RIGA TECHNISCAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Power Engineering

Jelena Dashkova-Golovkina
Doctoral student of the program „Electrical machines and apparatus”

RAISING OF THE EFFICIENCY OF MULTIPOLE WIND GENERATORS WITH EXCITATION FROM PERMANENT MAGNETS

Summary of Doctoral Thesis

Academic supervisor
Dr. habil. sc. ing.
V. Pugachov

Academic adviser
Dr. habil. sc. ing., profesor
N. Levin

Riga 2010

UDK 621.548+621.311.245] (043.2)
Da 807 e

Dashkova-Golovkina J. Raising of the efficiency
of multipole wind generators with
excitation from permanent magnets.
Abstract of a doctoral thesis.-R.:RTU, 2010.-29 lpp.

Printed according to the decision of
RTU Institute of Power Engineering,
29 June 2010, protocol Nr. 37(72)

This work has been partly supported by the European Social Fund within the National Programme „Support for the carrying out doctoral study programm's and post-doctoral researches" project „Support for the development of doctoral studies at Riga Technical University".

ISBN

PROMOCIJAS DARBS
IZVIRZĪTS INŽINIERZINĀTŅU DOKTORA GRĀDA IEGŪŠANAI
RĪGAS TEHNISKAJĀ UNIVERSITĀTĒ

Promocijas darbs inženierzinātņu doktora grāda iegūšanai tiek publiski aizstāvēts 2010. gada 27.oktobrī plkst. 16:00 RTU Enerģētikas un elektrotehnikas fakultātē Kronvalda bulvārī 1 – 117 telpā.

OFICIĀLIE RECENZENTI

Dr.sc.ing., asoc. profesore Anastasija Žiravecka
Rīgas Tehniskā universitāte, Latvija

Dr.sc.ing., profesors Aleksandrs Gasparjans
Latvijas Jūras akadēmija, Latvija

Dr.sc.ing. Valērijs Bezrukovs
Galvenais inženieris, vadošais pētnieks
Ventspils Augstskolas Inženierzinātņu institūts
„Ventspils Starptautiskais Radioastronomiskais Centrs”, Latvija

APSTIPRINĀJUMS

Apstiprinu, ka esmu izstrādājusi doto promocijas darbu, kas iesniegts izskatīšanai Rīgas Tehniskajā universitātē inženierzinātņu doktora grāda iegūšanai. Promocijas darbs nav iesniegts nevienā citā universitātē zinātniskā grāda iegūšanai.

Jeļena Daškova-Golovkina... (Paraksts)

Datums:................................

Promocijas darbs ir uzrakstīts latviešu valodā, satur ievadu, 4 nodaļas, secinājumus, literatūras sarakstu, 67 zīmējumus un ilustrācijas, kopā 116 lappuses. Literatūras sarakstā ir 114 nosaukumu.

CONTENTS

Contents of the work:

GENERAL DISCRIPTION OF THE WORK

Topicality of the work

The problem of using wind energy in our days has become topical. The era of chip energy sources has ended and usage of none traditional energy sources is becoming more frequent in use and efficient. First of all, it is related to users who live in rural areas, such areas are very frequent in Latvia.
Usage of traditional energy sources, such as oil, gas, coal etc. first of all is encouraging pollution of environment and advancement of greenhouse effect, and second of all the amount of such natural resources rapidly decreases, that leads to its gradually price increase and deficit.
That is why in todays usage of renewable energy sources in energetics has become an immediate interest, in other words it is the usage of sun's, river's, wind, geothermal energy, biomass energy, sea current, wave and flooding. Among them very effective is the usage of wind energy.
The network of electrical power plants from foreign manufacturers with general output approximately of $30{\cdot}10^3$ kW have already been installed in Latvia. Such perfect, but still expensive devices, are intended to enhance energy-output ratio of central host system. However, for farmers and long-distances country houses, it is necessary to build autonomous wind energy devices with advanced efficiency to use the wind energy. They are easy to use, safe, light, economical, noiseless, which work from a low usage of the speed of wind, and which are not expensive. Such an autonomous wind device can be created based on direct-drive (without multiplier) annular generator with excitation from permanent magnets.
This promotional work tries to resolve a high priority tasks, directed on the advancement of wind generator efficiency with excitation from permanent magnets.

The aim of the work, its subject and the tasks of investigation

The aim of this promotional work is to raise efficiency of generators of autonomous wind devices with excitation from permanent magnets.
To achieve this goal, the following aims were set:
– to advance and to settle criteria for the wind generator advancement for autonomous wind power plant (WPP) settlement which will promote efficiency of using wind energy;
– to settle the concept of execution in practice on generators with permanent magnets, this assures to decrease the weight/torque ratio while running on low speed synchronous machine;
– to determine the optimal active zone geometry of the electrical machine, also the amount of stator teeth and poles of synchronous machine, the size of magnets, coil form, it secures the maximum efficiency of wind generators;
– find rational and productive solutions for safe attachment of permanent magnets to meter and their safe a defective usage;
– check by experimental means reliability of mathematical models and construction solutions on how to advance effectiveness of wind generators;
– formulate an offer on how to develop wind generators with excitation from permanent magnets;
– to put to the test the results of the research.

The methods of research

To achieve the set of challenges one of the most innovative and fast developing numerous methods on how to calculate the ratio of magnetic field, finite elements method (FEM) was used. The results were compared with experimental data, which took place in a laboratory of the Institute for Physics and Power Engineering. The experiment has confirmed the justification of using mathematical models while advancing a wide range class of generators with excitation from permanent magnets.

The scientific novelty of the work

The scientific novelty of this paper resides of:

– received and confirmed information based on magnetic field calculations, which are expressed through determination of optimal pole overlapping

$$\alpha_\delta = 1 - \frac{\sqrt{h_m \delta}}{\tau},$$

by which means the known height of permanent magnet h_m, the size of air breather δ and pole pitch τ, reaches a maximum power-to-weight ratio of a generator with excitation from the radially magnetized prismatic permanent magnets;

The pole overlapping value should be between 0,8 and 0,95 in comparison with traditionally is taken over: 0,65 ÷ 0,7.

– optimal relationship has been found between numbers of poles and stator teeth of synchronous generator with teeth coil: $p = \frac{z_s}{2} + k$, where k – is the smallest whole number, by which means maximum power can be reached in nominal size;

– implementing the optimization of number of pairs in a synchronous generator with annual assemble and excitation from permanent magnets;

– it was proposed to assemble an induction generator with higher amount of pole pairs, but with a reduced amount of magnets in one polarity, which are installed between rotor teeth, and their magnetism was changed in the process;

– in order to increase the coefficient there was a proposition to use fixed wind turbines power with reduced rated wind speed to carry out winding on armature with the possibility to switch from "star" to "triangle" when the speed of wind will exceed the calculated.

– two patents were received, confirming the originality of the developed technical solutions.

Practical and theoretical value of the work

Theoretical value:

– An analytical formula was received in order to determine the optimal coefficient of pole overlapping,

$$\alpha_\delta = 1 - \frac{\sqrt{h_m \delta}}{\tau},$$

by which means the known height of permanent magnet h_m, the size of air breather δ and the pole pitch τ, reaches a maximum power-to-weight ratio of a generator with excitation from the radially magnetized prismatic permanent magnets;

The pole overlapping value should be between 0,8 and 0,95 in comparison with traditionally is taken over: 0,65 ÷ 0,7.

– optimal relationship was found between numbers of poles and stator teeth: $p = \frac{z_s}{2} + k$, where k – is the smallest intact number, by which means symmetrical three-phase winding reached the nominal size;

– a mathematical model was created for the synchronous machine with permanent magnets, designed to optimize the parameters of a multi-polar ring-shaped wind turbine.

Practical value:

– it was proposed to assemble an induction generator with reduced number of magnets of one polarity which are installed between rotor teeth, and their magnetism is changed in the process. It simplifies the fixation and reduces the manufacturing cost of the generator;

– in order to increase the coefficient it was proposed to use the installed capacity of wind turbine to carry out the armatures winding process with a possibility to switch from the "star" to "triangle", then till the rated wind speed the coiling of the armature will be turned on by a "star", but while enhancing the rated wind speed it will be turned on by a "triangle”.

Realization oh the work results

The main results of promotional work were reported at the international conferences:
- J. Daškova-Golovkina, N. Levins, V. Pugačevs Electrical generators of modern WPP. RTU zinātniskie raksti Enerģētika un elektrotehnika, sērija 4, sējums 15, 27.–32. lpp. 2005. g. (RTU 46. International Conference);
- J. Daškova-Golovkina, N. Levins, V. Pugačevs Обзор конструктивных схем электрических генераторов в современных ВЭУ. Науково прикладний журнал Технична электродинамика, 3 часть, 73 стр. IX International Conference “Problems of Present-day electrotechnics-2006” 5-9 June, 2006, Kiev, Ukraine;
- J. Dashkova-Golovkina, J. Dirba, N. Levin, V.Pugachov Synchronous generators in without gear installations. RTU zināniskie raksti, Eerģētika un Elektrotehnika, sērija 4, sējums 18, 19.-25. lpp. (RTU 47. International Conference);
- J. Dashkova-Golovkina, N. Levin, V. Pugachov Multipole Synchronous Generators with Permanent Magnets and tooth windings for low-power WPP in CD format , topic 3(CT3), texst 3.04. 5th International Conference CPE 2007 „Compatibility in Power Electronics”, May 29 – June1, 2007, Gdansk, Poland;
- J. Daškova-Golovkina, J. Dirba, N. Levins, V. Pugačevs Tooth Zone Analysis in Multipole Synchronous Generators with Permanent Magnets. RTU zinātniskie raksti, Enerģētika un Elektrotehnika, sērija 4, sējums 20, 96.-102. lpp. (RTU 48. International Conference);
- J. Dashkova-Golovkina, N. Levin, V. Pugachov Geometrical parameters of tooth zone in multipole synchronous generators with permanent magnets NdFeB, Науково прикладний журнал Технична электродинамика, 5 часть, 23-26 стр. X International Conference “Problems of Present-day electrotechnics-2008” 3-5 June, 2008, Kiev, Ukraine.

