produced generator with 10 rotor teeth and an experimental one with 14 rotor teeth.

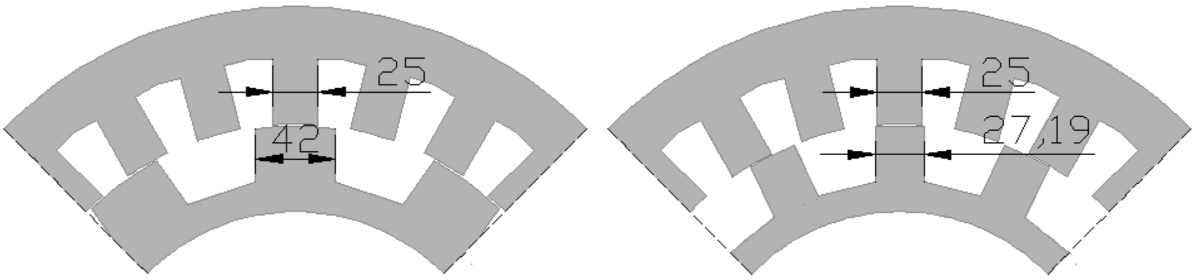


Fig. 4.2. Sectors of the stator and rotor sheets:

a) the lot-produced generator (Z_2=10); b) the experimental generator (Z_2=14)

In Fig. 4.3a the general view is presented for the rotor of a lot-produced generator with the number of teeth Z_2=10, and in Fig. 4.3.b – for the rotor of a generator with Z_2=14.

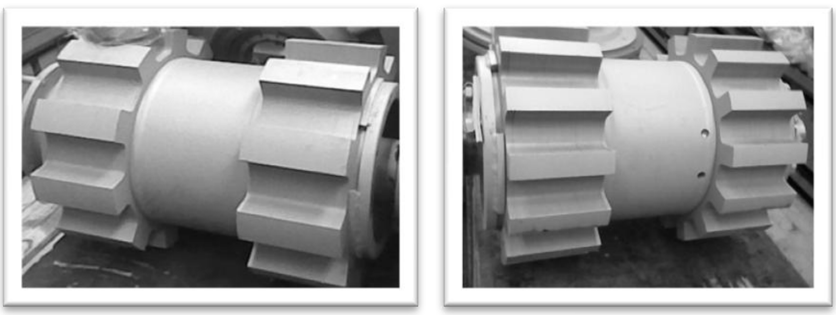


Fig. 4.3. Rotors of the generators:

a) of the lot-produced generator with Z_2=10; b) of the experimental generator with Z_2=14

The programme of experimental tests included:

- dc measurements of armature winding resistances;

- determination of the characteristics;
- determination of the short-circuit characteristics;
- determination of the adjusting possibilities of the generators;
- estimation of the heating and overheating conditions;
- determination of the shapes of voltage curves for the no-load and load conditions.

Figure 4.4 shows the experimental and calculated dependences of EMF on the excitation current at 10 and 14 teeth on the rotor. As can be seen, from the presented curves, the no-load curves for the 10 teeth case practically coincide with the calculated ones. This is evidence in favour of the chosen mathematical model based on the calculation and analysis of the magnetic field. At the same time, in this figure it is seen that the calculated no-load curve of the generator with Z_2=14 passes slightly higher than the experimental one. The difference in the results could be explained by the fact that the rotors of the tested generators were made by dissimilar technologies: thus, in the 10-tooth rotor case there was a cast frame and stamped rotor sheets, whereas in the case of 14 teeth − a frame consisting of two parts with a joint in the middle while the rotor teeth were made by milling.

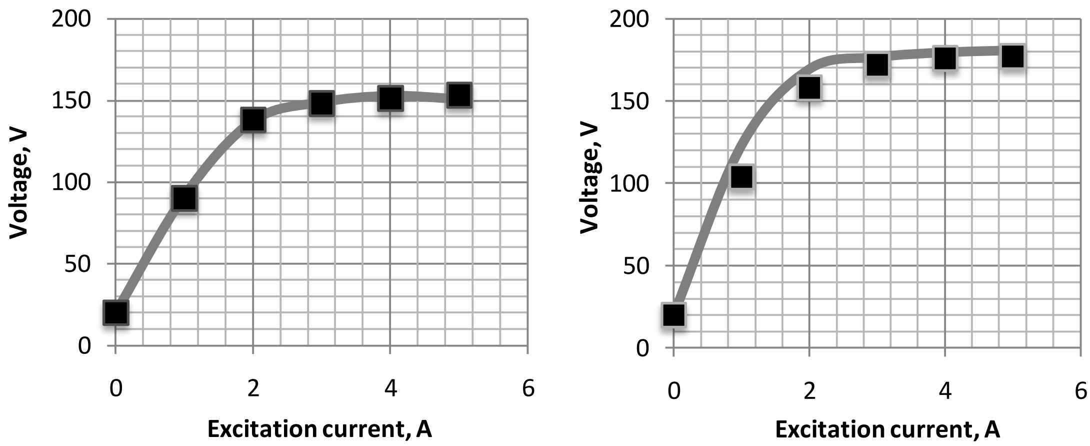


Fig. 4.4. No-load curves:

a) of the lot-produced generator with Z_2=10; b) of the experimental generator with Z_2=14.

