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DESIGN OF A 1kW 150 RPM PERMANENT-MAGNET SYNCHRONOUS GENERATOR FOR STAND-ALONE WIND-POWER APPLICATIONS

Examiners:	Professor	Juha Pyrhönen
	Associate Professor	Pia Lindh

ABSTRACT
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Master`s thesis

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A program for calculating low-speed low-power synchronous machine is presented. A permanent-magnet synchronous generator for 1 kW 150 rpm is designed. Optimization of magnet's and coil's dimensions was made.

Keywords: design, permanent magnets, synchronous generator, wind power.

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LIST OF SYMBOLS AND ABBREVIATIONS

2D – two dimensional

3D – three dimensional

AC – alternating current

$\cos\varphi$ – power factor

EMF – electro motive force

FEA – finite elements analysis

PM – permanent magnet

PMSG – permanent magnet synchronous generator

RMS – root mean square

A – stator linear current density

a – number of parallel branches

B – magnetic flux density

B_δ – magnetic flux density in the air gap

B_r – remanent flux density

b_c – thickness of the coil

C_{Cu} – cost of copper winding

C_{PM} – cost of permanent magnets

C_Σ – total cost of active materials

D_{out} – rotor outer diameter

D_{in} – rotor inner diameter

D_{av} – average rotor diameter

E – electromotive force

$E_{cond,max}$ – maximum EMF of a single conductor

$E_{turn,max}$ – maximum EMF of the turn

$E_{ph,max}$ – maximum phase EMF

f – network frequency

H – magnetic field strength

H_c – Coercitivity

h_c – height of the coil

h_{PM} – magnet's height

I_{ph} – phase current

$I_{ph,max}$ – maximum phase current

J – polarization

J_a – current density

K – crystallographic constant for magnet element

L_a – inductance of the winding

l_a – active length of the coil, magnet's length

l_{turn} – average length of one turn in the coil

l_σ – average length of the end winding

M – Magnetizing

m – mass

m – number of phases

N – number of turns in one coil

N_{ph} – number of turns in one phase

n – number of atoms per unit volume

n – rotation speed

n_n – nominal speed

P_{add} – additional losses

P_{Cu} – copper losses

P_{mech} – mechanical losses

P_{n} – nominal power

P_{out} – output power

p – number of pole pairs

q – number of slots per pole and phase

$R_{\mathrm{a,20°C}}$ – stator phase resistance at 20°C

$R_{\mathrm{a,80°C}}$ – stator phase resistance at 80°C

r_{av} – average radius of the rotor

r_{in} – inner radius of the rotor

r_{out} – outer radius of the rotor

S_{c} – cross-sectional area of one coil

S_{n} – nominal apparent power

S_{turn} – cross-sectional area of one turn

T – torque

U_{ph} – phase voltage

U_{ph0} – phase voltage of no-load regime

V – volume

V_{PM} – volume of permanent magnets

v_{av} – average linear velocity

W – amount of energy per volume

W' – relative energy

$w_{\mathrm{PM,av}}$ – average width of the magnet

$w_{\mathrm{PM,max}}$ – maximum width of the magnet

$w_{\mathrm{PM,min}}$ – minimum width of the magnet

x_{a} – reactance of the phase

x_{σ} – reactance of the end winding

Z – number of virtual slots

Z_a – impedance of the phase

α – temperature coefficient

$\mathit{\Delta}$ – mechanical air gap between rotor and stator

$\Delta\tau$ – distance between magnets

δ – air gap, distance between magnets of different rotors

η – efficiency

$\mathit{\Pi}_{av}$ – average perimeter of the rotor

$\mathit{\Pi}_{in}$ – inner perimeter of the rotor

$\mathit{\Pi}_{out}$ – outer perimeter of the rotor

ρ_{Cu} – density of the copper

μ_0 – permeability of the vacuum

μ_m – magnetic dipole moment

μ_r – relative permeability

σ_{tan} – tangential stress

$\tau_{p,av}$ – average radius pole pitch

$\tau_{p,max}$ – outer radius pole pitch

$\tau_{p,mix}$ – inner radius pole pitch

$\mathit{\Phi}$ – flux

ω – rotor angular velocity

1 Introduction

1.1 Historical reference

For centuries people have used the energy of wind. Windmills and watermills were the source of motive power to lighten the life of man executing mechanical applications, many of which are still in use now.