Patents:

1. Dirba. J., Daškova J., Ketners K., Levins N., Pugačevs V., Serebrjakovs A. Iduktorģenerators ar pastāvīgā magnēta ierosmi. LV Patents № 13822B. 20.01.2009.
2. Dirba. J., Daškova-Golovkina J., Ketners K., Levins N., Pugačevs V. Sinhronās mašīnas rotors ar pastāvīgajiem magnētiem. LV Patents № 13924B. 20.08.2009.

Structure of the work:

CONTENTS OF THE WORK

Annotation

The main direction of the work and its actuality. The main results of the study are presented. Evaluation of the work amount.

Introduction

Lack of Latvia's own energy resources has created a basis for dependency on importers of electro energy. Thus to reduce this dependence it is necessary to stepwise expanding capacities for electrical energy, which in its turn leads to an increase in dangerous waste and the reinforcement of greenhouse effect. One of the ways to reduce the import of electrical energy, and thereby ensure the energy independence of Latvia, while improving the current negative environmental conditions, could be the use of clean energy sources, including wind.

The problem of the usage of wind energy in our days has become a hot topic for discussion. The age of cheap energy comes to an end and the usage of alternative energy will continually become more economically rational. In any case, this applies to users of remote rural areas, which there are a lot of in Latvia.

Successful solution for this problem will be possible only if a WPP of high efficiency will be created, especially it will affect the autonomous WPP. They must be constructively improved by increasing power generation at low wind speed.

Most fully satisfying of the requirements of high performance are direct-drive wind turbines with generators with excitation from permanent magnets. In world practice, direct-drive generators with excitation from permanent magnets are already widely used, even without using optimal parameter schemes and geometrical parameters.

Latvian scientists have made a significant contribution to the development of wind power energetics and to the innovation of the elements of WPP. However, there are still a lot of problems and challenges that need to be resolved in the fast development of wind energy in Latvia.

In recent years, Latvia has successfully represented and defended some promotional work on the effectiveness of autonomous WPP, both in terms of increasing the dependence and reducing weight and improving the usage rate of installed wind plant capacity. It was done based on the improvement of wind turbine, and on improvements on wind focus of WPP.

However, it did not fully address the issue of effectiveness in the usage of generators with excitation from permanent magnets. Modern magnets have received a large increase in the specific energy, but there are no recommendations on their rational use. The last ones are particularly important because of the increased cost on such magnets and their impact on the surrounding automation devices work.

Subject to the foregoing, this work is devoted to improve the efficiency of generators with permanent magnets and their use in autonomous wind turbines.

As a result, the goal was set and the aims of exploration were presented in the section "general description of the work".

1. Improvement of the efficiency of autonomous wind generators WPP based on the selection of rational drive scheme of electrical machines and the study of its magnetic field

To achieve maximum efficiency from the wind generator it is necessary to have in mind certain criteria, based on which not only efficiency could be evaluated but also the increase of its influence on any of the above mentioned steps. Let us analyze these criteria.

First, the generator should be simple by design and technologically advanced in production, so that it would be on its lowest price while it is in production and so that maintenance would be cheap.
Secondly, the generator must be reliable while operating it under specified conditions, the external environment.
Thirdly, the generator should be designed for a low frequency rotation, so it can be articulated with wind turbines without the use of the multiplier.
Fourthly, the generator must have a minimum number of windings, the frontal parts of which would not be crossed. This improves reliability and maintainability.
Fifthly, the generator should have a minimum noise level and electromagnetic radiation, effecting the environment. This will ensure minimum of negative hazards to the environment.
Sixth, the generator should be maintainable, and the repair costs should not be high, the repair or maintenance should not take a lot of time for its execution.
Seventh, the low cost of manufacturing the generator should allow a rapid return of money spend on wind turbines.
Eighth, the preservation abilities on properties of the generator, in other words the generator must keep its energy performance and reliability throughout its lifetime.
Synchronous generators with excitation from permanent magnets which are creating a magnetic excitation flux do not consume energy, so they can be not only without a brush and rings, in other words noncontact, reliable, but also multipolar and directly articulated with the wind turbines. From this follows that synchronous generators with excitation from permanent magnets according to all criteria is the most appropriate to use on autonomous wind stations.
The advantages of such generators are as follows. Electrical machine decreases in size and weight, because of replacing the charge winding's, permanent magnets have a smaller mass and volume. It becomes possible to create an electrical multipolar car by decreasing its size and weight. Efficiency output is increasing, since it eliminates the need to spend energy, since it consists up to 10% of generated power to create a magnetic flux excitation. Reliability grows, since the charge coil is excluded, because of the damages and aging time of isolation it decreases its stability compared with the magnet reliability. Brush-contact transition, also is not used which has the poorest reliability of WPP in toughest operation circumstances. Operating cost decreases because there is no need in maintenance of brush-contact transition and the periodic replacement of brushes or slip rings as they are abrades. Faster access to the nominal mode of operation is usually delayed because of the presence of transaction processes with high time constant. The demagnetizing reaction on armature is much lower, in other words it provides greater stability to the generator.
The disadvantages associated with the use of permanent magnets, should include:

- higher cost compared to the poles and charge coils;
- critical limit of temperature and mechanical overload (shits, vibration, overheating);
- the complexity of installment without compromising energy performance;
- difficulties in regulating the magnetic flux;
- increased negative effects of the magnetic field on the surrounding elements and the need for protection of the last mentioned from this influence;
- the appearance of the phenomenon of "sticking" with the rotor and stator when starting and low speed of rotation.

In electrical machines with permanent magnets the transformation energy is carried out by the magnetic field, the energy of which is concentrated mainly in the air breather and permanent magnets. Rest of the magnetic circuit is meant only for the communication link with the conductor's armature winding. The paper shows that for the study of the magnetic field in generators with permanent magnets, a numerical finite element method (FEM) can be used.
In our days, there are effective programs to calculate the magnetic field finite element method. One of the programs is "QuickField".
By applying the finite element method to calculate the magnetic field in the cross section of electrical machines the following main stages of work were set.

First stage. The choice of constructive assembling of electrical machinery (approximate number of stator teeth, the number of magnets and their arrangement, the need to use secondary elements and materials).
Second stage. The choice of material, shape and size of the magnets. This step is very important, because the pursuit for material with high specific energy often does not consider its other qualities, such as heat and vibration, the possibility to use various technological methods. In this work, the factor of temperature is substantial and it certainly was considered throughout the choice of the materials and the volume of change in poles, made from selected hard magnetic material.
To ensure materials magnetic systems with better characteristics means to create such a magnetic system that there are smaller stray fluxes and magnetic flux paths, higher heat and higher resistance to vibration of the object as a whole.
A thermal effect is associated not only with a magnet, but also with armature winding, and surface area of cooling, which provides sufficient heat transfer to the environment. From this perspective, in some cases it is reasonable to carry out the winding with several coils, which in turn affects the design, shape and geometric size of magnetic cores.
A very significant factor which influences the choice of materials for magnetic systems is the manufacturing technology. It is advisable to use New Technologies, which would allow maximum mechanization and automation of manufacturing processes, for example, stamping (magnetic core is formed from electrical-sheet steel), which allows without any difficulties to create a magnetic core of any form. On the other hand metal-ceramic technology for the production of magnetic cores and their elements is more progressive, because it is a waste-free production.
While choosing a magnet system it is necessary to strive for the size as small as possible, because in this case, it reduces consumption of materials and their cost.
In the third phase, when soft and hard magnetic materials were chosen, their shape and orientation in joint core, when an executed and accurate sketch of a magnetic circuit with metric symbols and variations of possible changes were taken into account (necessary for the rapid enumeration of various options to change the magnetic field characteristics and selection of optimal solution).
Special attention was given when the parameters of permanent magnets were set.
On the fourth stage the interface conditions were introduced. Interface conditions were set on the outer and inner boundaries of the model. The border along the outer perimeter is the boundary between ferromagnetic medium and air, that is why air can be approximated by $\mu = 0$. This approximation allows determining related area frontier line, which coincides with the outer surface of the stator electrical machine. Physically this approximation means that the magnetic field is concentrated in the machine itself and does not go beyond it, in other words on the outer surface of the stator, a normal component of magnetic induction is $B_n = 0$ (lines of magnetic force run along the border). At the border, $\frac{\partial A}{\partial \tau} = 0$ or the magnetic vector potential is $A = const$.
On the fifth stage, after setting the main sizes and entering data on the properties of materials parameters of magnetic field were determined and the analysis of the received results was carried out in order to justify the possible changes in the magnetic circuit for further calculation.
On the sixth stage the final analysis was concluded about all the received results, build schedules, charts, and the final conclusions were made about the optimal parameters of the object.

2. Optimal geometric parameters of the magnetic system elements of the synchronous multi-polar wind generator with excitation from permanent magnets

In this paper the designs of generators with different magnetic systems were examined, namely: radial excitation, with tangential-radial excitation, with axial-radial excitation and axial excitation.