calculated, ■ experimental

In the search for an optimal geometry of the tooth zone of a under-van inductor generator the optimal stator and rotor tooth number ratio was found along with the relative slot and rotor tooth widths. However, the obtained optimal number of 14 for rotor teeth leads to the increase in the current frequency, and, consequently, to an increase in the steel losses and a decrease in the generator efficiency. Therefore, to reduce the current frequency as well as the mentioned losses it is proposed to adopt the generator design with 10 teeth on the rotor and the number of stator teeth reduced to 18. At such numbers of rotor and stator teeth the current frequency will remain equal to that for the lot-produced generator.

Figure 4.5 presents sketches for the stator and rotor sheets of the proposed generator.

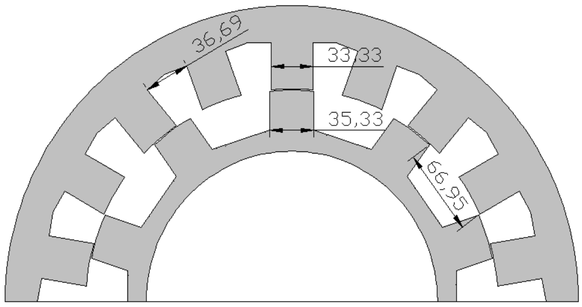


Fig. 4.5. Geometry of the generator tooth zone for Z_1=18, Z_2=10

In Fig. 4.6 are depicted the no-load curves for generators with different stator/rotor tooth number ratios. From these curves it is seen that at the minimum excitation current of 3 A the generators of the offered designs have the same EMF − exceeding that of the production generator by 29%.

The tooth zone geometry of an 18-tooth generator allows maintaining the current frequency at the same level, while the specific power increases by 29% and the technology of making the electric machines is simplified considerably. Apart from that, the rate of rotor flux variations decreases, and, consequently, the total losses are also reduced, which means a higher efficiency for the generator.

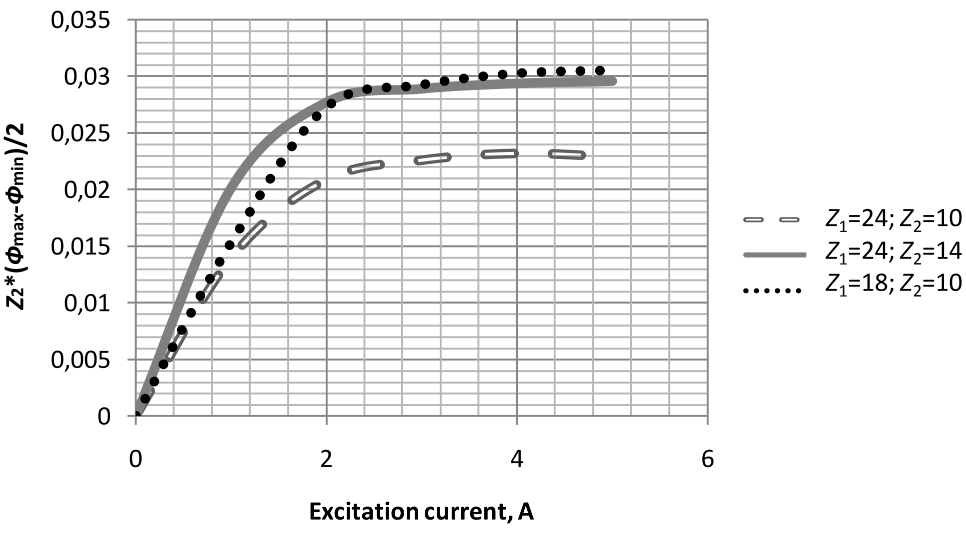


Fig. 4.6. No-load curves for the generators with different ratios of stator/rotor tooth number

Conclusions

1. Inductor machines have received wide recognition owing to their operational reliability, ease of fabrication and servicing by virtue of the absence of brush contacts and rotating windings. Comparative analysis of radially-excited and axially-excited inductor machines has shown that the axial inductor machines require less copper consumption, and possess a good maintainability. All this makes them preferable in many applications, including railway transport.

2. Comparative analysis of two methods for magnetic field calculation: of a method for transforming the three-dimensional problem to two two-dimensional ones with the proposed method for transforming the three-dimensional problem to one two-dimensional − has shown that both the methods are suitable for determining the parameters of magnetic field in an axial inductor machine.