The history of windmills has been written down by Wilson Clark in his work “Energy for survival: The Alternative to Extinction”. With regard to Europe, he says, “Developed in Seventh century in Persia, windmill reached Europe through Dutch and England in thirteenth century enabling them to generate one billion kilowatt-hour of electricity. The wind energy produced by windmills was used as a source of power to the sailing ships. The Persians again became the first to use wind to develop mechanical power and used windmills to put out water for irrigation. Whereas windmills were used in Persia in the seventh century, it reached France in 12th and Denmark, Germany and Netherland in early 13th century.” [1]

Mankind has been using wind in their daily work for around four thousand years. Sails revolutionized seafaring, which no longer had to make do with muscle power. Since 1700 B.C. wind has been used to power scoops for irrigation systems. First country of usage was Mesopotamia. Besides pumps for irrigation or drainage, windmills were also used to ground grain. Nowadays we still use the term "windmills", even when we are talking about machines that do not actually grind, e.g. saw-mills and hammer-mills.

However, the new history of wind turbines that generate electricity today began with a few technical innovations, such as modern aerodynamic form and sizes of blades. Developments in the fields of mechanical and electrical engineering, control technology, aerodynamics and power electronics provide the technical base for wind turbines to be successfully and commonly used today.

Wind turbines that generate electricity and pass it directly to the grid was the first step in the succesful development of this field. Between 1920 and 1926, a German physicist Albert Betz calculated the maximum wind turbine performance (now it is called the "Betz limit"), and the optimal geometry of rotor blades. His book "Wind-Energie und ihre Ausnutzung durch Windmühlen" (in English - "Wind Energy and its Use by Windmills") gives a good account of the understanding of wind energy and wind turbines at that period.

In 1950, a German Professor Ulrich Hütter applied modern aerodynamics and modern fiber optics technology to the construction of rotor blades on the wind turbines in his experimental system. [2]

A Danish scientist, inventor and educationalist Poul la Cour developed a wind turbine that generated direct current. In 1958 his pupil Johannes Juul invented the "Danish Concept", a system that allows alternating current to be fed to the grid. This concept became very popular. Today, after more than half of a century passed, about half of all wind turbines in the world operate according to this principle.

Since 1980, dimensions and efficiency of wind turbines have been significantly increasing. This can be seen from table below.

Table 1. Growth in the capacity of wind turbines for previous 30 years [4]

	Year						
	1980	1985	1990	1995	2000	2005	2010
Rated power, kW	30	80	250	600	1500	3000	7500
Rotor diameter, m	15	20	30	46	70	90	126
Painted rotor surface area, m^2	177	314	707	1662	3848	6362	12469
Hub height, m	30	40	50	78	100	105	135
Annual energy yield, MWh	35	95	400	1250	3500	6900	20000

In the 1980s, the in Danmark small turbines with a nominal output of 20 kW to 100 kW were developed. With a help of government subsidies, these turbines were set up on farms and on the shore to provide power to the local consumers and non-consumed energy was fed to the power grid. [3]

1.2 About wind turbine

Wind turbines and windmills are mounted on a tower to get the maximum of energy. The tower of wind power plant should be tall because the wind is remarkably stronger at higher heights. Every turbine has its own friction and inertia and because of those, turbine begins to rotate only since corresponding wind speed that can move the blades. Usually such speed is higher than 2-3 m/s for different turbines. In addition, there is a limit of wind speed and turbine stops if wind force is too strong. It prevents the turbine from destruction.

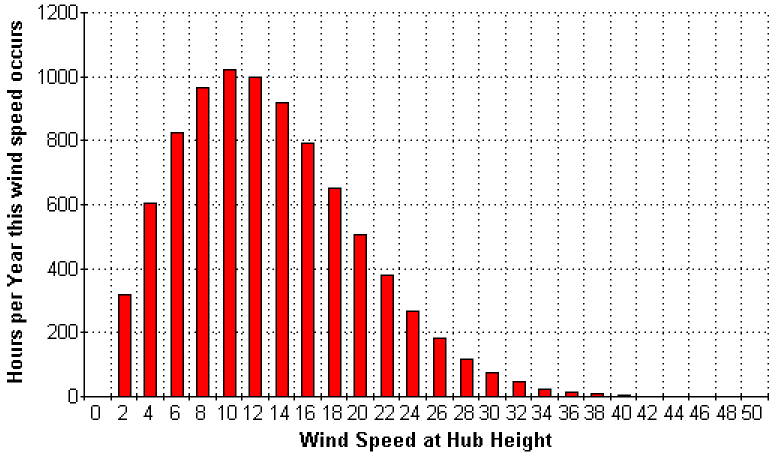

Fig.1. Wind distribution [5]

Turbines catch the energy of wind with a help of their blades. Usually there are three blades on a horizontal shaft.