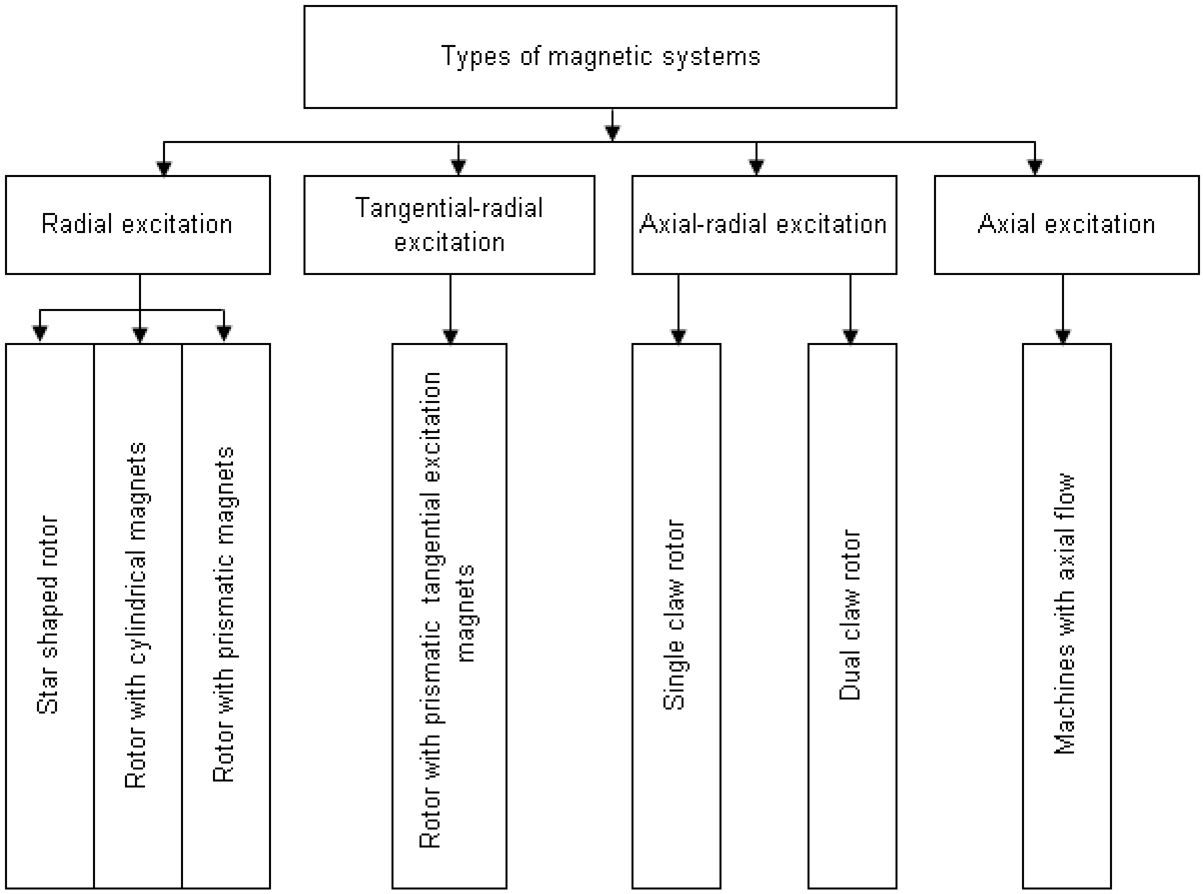

Fig. 1. The classification of structural types of magnetic systems and rotor with permanent magnets in these systems

From the results presented in Fig. 1. various designs of generators, after analysing their strengths and weaknesses, preference was given to a generator with prismatic radially magnetized magnets. This generator (Fig. 2.) has a high degree of using magnets, has a high multipolarity and, as it is shown in Table 1. is best suitable for the use in autonomous WPP.

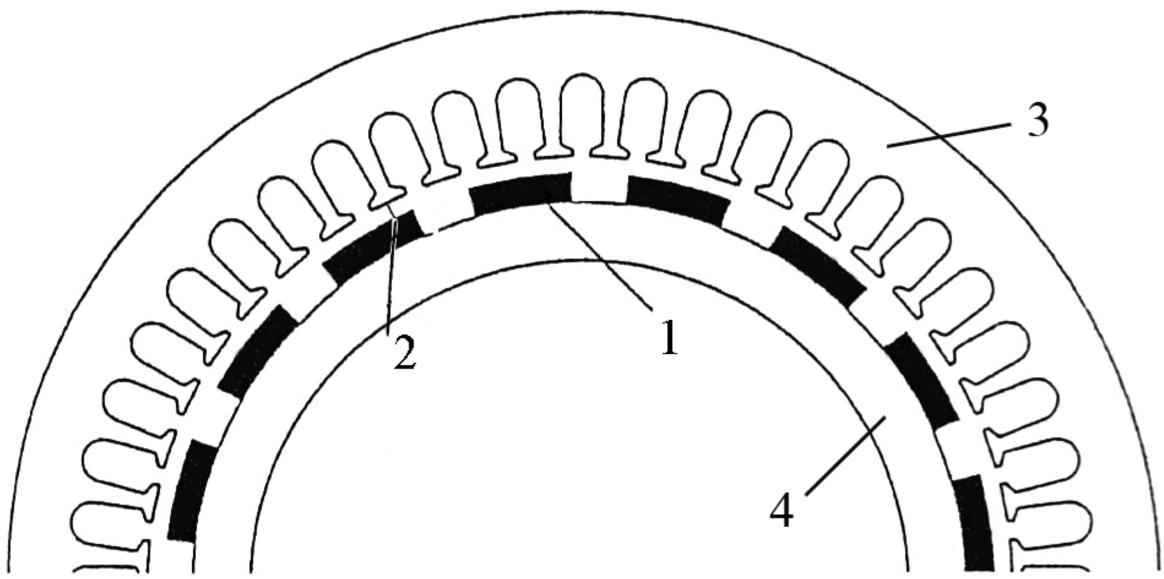

Fig. 2. The design of the generator with prismatic radially magnetized magnets: 1 – magnet, 2 – air breather, 3 – stator with slots and 4 – the yoke of the rotor

Table 1.

Positive qualities of rotors of various designs with excitation from permanent magnets

№	Advantages	Design of rotors						
		Star shaped	Prismatic-radial excitation	Prismatic-tangential	Cylin-drical	Claw shaped	Dual claw shaped	Axial
1.	Simple design and its fabricability	●	●	●	●			
2.	Possibility of effective magnetizing of magnets		●	●		●	●	●
3.	Absence (small) loses in rotor along with overheating		●	●				
4.	Magnets are protected from demagnetizing		●	●		●	●	●
5.	Possibility to use high-coercively-magnets(Nd-Fe-B)		●	●				●
6.	Multipole		●	●				●
7.	Secure mounting on rotor		●	●	●	●	●	
8.	Concede fast linear speed		●	●	●			
9.	Short stray flux		●		●			
10.	High mechanical resistance of magnets		●	●	●	●	●	●
11.	High flux density in the air breather		●	●				
12.	High packing factor		●	●	●			

Further analysis and the search for optimal solutions a construction was put through a multi-polar synchronous wind turbine with radial magnetized prismatic magnets. This construction has a smaller stray flux (compared to tangential magnetized magnets), and this is a very important property to ensure high efficiency.

It was shown that to improve the efficiency direct-drive turbines to increase the number of poles of an electrical machine it is reasonable to perform a simultaneous increase in the diameter of the stator bore and decrease in rotors pack length (ring-shaped design arrangement).

Fig. 3. shows the dependence of relative EDP in armature coil from the number of pole pairs p and pole overlapping α_δ, if z_s=18. From the analysis it can be seen that the generators with z_s=18, with p=6 EDP is at minimum. With an increase in the number of permanent magnets, EDP increases significantly too, reaching the maximum of p=10. Further increase in the number of permanent magnets on rotor leads to the decrease of EDP in armature coil. The increase in the pole overlapping also leads to an increase in the EDP $E_k^* = \frac{E_k}{c}$, where $c = 4{,}44 w_k \frac{n}{60} k_w$ – is the constant, in which

w_k – is the number of turns in the coil windings of the armature, n – rounds per minute, k_{w1} – breadth coefficient for the first harmonic.

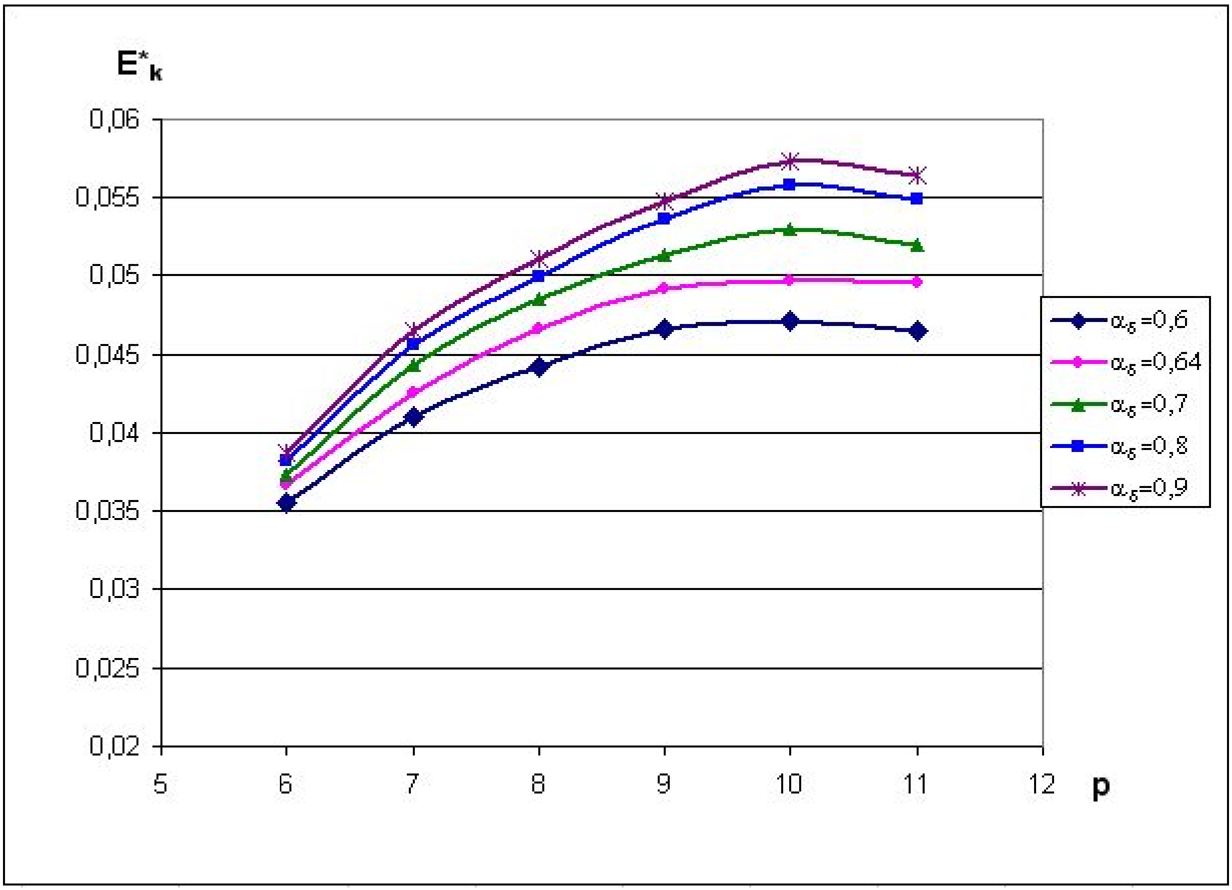

Fig. 3. Dependence on relative EDP coil on the number of pole pairs p and the pole overlapping α_δ = 0,6; 0,64; 0,7; 0,8; 0,9 at z_s=18

Thus, based on the analysis of the magnetic field in the cross section of the machine, the optimal ratio between the number of permanent magnets and the number of teeth with coils on the stator was determined by optimum ratio

$$p = \frac{18}{2} + 1 = 10, \text{ t.i. } p = \frac{z_s}{2} + k, \quad (1)$$

where the k – smallest ceiling which insures symmetrical (z_s is fold to $2m$) formation of three-phase armature windings with a maximum EDP. It was determined that the received ratio does not depend on the number of teeth on the stator in electrical machine.