3. To find out the optimal geometry of the tooth zone was proposed to apply an objective function

$$C_g = \frac{\pi}{120} k_{w1}^2 n_N Z_1 Z_2 \frac{(\Phi_{\max} - \Phi_{min})^2}{\dfrac{(\Phi_{\max(k)} + \Phi_{\min(k)})}{F_k}},$$

where k_{w1} is the number of turns in one coil of armature windings;

n_N is the rotational speed;

Z_1 is the number of stator teeth;

Z_2 is the number of rotor teeth;

$\Phi_{\max}$, $\Phi_{\min}$ are the maximum and minimum magnetic fluxes;

$\Phi_{max(k)}$, $\Phi_{min(k)}$ are the maximum and minimum values of the magnetic flux that determines the no-load EMF and the short-circuit current I_k;

F_k is the short-circuit MMF.

4. Based on the results of magnetic field calculation, recommendations have been derived concerning the substantiation of a tooth zone's rational geometry for the axial inductor machine. These recommendations are:

- the number of stator/rotor teeth should satisfy the relationships:

$$Z_1 = 2k_1 m;\ Z_2 = \frac{Z_1}{2} + k \neq k_2 m,$$

where k_1 and k_2 are integers; k is small integer; m – number of phases.

- the ratio of the stator (rotor) tooth width to the air gap should not be less than 20, i.e.

$$\frac{b_{Z1}}{\delta} \geq 20;\ \frac{b_{Z2}}{\delta} \geq 20,$$

where δ is the air gap;

- the ratio of the rotor tooth width to the stator tooth width should be:

$$\gamma = \frac{b_{Z2}}{b_{Z1}} = 1.02 \div 1.1.$$

5.In order to reduce the rotor steel losses and to raise the efficiency of an inductor generator of the type it is expedient to reduce the number of stator teeth from 24 to 18, with the number of rotor teeth kept equal to 10, which would allow a 16% increment in the specific power of the generator.

6. The experimental investigations have validated the proposed mathematical model based on the magnetic field analysis using the Quick Field software package.

For the defense the following new scientific results are presented:

- the method for transforming the three-dimensional field problem to a two-dimensional one using the method of finite elements;
- the objective function which takes into account the specifics of the generator's operation under the load and no-load conditions;
- the recommendations on the rational geometry of the tooth zone of axial inductor machines;
- the generator 2ГВ.13.2У1 design with the number of stator teeth reduced to 18, with the number of rotor teeth kept equal to 10.

AUTHOR’S PUBLICATIONS

1. Orlova S., Pugachov V., Levin N. Magnetic field in the tooth zone of an axial inductor machine (AIM) // 5th annual Conference of Young Scientists on Energy Issues – 29 May, 2008, Kaunas, Lithuania, CD proceedings. II-20 – II-27.

2. Magnetic field in the tooth zone of an axial inductor machine. Orlova S., Pugachov V., Levin N., Kamolins E. // Problems of present-day electrotechnics 2008 - Kiev 2008, pp. 31-34 (in Russian).

3. Research of magnetic field of an axial inductor machine. Orlova S., Pugachov V., Levin N., Bezsmertnij A. //RTU scientific articles “Enerģētika un elektrotehnika”, 4.series. - volume 23, (2008), 117.-122.lpp

4. Optimization of the tooth zone of an axial inductor machine based on analysis of magnetic field. Levin N., Orlova. S., Pugachov V., E. Kamolins. // Latv. J. Phys. Tech. Sci. - Nr.2 (2009), pp. 21-28.

5. Rational geometry of a magnetic circuit of an axial inductor generator. Orlova S., Pugachov V., Levin N., Kamolins E.// The 4TH International Conference on Electrical and Control Technologies, 2009. May, Lithuania, Kaunas. – Kaunas: “Technologija”, 2009, pp. 219-222.

6. Optimization of the circuit of an axial inductor machine based on the calculation and analysis of magnetic field. Dirba J., Levin N., Orlova S., Pugachov., Ribickis L. // 13th European Conference on Power Electronics and Applications, 2009. September, Spain, Barcelona. – Barcelona:CD proceedings, 2009.

7. Optimization of the magnetic circuit of an axial inductor machine. Dirba J., Levin N., Orlova S., Pugachov V. // RTU scientific articles “Enerģētika un elektrotehnika”, 4.series. - volume 25, (2009), 57.-60.lpp

8. Non-overlapping concentrated windings in homopolar inductor machines. Orlova S., Pugachov V., Levin N., Konuhova M. //20th International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2010. June, Italy, Pisa.-Pisa: CD proceedings, 2010.

9. Optimization of the magnetic circuit of the homopolar inductor machine with non-overlapping concentrated windings. Levin N., Orlova S., Pugachov V., Ribickis L. // 14th International Power Electronics and Motion Control Conference, EPE-PEMC, Ohrid, Republic of Macedonia, September 2010. – Ohrid: CD proceedings, 2010.

10. Inductor machine. Bezsmertnij A., Dirba J., Ketners K., Levins N., Orlova S., Pugachov V. // Patents Nr. 13947 no 20.08.09.

11. Axial inductor machine. Dirba J., Ketners K., Levins N., Orlova S., Pugachov V. // Patent Nr. 13971 no 08.04.09.