A blade behaves like wing of an airplane. When the wind is blowing, a pocket of low-pressure air is formed on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, which causes the rotor to turn – this is “lift”. The lift force is much stronger than the wind's force against the front side of the blade – that is “drag”. The combination of lift and drag forces causes the rotor to rotate like a propeller, and the shaft turns a generator which produce electricity.

Wind turbines can be used as stand-alone power sources or can be connected to the common power grid or even combined with a solar-power system. To make a strong source of wind energy, a big number of wind turbines are installed in the row to form a wind power. Several electricity providers now use such wind power plants to supply their customers with renewable electricity.

Private wind turbines are typically used to power water pumps and communications. Householders and farmers in windy areas can also use wind turbines to reduce their electric bills.

Advantages

- Wind generators do not consume fossil fuels. Working 20 years, the wind turbine with a capacity of 1 MW saves approximately 29 000 tons of coal or 92 000 barrels of oil. [6]
- Wind generators do not produce any emissions or pollution. Wind turbines with a capacity of 1 MW reducing annual atmospheric emissions of 1800 tons of CO_2, 9 tons of SO_2, 4 tons of nitrogen oxides. [6]
- Unlike traditional thermal power plants, wind plants do not use water, which can significantly reduce the pressure on water resources.
- A little piece of land is needed to install the tower of turbine. The ground around tower still can be used.
- Can be built relatively fast.
- Micro wind turbines can be easily used in remote areas where there is no electricity grid and they start pay back very soon.

Disadvantages

- Near to the turbine axis noise can exceed 100 dB. The laws of the UK, Germany, the Netherlands and Denmark, limit the level of noise emitted by wind power plant to 45 dB in household areas.[7] The minimum distance between installation and residential buildings is 300 meters. And in some countries (e.g. Finland) it is recommended to have 2 km distance.
- Metal construction of wind turbines, particularly elements of the blades can cause significant interference in radio signal reception. The larger wind turbine, the more interference it may create. In some cases, to solve this problem it is needed to install additional rebroadcasting transmitters.

- Wind turbines could cause a radar jamming making an emission of radio frequency signals which interfere with the operation of radars by saturating their receiver with noise or false information.
- Wind power plants produce two types of noise:
  - mechanical noise - the noise from the mechanical and electrical components
  - aerodynamic noise - the noise from the interaction of the wind flow with blades (increases when the blade is passing by the tower of wind turbine)
- Low-frequency vibrations transmitted from the megawatt-class wind turbines through the ground may cause significant bounce of windows in the houses at a distance of 60 m.
- Operating in winter with a high humidity, it is possible that ice build-up on the blades takes place.
- Visual impact of wind turbines (a subjective factor).
- Large wind turbines may have significant problems with repairs, since the replacement of the large details (blades, rotor, etc.) on a height of about 100 meters is a difficult and expensive.

Despite some problems connected to wind generation, this power producer becomes more popular because of it does not need any fuel and does not make any harm to environment.

Micro turbines do not produce any noise and are almost harmless to birds.

1.3 Axial-flux synchronous generators with permanent magnets

There are three main concepts for the feed of electricity to the power grid but in this Thesis only one of them is discussed – direct drive generator with full-power converter (Fig.2). It means that the system has synchronous machine with permanent magnets as a generator and does not have a gearbox, which means less cost, less dimensions and less losses, however, it should have quite complicated power electronics component. The system has a DC-link, after which it is possible to convert voltage into required waveform.