In this case and in the following studies as a basis for the examined generator an electrical generator WPP was taken, manufactured by Riga Electrical Machine Building Works (JSC "RER"). The width of the stator teeth (armature) in basis model is 27 mm. It was decided to increase the tip of the stator teeth by 5 divisions with step of 4 mm. in other words if b_{z1}=27 mm, then b_{z2}=31mm; b_{z3}=35 mm; b_{z4}=39 mm; b_{z5}=43 and b_{z6}=47 mm.

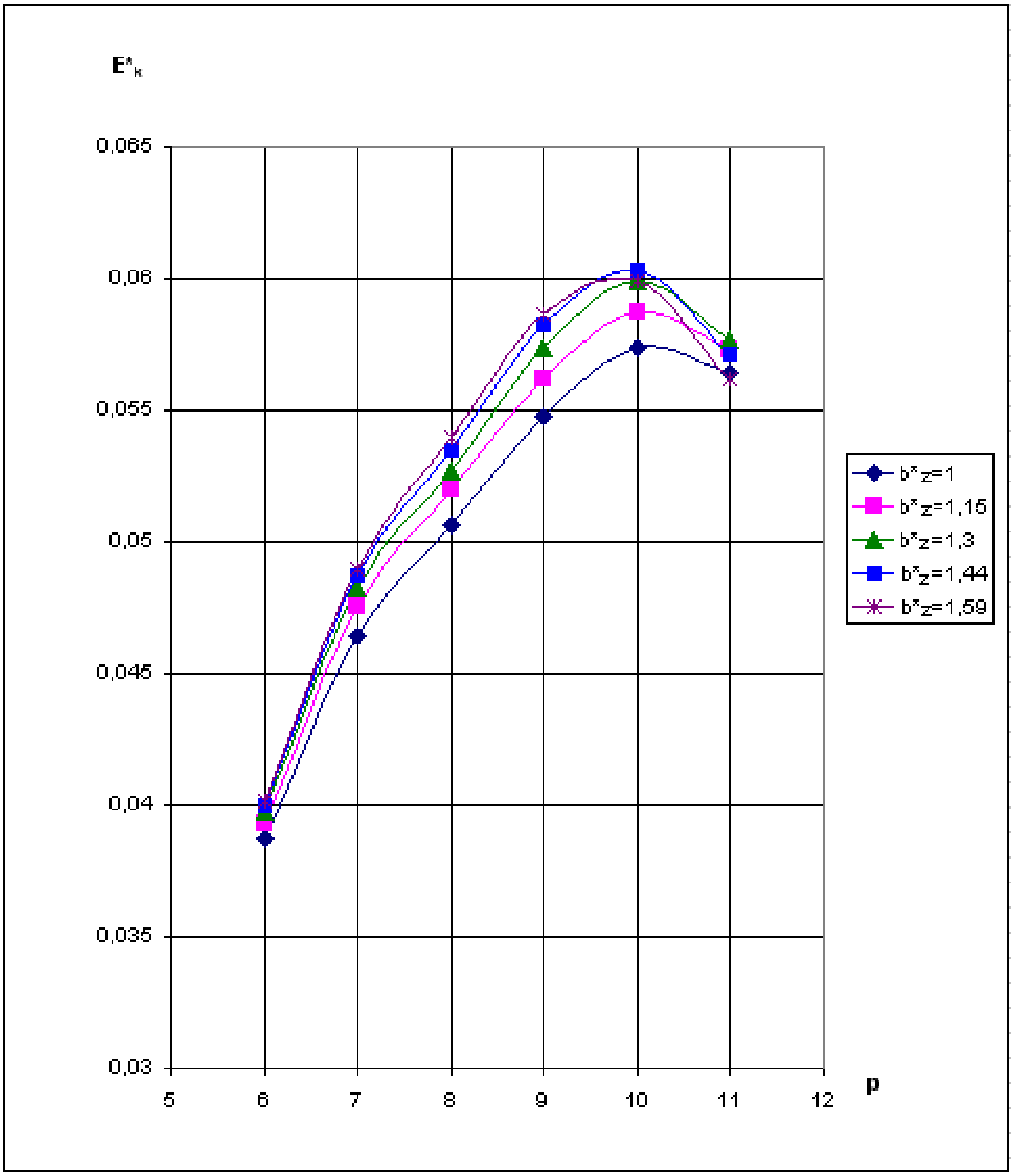

Fig. 4. Dependence on E^{*}_{k} $=f(p;b^{*}_{z})$; α_{δ}=0,9; h^{*}_{j1}=1

As a result from Fig. 4. follows, that with increasing width of stator teeth increases E^{*}_{k} minimum at p=6 and p=11 and maximum at p=10. Optimal value is at p=10, b^{*}_{z4}=1,44. The optimum width ratio of the magnet to the stator tooth width is b_{m}/b_{z}= 41/39 =1,05.

Relative dependence for the three values of the yoke in the stator is shown in Fig. 5.

With an increase of pole pairs, EDP reaches a maximum value at p=10. With the increase in relative height the yoke of the stator with h^{*}_{j1}=1 to h^{*}_{j2}=1,5 increase in EDP is 11%, and with h^{*}_{j3}=2 in addition is 6%. Optimal values of height and width of the yoke at p=10, h^{*}_{j3}=2, b^{*}_{z4}=1,44.

Here we see that when increasing the height of the yoke at 1,5 times, that is, till value $\frac{\tau}{4}\alpha_{\delta}$, more than sufficient to acquire growth of EDP and as it follows power-weight ratio.

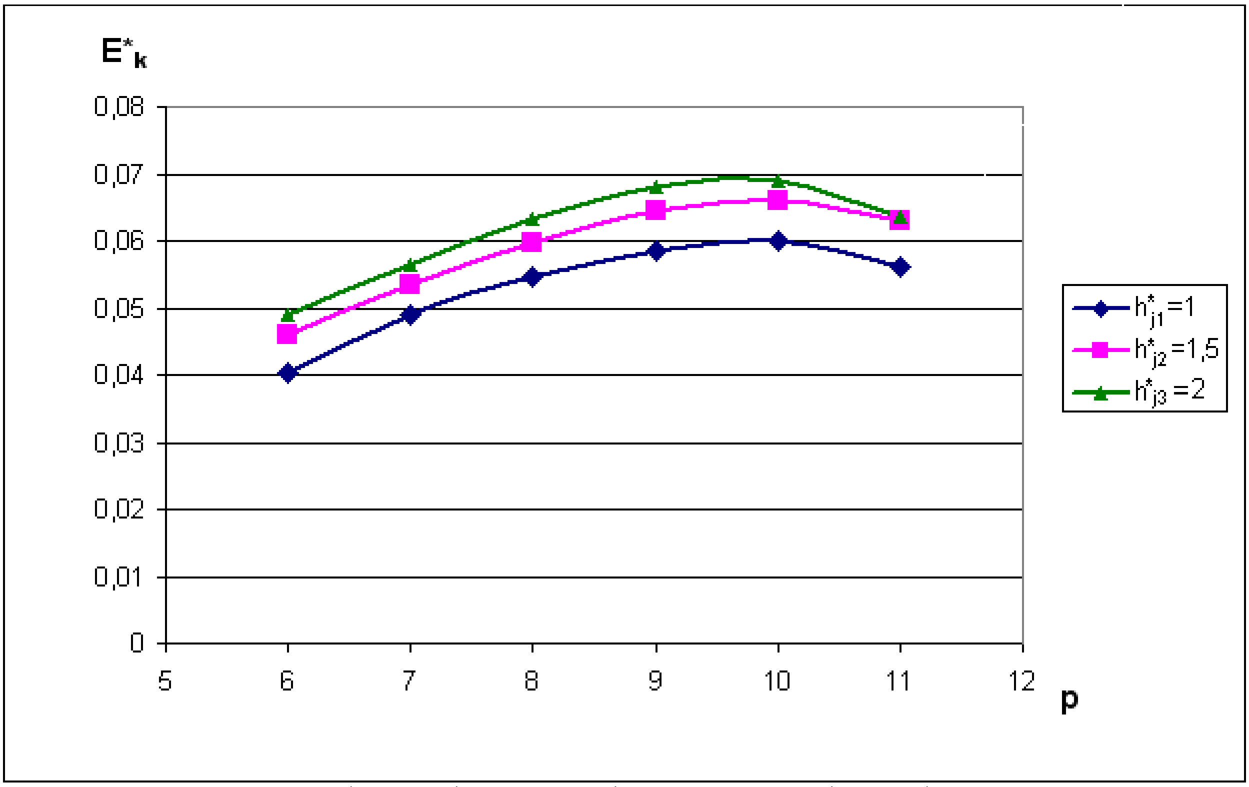

Fig. 5. Dependence on $E^*_k = f(p;h^*_j)$; α_δ=0,9; b^*_z =1,44, where b^*_z and h^*_j are per unit quantities

Traditionally it was assumed on the basis on providing sinusoidal form of EDP curved line and the acceptable level of scattering, that the pole overlapping $\alpha_\delta = \frac{b_m}{\tau} = 0,65 \div 0,7$. However, with the improvement of semiconductor technology, where very often the produced energy of alternate current was exposed to rectification and inversion, when the height of the magnet was reduced and the scattering was decreased, it was a disadvantage to underrate the magnitude of arc pole, in other words the volume of the magnets zone was not used. Indeed, if to increase the pole arc b_m, then we can expect an increase in the useful magnetic flux coupled to the stator windings. However, the increased overmach in the pole overlapping α_δ decreases the distance between the magnets, and this leads to increasing flows of stray flux, which is deducted from the calculated flow of useful pole (magnet). It seems like there is an optimum value α_δ, when the most useful flux from a magnet can be received, from it follows, the maximal flux linkage with armature winding (Fig. 6).

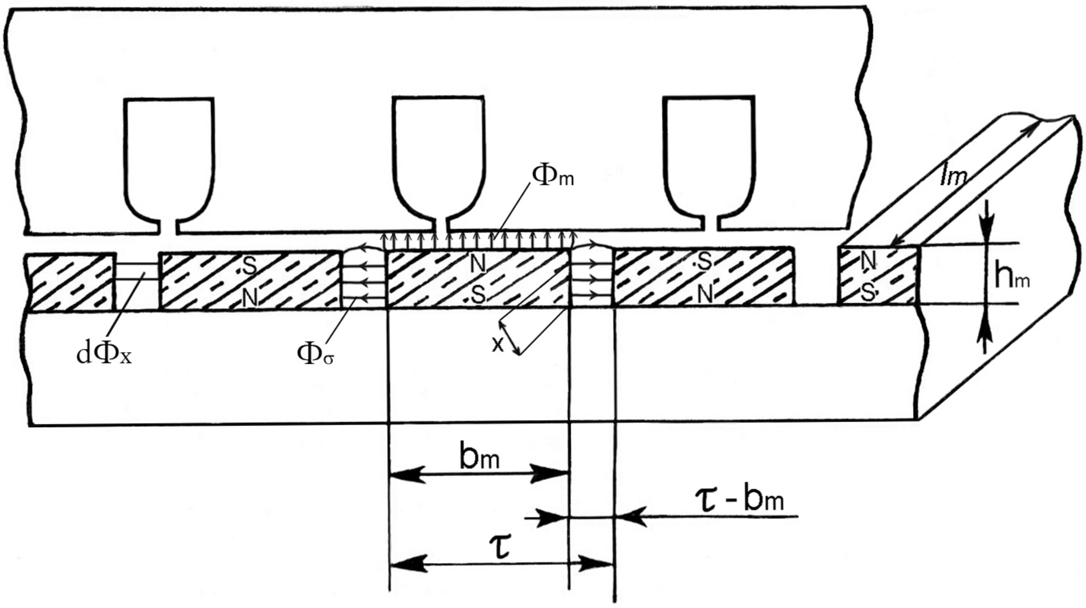

Fig. 6. Illustration to the determination of the optimal value $\alpha_\delta = \frac{b_m}{\tau}$

Based on the solutions of the equation

$$\Phi = \Phi_m - \Phi_\sigma = B_\delta b_m l_m - \int_0^{h_m} \frac{2F_m l_m \mu_0 x}{h_m(\tau - b_m)} dx = \frac{F_m l_m h_m}{(\tau - b_m)} \mu_0, \tag{2}$$

where F_m – randomly selected calculation of magnets magnetomotive force;
x – the coordinate of the considered elementary stray flux tubes scattering $d\Phi_x$, an analytical expression for the pole overlapping was received, on the output of which the end leakage flux

$$\alpha_\delta = 1 - \frac{\sqrt{h_m \delta}}{\tau} = 1 - \frac{2p\sqrt{h_m \delta}}{\pi D}, \tag{3}$$

where not taken into account, because of their small size compared to the stray flux between poles of different polarity.
Equation (3) was confirmed on the basis of calculation on magnetic field FEM (Fig. 7). The significance of it, is that it allows to set the interdependence of the geometric size of the optimized construction of electrical machines, thereby reducing the number of analyzed versions.
Supposing that initially there were selected 10 defined parameters which can be:
p – the number of pairs of poles;
z_s – number of stator teeth;
b_m – the width of the magnet;
b_z – the width of stator teeth;
D – stator bore diameter;
l – stator package length;
δ – air breather;
h_z – tooth height,
h_j – the height of stator (rotor) yoke;
h_m – height of the magnet.

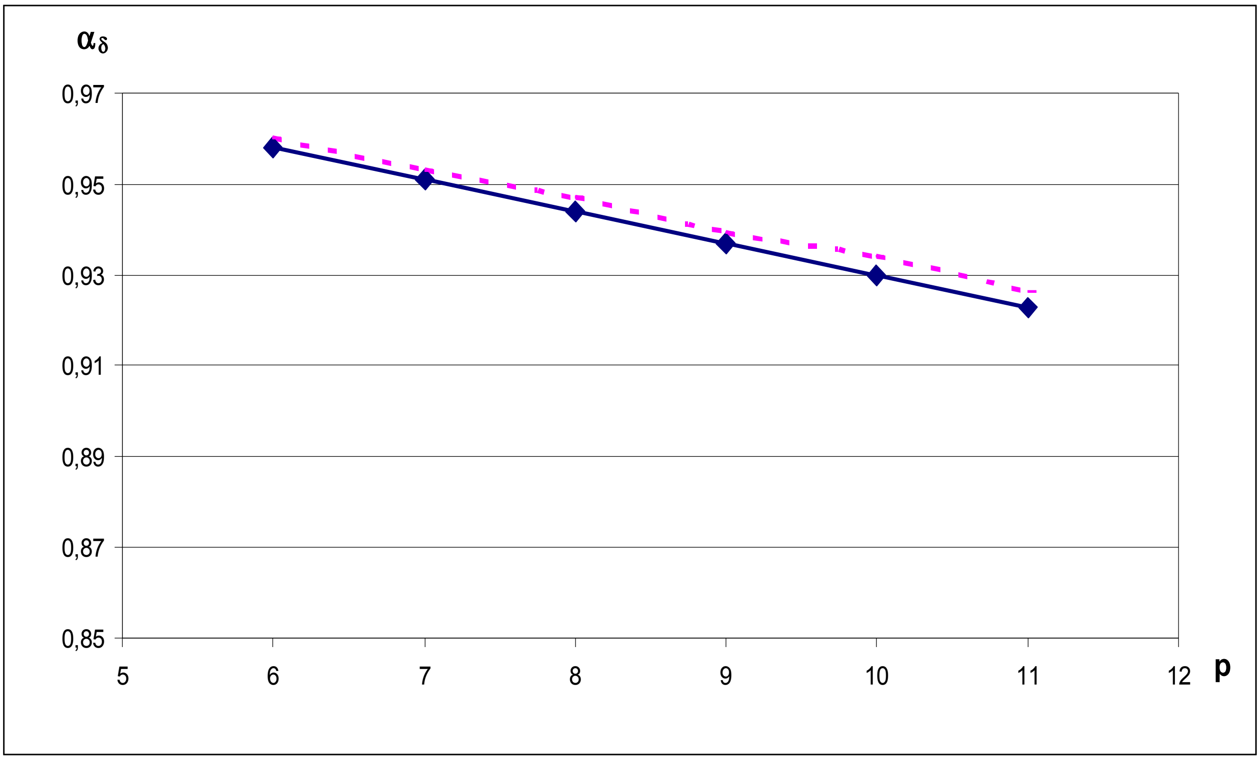

Fig. 7. The dependence of the coefficient of the pole overlapping on the number of pairs of poles:

——— – obtained from the calculation of magnetic field FEM,

- - - - - – obtained on the basis of an analytical formula

Then analyzing the number of options (if each of them takes at least 3 values) increases to $N=3^{10}$. This is a very large number.

Therefore, let's take a look which parameters dependent on each other. Usually the given are the power, rounds per minute and electromagnetic capacity. Therefore, the known experience of construction of ring-oscillators attitude, D and l could be determined. In such a way, two options can be excluded l and D. Air breather δ is rigidly bound to stator bore diameter of a machine, then it is also excluded as an independent parameter. Height of the magnet h_m is determined by a given maximum possible magnet flux density B_δ in an air breather and the breather's width δ, in other words they are also excluded as independent parameters. Number of stator teeth z_s of an optimal deconstruction is also tightly linked to the number of pairs of poles (1), i.e. this option is excluded as an independent. Also excluded are the widths of the groove and stator tooth, because in the optimal construction, they are approximately equal to each other and are rigidly connected with electrical loading A, which is preliminary given at maximum possible rate, plus thermal constraints were taken into consideration.

Thus, optimization may be a subject only to the number of pole pairs p and the coefficient of pole overlapping α_δ. Here with the height of stator's (rotor's) yoke h_j „strict" connected to the polar pitch τ. To use the above derived analytical interrelation (3), can be a simple enumeration of pairs of poles, using well chosen target function, determining the optimum, i.e. effective construction of turbine with excitation from permanent magnets.