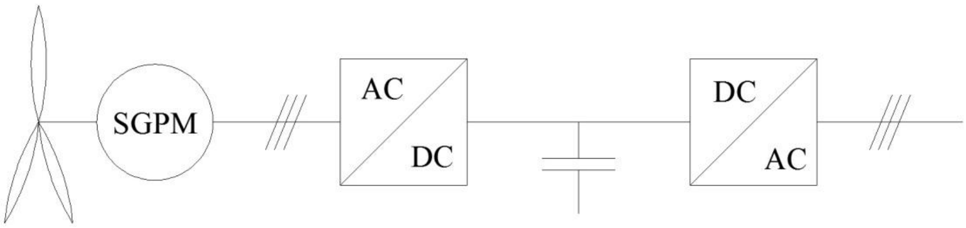

Fig.2. A scheme of direct drive generator with full-power converter

Despite the development of very high power turbines, there is currently also significant interest to develop small-size wind turbines with horizontal or vertical axis for urban environments. In addition, such a turbine is an attractive choice for autonomous applications and for rural areas where it is more difficult and expensive to install a distribution grid.

The power range of those systems is usually from 300 W to 5 kW. Efficient and low-loss permanent magnet excitation is usually used in this power level because the required volume of permanent magnets does not demand very high investment. From this point of view, we have an advantage of saving energy because a PMSG does not require any external excitation as wound-rotor generators do. That also means a decrease in the rotor losses and allows the use of a diode bridge rectifier in some cases.

Excitation from permanent magnets allows decreasing the pole pitch and consequently the reduction of cost and mass. Using high number of poles, it is possible to make a configuration of direct driven generator without any gear-boxes.

Axial flux machines' main feature is an axially directed air gap flux. The simplest structure uses one stator ring form and a disk rotor, both having the same active inner and outer diameters which define the active part of the machine where the electromechanical conversion takes place.

The flux density defines the axial length of the stator and rotor yokes. Hence, yokes can be fully utilized with a proper yoke design. Consequently, with the increase of pole number, the radial active part remains almost the same, but the axial length can be reduced and the torque becomes higher. So that, axial flux machines suit for low-speed, high-torque low-power applications, e.g. wind power systems.[8] At higher powers the axial flux systems brings mechanical difficulties for the construction.

The double-sided structure with internal rotor simplifies the manufacturing process due to easier fixation of the stator rings to the frame; it also favors the cooling process because the main heat source is located near the surface. However, extra care is needed to have a good thermal contact from the stator lamination to the frame. Slotted stators enable high air-gap flux density due to shorter air gap. This reduces the required amount of permanent magnets. Permanent magnet excitation may evoke undesired torque pulsations, but the adopted structure allows stator skewing by one half of the slot pitch, which results in reduced torque ripple and space harmonic components.

Current ripple in slotted stators may also be reduced by higher leakage inductance compared to slotless (ironless) stators. It is currently assumed that concentrated non-overlapping windings are an effective way to reduce Joule losses in low-speed machine windings. However, they generate both odd and even harmonics, and some of them also produce sub-harmonics in the electro-motive force (EMF). All extra harmonics create additional fluxes in the machine, which result in high eddy-current losses in a conducting rotor and in the permanent magnets, which may cancel the benefits of the shorter end windings. A conventional distributed winding with one slot per pole and phase is preferred. The flux travels axially in the rotor structure and completes its path by returning circumferentially around the stators cores. [8]

In the 1980’s there were the first attempts to penetrate into the market with radial-flux permanent-magnets synchronous machines. The basic idea was to increase the efficiency of the traditional machines by permanent magnet excitation (Sm-Co magnets). The benefits were not good enough and the attempts to enter the market were finished. However, several manufacturers released small permanent-magnet machines successfully.

Axial-flux permanent-magnet machines were under research for special applications with limited space for machine length. An opportunity to have a very short axial length makes axial-flux machines very attractive in cases when the axial length of the machine is limited. Such machines are used in high-torque applications.

According to winding arrangements, the number of rotors and stators and their configurations, four most useful structures can be found:

- one rotor - one stator;
- one stator - two rotors;
- one rotor - two stators;
- several rotors and stators

The *one stator – two rotors structure* is called a “Torus” type axial-flux machine. Phase winding is located on a slotted or non-slotted stator. The first machine of that type with non-slotted stator was made in the end of 1980’s [14]. The toroidally wound winding has short end-windings, which increases the power density and machine’s efficiency. The disadvantage of the “Torus” machine is more complicated frame and compared to another structure where the rotor is between two stators, less gap for the winding. Cooling of the stator may also be difficult in the middle of the machine.