3. Raising of the efficiency of wind turbine with permanent magnets on the basis of a ring-shaped design with optimal number of poles and the armature winding scheme

Assuming that in such conditions as direct-drive and low-speed oscillator, the ring-shaped structure with a small ratio of stator package length l to diameter of stator bore D, i.e. l/D=0,1, is already accepted in world practice, and it is valuable.

$$\delta = \frac{D}{350 \div 450}. \tag{4}$$

As for the height of the magnet, it can be determined

$$F_\delta = \frac{B_\delta \delta}{\mu_0} \approx 0{,}1 H_c h_m, \tag{5}$$

where H_c – coercive force of the chosen material for the permanent magnet.
The experience of designing electrical machines value F_δ, i.e. MMF accounted to air breather should be about 10 times less than coercive MMF of magnet, F_c=$H_c h_m$.
Taken into account (4) on the basis of (5) can be obtained

$$h_m = \frac{B_\delta \delta}{0{,}1 H_c \mu_0}. \tag{6}$$

Then in the final formula (3) becomes

$$\alpha_\delta = 1 - \frac{p\sqrt{\frac{h_m}{\delta}}}{\pi(175 \div 225)}, \tag{7}$$

where, for example, hard-magnetic material Nd-Fe-B with B_r≈1,35 T, H_c≈850·10³ A/m, B_δ≈1,1 T

$$\frac{h_m}{\delta} = \frac{B_\delta}{0{,}1 H_c \mu_0} = \frac{1{,}1}{0{,}1 \cdot 850 \cdot 10^3 \cdot 4\pi \cdot 10^{-7}} = 10{,}3. \tag{8}$$

Formulate a function of a goal as the interrelation of weight of the generator with the active materials to the rated power, i.e.

$$C_g = \frac{\pi(D_1^2 - D_0^2)l}{4S\eta}. \tag{9}$$

Here D_1 – outside diameter of the generator by stator package, m;
D_o – the inner diameter of the rotor package, m;
l – length of the stator packet, m;
$S=mEI$ – rated power m-phase generator, VA;
η – efficiency factor.
The external diameter of the stator can be represented as

$$D_1=D+2h_z+2h_j, \tag{10}$$

and the inner (rotor) like

$$D_0 \approx D-2h_m-2h_j, \tag{11}$$

where h_z – tooth height,
h_m – height of the magnet,
h_j – the height of the yoke of the stator (rotor).
If imagine

$$h_z = \frac{2A}{j_a k_{Cu}};\ h_j = \frac{\tau}{2}\alpha_\delta = \frac{\pi D \alpha_\delta}{4p}, \quad (12)$$

then the above values of diameters can be represented as

$$D_1 = D\left(1 + \frac{4A}{j_a k_{Cu} D} + \frac{\pi\alpha_\delta}{2p}\right), \quad (13)$$

$$D_0 = D\left(1 - \frac{2h_m}{D} - \frac{\pi\alpha_\delta}{2p}\right), \quad (14)$$

where k_{Cu} – coefficient of filing the groove with cooper;
j_a – current density in the armature winding, $\frac{A}{m^2}$;
A – line-distributed load, $\frac{A}{m}$.
Then, taking into account (13, 14) the objective function becomes

$$C_g = \frac{\pi D^2\left[\left(1 + \frac{4A}{j_a k_{cn} D} + \frac{\pi\alpha_\delta}{2p}\right)^2 - \left(1 - \frac{2h_m}{D} - \frac{\pi\alpha_\delta}{2p}\right)^2\right] l}{4S\eta}, \quad (15)$$

where the diameter of the stators bore is determined from the well-known expression

$$D^2 l = \frac{S}{0{,}18 B_\delta A n \alpha_\delta}. \quad (16)$$

Optimizing the number of pole pairs p and coefficient of pole overlapping α_δ were carried out on the example of turbine with the rated power S=10 kVA; rounds per minute n=150 min^{-1}; relation ratio $\lambda = \frac{l}{D} = 0{,}5$; line-distributed load $A = 2\cdot 10^4 \frac{A}{m}$; the current density in windings $j_a = 5\cdot 10^6 \frac{A}{m^2}$; magnetic induction in the air breather B_δ=1,1 T; coefficient of filing the groove with cooper k_{Cu}=0,6. It can be seen from the Table 2. that the results of the calculation of the objective function for four values with $\lambda = 0{,}5$; $\lambda = 0{,}1$; $\lambda = 0{,}05$ and $\lambda = 0{,}15$, and, as well as for several values of p=10, 20, 30, 40, 50, 60.
From table 2. follows that the best option, at which the minimum aim function, is provided is the number of pole pairs p=40 with a coefficient of pole overlapping α_δ=0,8. The table also shows that a ring-shaped design of the generator reduces the weight almost by half, compared to regular construction. In addition, the table shows that the choice of λ=0,1 is optimal, since reducing λ and its increasing (λ = 0,05 and 0,15) does not reduce the mass of the generator.
Armature winding in a synchronous machine with excitation from permanent magnets is one of the elements that can lead to frequent failures. The reason for this is the damage of isolation in the process of winding in production or in the process of its operation due to temperature effects, or effects of moisture and aggressive environment.

In such circumstances, different scheme winding may be different because of the degree of reliability or failure. If the winding multilayered with a large space, i.e. its coil covers several teeth of stator, then such laying of winding is exposed to a large mechanical resistance and tenure of sides, the frontal parts are crossing and are coming in to contact with each other in large areas. Naturally, such windings are likely to be damaged or come into a state of low reliability.
Therefore, for wind turbines autonomous WPP is advisable to apply one-shank coil winding, because they are the most reliable and easy to manufacture and repair.
With the optimum ratio of teeth numbers and stator poles EMF coils are creating a multipath star, where the EMF vector have minimal match, that creates conditions for the reduction of higher harmonics in the EMF phase.

Table 2.

Parameters of wind turbine, depending on the number of pole pairs

№	Parameters	p=10 z_s=18 λ=0,53	p=20 z_s=36 λ=0,1	p=30 z_s=54 λ=0,1	p=40 z_s=72 λ=0,1	p=50 z_s=100 λ=0,1	p=60 z_s=120 λ=0,1	p=40 z_s=72 λ=0,15	p=40 z_s=72 λ=0,05
1.	D^2l, m^3	0,0143	0,0146	0,0158	0,0168	0,0180	0,0192	0,0168	0,0168
2.	D, m	0,300	0,526	0,540	0,552	0,565	0,577	0,482	0,695
3.	D_1, m	0,38	0,597	0,597	0,601	0,612	0,622	0,531	0,750
4.	D_0, m	0,236	0,463	0,490	0,506	0,518	0,503	0,447	0,639
5.	δ, m	0,001	0,0013	0,0013	0,0014	0,0014	0,0015	0,001	0,0017
6.	h_m, m	0,01	0,013	0,013	0,014	0,014	0,015	0,01	0,017
7.	l, m	0,160	0,053	0,057	0,055	0,057	0,058	0,072	0,034
8.	τ	0,047	0,041	0,028	0,022	0,018	0,015	0,019	0,027
9.	α_δ	0,94	0,90	0,85	0,80	0,75	0,7	0,83	0,8
10.	$V=\frac{\pi(D_1^2-D_0^2)l}{4}, m^3$	0,0113	0,0059	0,0049	0,0045	0,0048	0,0050	0,0046	0,0041
11.	η	0,88	0,92	0,93	0,93	0,93	0,92	0,92	0,91
12.	$C_g=\frac{V}{S\eta}, \frac{m^2}{kVA}$	0,00185	0,00064	0,00053	0,00048	0,00052	0,00055	0,0005	0,00045 +δ_k
13.	G_a – mass of active materials, kg	83	44	37	34	36	38	36	31
14.	G_k – mass of constructive materials, kg	16	23	23	23	24	25	23	29
15.	ΣG_g – total mass of the generator, kg	99	67	60	57	60	63	59	60

At the same time winding is divided and characterized by the distribution ratio

$$k_s=\frac{\sin a\frac{\alpha}{2}}{a\sin\frac{\alpha}{2}}<1, \tag{17}$$

where a – the number of coils in the phase band; α = 20° – the angle between vectors of EMF.

Fig. 8. as an example, a star shaped grooving of EMF is shown in case $\frac{z_s}{p}=\frac{18}{7}$, kur a=3; α= 20°.

In this case the distribution coefficient of coils k_s in the phase of winding must be taken into account, which is determined by formula

$$k_s = \frac{\sin a \cdot \frac{\alpha}{2}}{a \cdot \sin \frac{\alpha}{2}} = \frac{\sin 3 \cdot \frac{20}{2}}{3 \cdot \sin \frac{20}{2}} = 0{,}96. \quad (18)$$

Thus, when the process of one-shank windings from armature coils at optimal ratio of pole numbers and stator teeth is being formed, a high reliability is provided, power-weight ratio, manufacturability and maintainability, but also a lower level of higher harmonics maintenance in phase structure of EMF is provided.

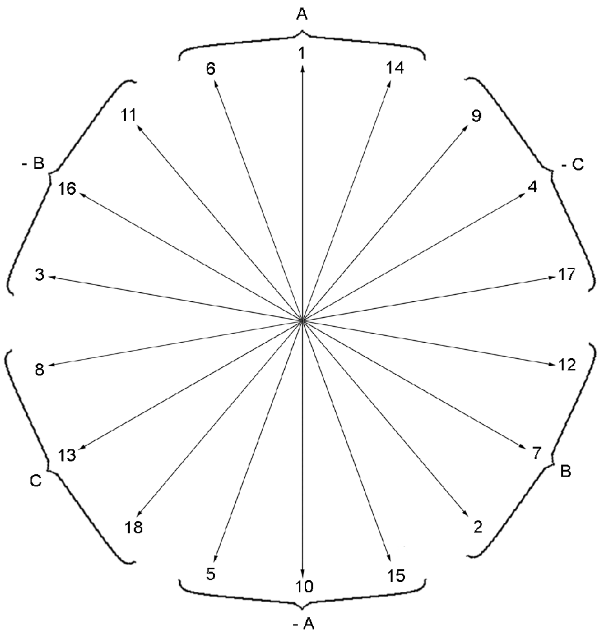

Fig. 8. Star shaped grooving of EMF at the ratio z_s/p = 18/7

4. Experimental studies of synchronous generators with excitation from permanent magnets and prospective for its improvement

To carry out experimental studies of a generator with excitation from permanent magnets multi-purpose integration bed of dynamometer DS 546–4V was used, which is installed in a laboratory "Modeling Physical EMUs processes" in the Institute for Physics and Power Engineering. General view on the test stand is shown in Fig. 9. On this test-bench the experimental model of low-power generator was studied.

Experimental direct-drive generator has the following parameters:

- power P_N=600W;
- voltage U_N=25 V;
- rated current I_N=14 A;
- rounds per minute n_N=500 min^{-1};
- size: 170 x 80 mm^2;
- outer diameter D_1=170 mm;
- axial length l=38 mm;
- number of phases m=3;
- mass of the generator G=7,5 kg.

Fig. 9. General view on the test-bench

The generator has an inner fixed stator with coil armature and the outer rotor with 16 prismatic magnets, forming 8 pairs of poles (*p*=8). Magnet material – Nd-Fe-B, is characterized by the following parameters:
remanent magnetism – B_r=1,15 T;
coercive force – H_r=850 kA/m.
Directly to the rotor supposedly three blades are attached of wind turbines (Fig. 10).

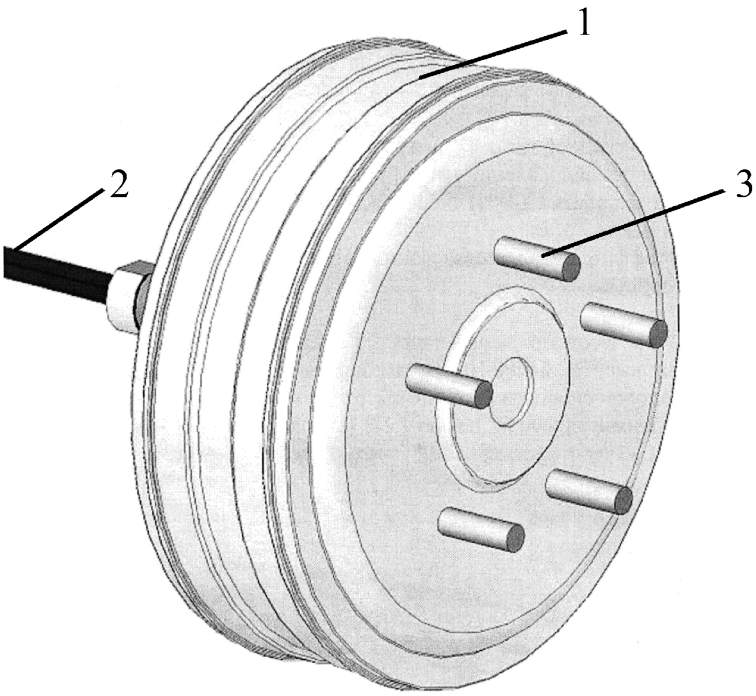

Fig. 10. General look facing the design direct-drive wind turbine:

1 – the outer rotor, 2 – winding end of armature, 3 – elements to mount blades

Table 3.

Parameters of the experimental model of wind turbine

№	Parameters	Dimension	Numerical value
1.	Nominal rating power, *P*	W	600
2.	Rated voltage, *U*	V	25
3.	Rated round per minute, *n*	min^{-1}	500
4.	Rated current phase, *I*	A	14
5.	Stator bore diameter, *D*	mm	143,8
6.	The axial length of stator packet, *l*	mm	38
7.	Number of phases, *m*		3
8.	The number of turns in the phase, *w*		104
9.	Phase resistance, *R*	Ohm	0,9
10.	Inductive winding resistance, x_L	Ohm	0,4
11.	Weight of the generator, G	kg	7,5
12.	Pole overlapping, α_δ		0,9
13.	Size of magnets, h_m x b_m x l_m	mm^3	12,7x25,4x38,1

In the process of the experiment such characteristics were taken:
- external characteristics of $U_d=f(I_d)$;
- characteristics of blank run $E_d=f(n)$;
- momentum characteristics $M=f(I_d)$;
- characteristic of efficiency factor $\eta=f(R_l)$.

As an example, only external characteristics are presented (Fig. 11.) for different values of round per minute *n*. Moreover, the characteristics obtained by calculation, are represented by solid lines, and the experimental results are shown using points.

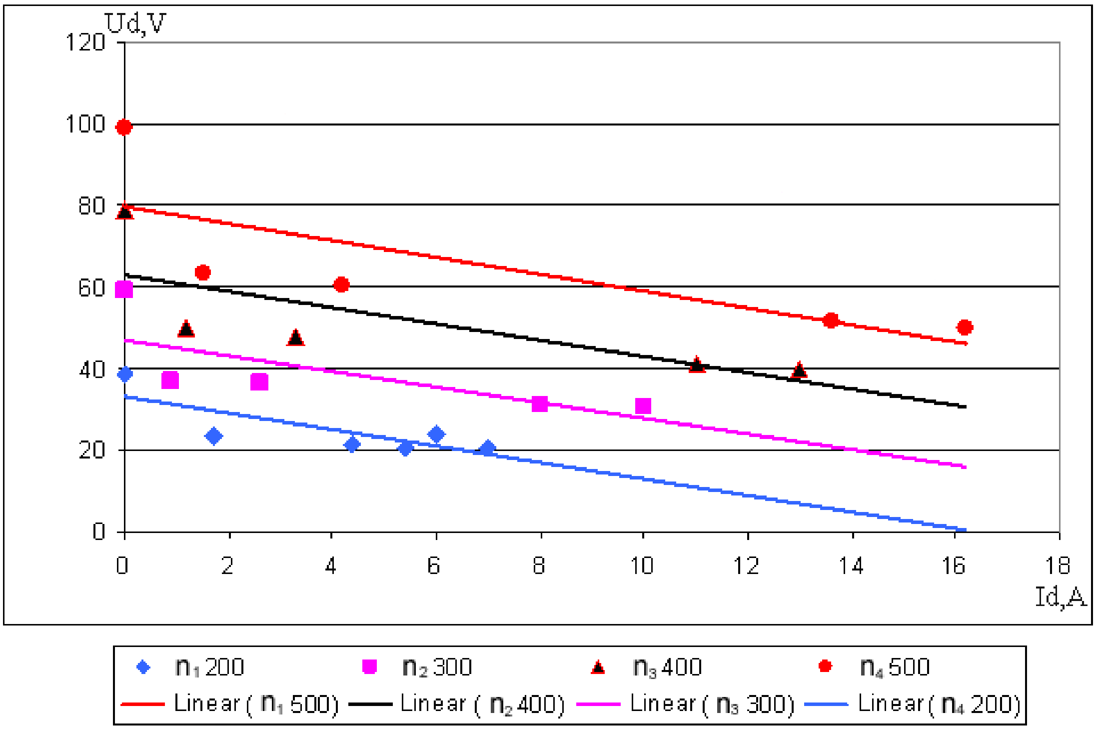

Fig. 11. The external characteristics of the generator, i.e. are depending

Below, in Table 4. the given data was obtained by calculation and experiment (experimental).

Table 4.

Comparative data, obtained by calculation and experimental

№	Parameters	Dimension	Numerical value	
			From experience	Calculation
1.	The active resistance phases at t =15° C, A-x B-y C-z	Ohm	0,94 0,99 0,93	0,9 0,9 0,9
2.	Inductance phase A-x B-y C-z	H	$0,95 \cdot 10^{-3}$ $0,96 \cdot 10^{-3}$ $0,94 \cdot 10^{-3}$	$0,97 \cdot 10^{-3}$ $0,97 \cdot 10^{-3}$ $0,97 \cdot 10^{-3}$
3.	Magnetic flux of pole	Wb	$0,97 \cdot 10^{-3}$	$0,90 \cdot 10^{-3}$
4.	Torque factor	$\frac{Nm}{A}$	1,3	1,25

It can be seen from Table 4, the calculated data and experimentation data are well conceded, it confirms the correctness of the chosen mathematical model and its accuracy.

The paper takes into account perspectives of correlation in order to improve wind turbines with excitation from permanent magnets. A possible promising solution is to perform winding of armature while switching from "stars" to "triangle".

For example, in the phase of pre calculated wind speed of the generator armature the winding is connected to the "star". When calculated speed of armature winding of a generator is achieved it switches from "stars" to "triangle". The generator is able to achieve an increase in rounds per minute and output current by $\sqrt{3}$ without overheating. The switching must be performed, of course, with high-speed elements (for example, semiconductor switch) with the usage of stabilizing filters.

Such a scheme substantively expands the working range of winds and allows to increase power output of WPP at $\sqrt{3}$ in comparison with the nominal.

The proposal to increase the number of pairs of poles in synchronous machine without increasing the number of permanent magnets is interesting. This proposal can be carried out for the machines with tooth windings and it is achieved through the use of toothed pole tips, attached to permanent magnets. Fig. 12. shows a variant of construction of such a generator.

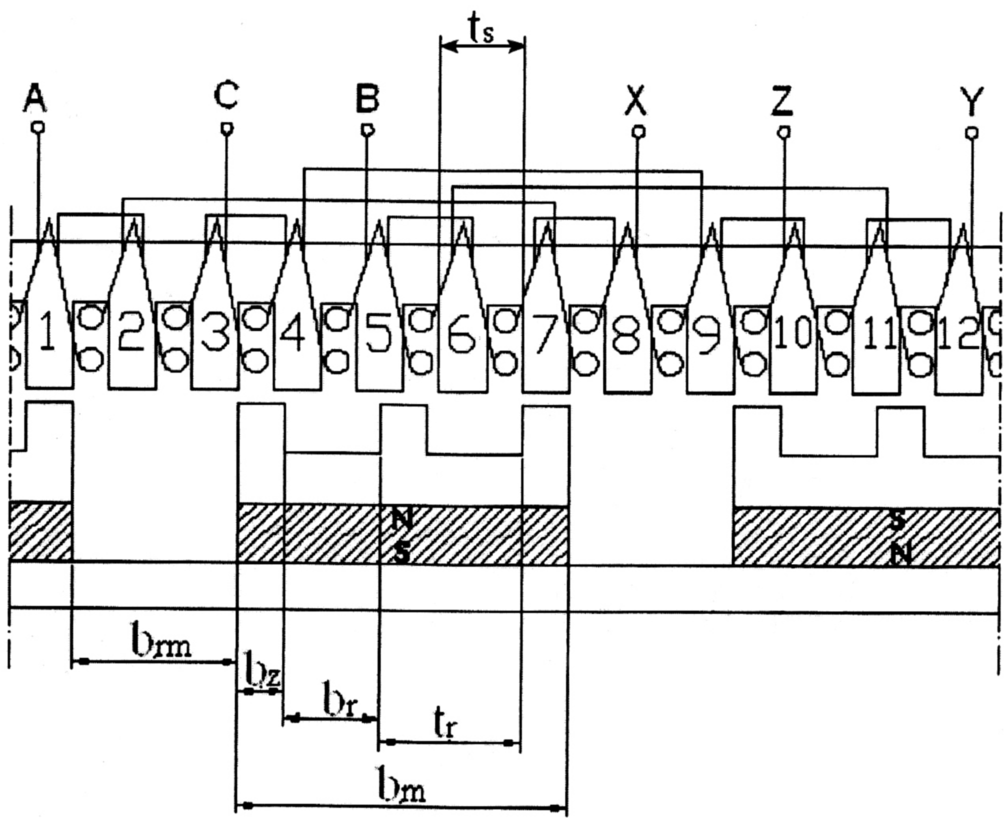

Fig. 12. Multipolar generator with toothed pole tips

The improvement in fastening of magnets is also promising. One option leading towards, that an electrical machine has a reversed execution – rotor covers stator. In this case, when a rotor rotates, the magnets are pressed by centrifugal force towards external ferromagnetic yoke, and distancing one from another by a special nonmagnetic separator. The separator has a trapezoidal slot to place trapezoidal shaped magnets (Fig. 13).
Fig. 14. shows another variant of fastening magnets, i.e., rotor with an incomplete number of magnets. Here, magnets and rotor teeth are interchanging: magnet-tooth-magnet, etc. All magnets come out of an air breather, with the pole of the same polarity. Then interchanged teeth with magnet have opposite, but each one the same polarity.

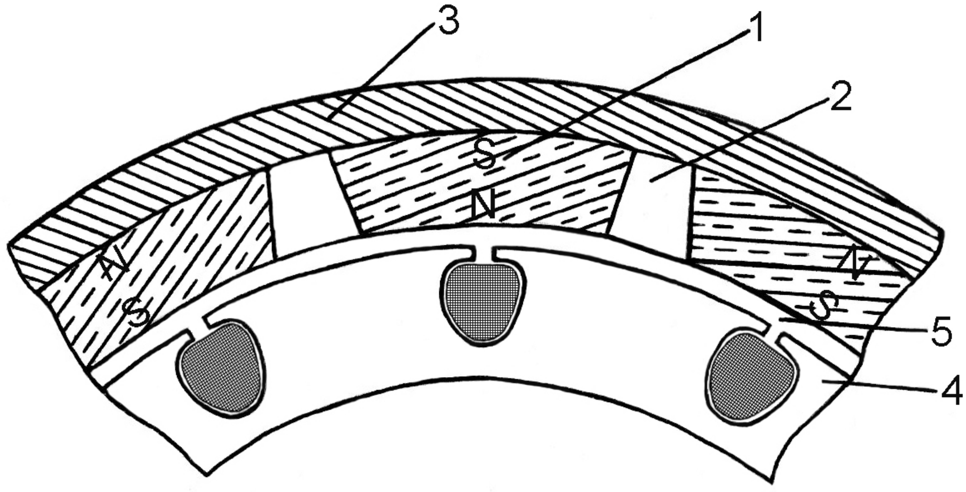

Fig. 13. Construction fragment of the generator with external rotor:
1 – magnet, 2 – non-magnetic separator 3 – the yoke of the rotor;
4 – stator with armature windings, 5 – air breather

The unique feature of this design is the following. Magnets and teeth have a trapezoidal shape. However, the width of the magnet is facing the air gap and is equal to the width of tooth in the air gap. The lower base of a magnet which gets in to contact with the yoke of a rotor, must be wider than the groove, i.e. it must be the distance between the teeth in the air gap. The magnet is inserted into the slot from the end. Nonmagnetic elements eliminate the possibly that sides of the magnets and teeth will tangle.

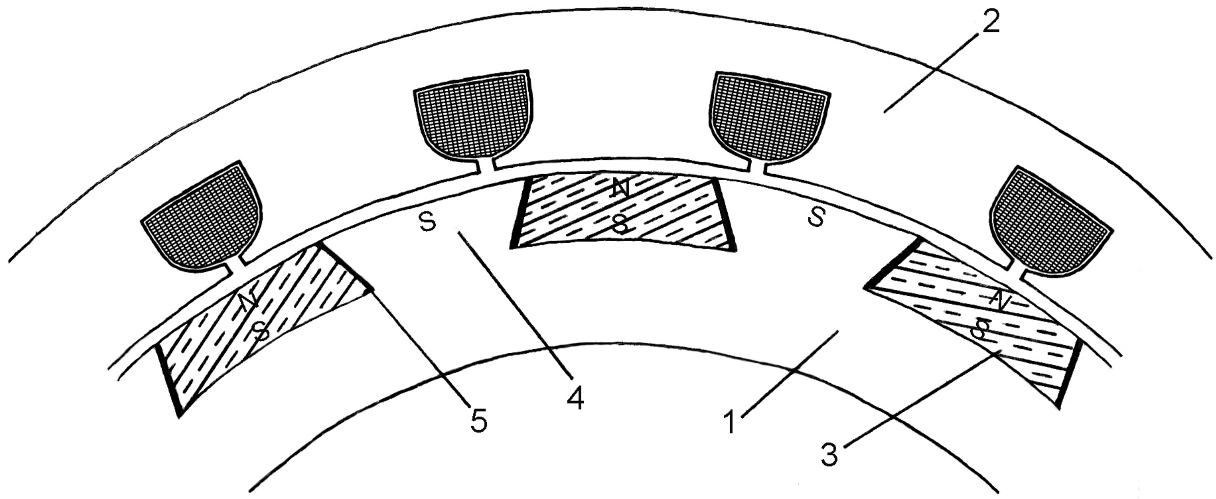

Fig. 14. Rotor with incomplete number of magnets, alternating with teeth:
1 – rotor with magnets, 2 – stator with armature windings 3 – magnet, 4 – tooth of the rotor;
5 – non-magnetic element between the teeth and the magnet

The thickness of nonmagnetic element Δ between magnets and teeth is chosen according to the ratio of (3), i.e.

$$\Delta = (1 - \alpha_\delta)\tau. \quad (19)$$

where $\alpha_\delta = 1 - \frac{\sqrt{h_m \delta}}{\tau}$.

Conclusion

The results of the research were presented in the paper, based on which is shown the possibility to increase efficiency of WPP with synchronous generators with excitation from permanent magnets. They are as follows:

1. Formulated criteria, which needs to be complied when selecting or creating a wind turbine, these criteria will allow to increase the efficiency of the generator and, consequently of WPP.
2. Based on the analysis of different types of machines it was stated, that most fully satisfying the efficiency criteria is multi-pole synchronous generators with radially magnetized prismatic magnets, made from high-energy material.
3. An analytical formula was received in order to determine the optimal coefficient of pole overlapping, which to certain height of permanent magnet h_m, the size air breather δ and the polar pitch τ reaches a maximum of power-weight ratio of the generator with excitation from radially magnetized permanent magnets, according to (3).
   The pole overlapping value should be between 0,8 and 0,95 in comparison with traditionally is taken over: 0,65 ÷ 0,7.
4. The optimal ratio between the number of pairs of poles p should be equal a half of the stator teeth z_s plus k, where is k – the smallest ceiling, that ensures the formation of symmetrical three-phase windings of armature, according to (1).
   Height of permanent magnet h_m should be greater then stator teeth height at air breather value.
5. It is shown that only an ring-shaped wind turbine and the optimal number of poles it is possible to substantially reduce the size and weight of an electrical machine.
6. It was suggested to construct an inductor coil with a reduced number of magnets of one polarity, which would be installed between the teeth of the rotor, while acquiring the opposite polarity to magnets. This simplifies mounting of magnets and reduces the manufacturing cost of the generator.
7. It was proposed to wind the armature of generator with the possibility to switch from "stars" to "triangle" in order to increase the coefficient of the installed capacity of wind turbine. At the same time untill the calculated wind speed winding of the armature should be turned on by "star", and by exceeding the calculated speed of wind by "triangle".

References

1. J. Daškova, E. Kamoliņš, N. Levins Tiešas piedziņas vēja elektrostaciju iekārtu daudzpolu elektriskie ģeneratori. Latvian Journal of Phisics and Technical Sciences. 2004, Nr. 4, pp. 41– 47.

2. N. Levins, V. Pugačevs, J. Daškova, E. Kamoliņš, A. Mesnjaevs Daudzpolu momentdzinēja izmantošana vēja iekārtas azimutālās orientācijas bezreduktora sistēmā. LFTZ žurnāls 2005. g. № 3. 37.– 42. lpp.

3. J. Daškova-Golovkina, N. Levins, V. Pugačevs Electrical generators of modern WPP. RTU zinātniskie raksti Enerģētika un elektrotehnika, sērija 4, sējums 15, 27.–32. lpp. 2005. g. Power and Electrical Engeneering International Conference, Riga, RTU, 16 October 2005.

4. J. Daškova-Golovkina, N. Levins, V. Pugačevs Обзор конструктивных схем электрических генераторов в современных ВЭУ. Науково прикладний журнал Технична электродинамика, 3 часть, 73 стр. IX International Conference "Problems of Present-day electrotechnics-2006", 5-9 June, 2006, Ukraine, Kiev.

5. J. Dashkova-Golovkina, J. Dirba, N. Levin, V.Pugachov Synchronous generators in without gear installations. RTU zinātniskie raksti, Enerģētika un Elektrotehnika, sērija 4, sējums 18, 19.–25. lpp. Power and Electrical Engeneering International Conference, Riga, RTU, 12–14 October 2006.

6. J. Dashkova-Golovkina, N. Levin, V. Pugachov Multipole Synchronous Generators with Permanent Magnets and tooth windings for low-power WPP. In CD format, topic 3(CT3), texst 3.04. 5th International Conference CPE 2007 „Compatibility in Power Electronics", May 29-June 1, 2007, Poland, Gdansk.

7. J. Dashkova-Golovkina, V.Pugachov Plastic bonded BaFe Permanent Magnets, tēzes 98. lpp., pilns raksts – CD These and Reports 134.–136. lpp. 5 starptautiska konference MET 2007 „Metāli, metināšana un pulvermetalurģija", 13.–14. septembrī 2007. g. Rīgā, Latvijā.

8. J. Daškova-Golovkina, J. Dirba, N. Levins, V. Pugačevs Tooth Zone Analysis in Multipole Synchronous Generators with Permanent Magnets. RTU zinātniskie raksti, Enerģētika un Elektrotehnika, sērija 4, sējums 20, 96.–102. lpp. RTU 48. starptautiskā zinātniskā konference, Rīgā 2007. gada 11.–13. oktobrī.

9. J. Dashkova-Golovkina, N. Levin, V. Pugachov Geometrical parameters of tooth zone in multipole synchronous generators with permanent magnets NdFeB, Науково прикладний журнал Технична электродинамика, 5 часть, 23–26 стр. X International Conference "Problems of Present-day electrotechnics-2008", 3–5 June, 2008, Ukraine, Kiev.