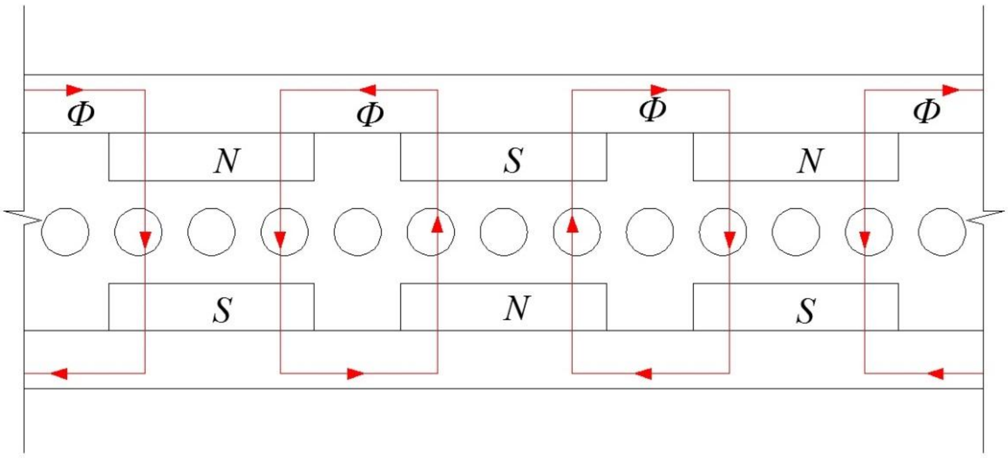

Fig.3. Flux distribution

1.4 Target of work

In modern micro wind power plants a variety of different electromechanical energy converter systems are used. Meanwhile, among the autonomous gearless wind turbines, multipole synchronous generators with permanent magnets are becoming more popular and widely used. The reason of such success is their high reliability, simple design and maintenance, high efficiency. At the same time, the design and calculation of these machines do not receive enough attention. Existed methods of calculating the PMSG are focused primarily on high-speed machines which are used in aircrafts as an independent power supply driven with turbines, or low-power tachogenerators to measure the speed of rotation of the main machine. These usually are generators with small number of poles and their rotation speed may be thousands of revolutions per minute, which highlights the provision of mechanical strength of the rotor and magnetic system, the choice of electromagnetic loads and thermal conditions of the machine.

For wind turbine generators along with those factors, it is necessary to consider other specific features. In particular, although the rotor speed is small, there are dynamic torques constantly present. They are associated with non-stationary nature of the speed and force of the wind. Without any mechanical damper, it may cause additional heating of the active parts of the machine. On the other hand, when the number of poles is sufficiently large, there are difficulties in providing the desired magnetic flux in the air gap of the generator, which causes the increase in the amount of copper in the associate winding, and consequently, difficulties with winding's placement. Altogether it leads to deterioration of characteristics of the generator.

With a large number of pole pairs and enlarged internal diameter of the stator core the moment of inertia of the rotor naturally increases, which to some extent enhances dynamic vibration damping during the violent gusts of wind. One of the main problems of calculation is to determine the optimal ratio between the size of the magnet and the main dimensions for stator core.

Investigation of the literature on the subject reveals that the analytical design of axial-flux permanent-magnet machines is not accurate. However, the developing of such low-speed machines may become practically demanding and beneficial, especially because magnetic materials with high-performance properties are invented already.

The target of this work is to develop an optimized design method for the axial-flux permanent-magnet machines with two rotors and one stator in between. Unusual feature of this generator will be an ironless stator. Using previous researches and knowledge, the calculation and optimization methodic of such machines will be presented. It is an attempt of finding appropriate dimensions and characteristics of a generator with a goal of getting a high efficiency, high simplicity and low cost.

2 Design of low-speed axial-flux permanent magnet generator

2.1 Principles of design

Design of the electrical machines is a field of engineering that has been developing since scientist got the understanding of possible usage of electricity. Improvement of the construction constantly moves forward in the pace of science. Successful research in Power electronics opened new horizons. Elaboration of insulation materials, performance permanent magnets, steel and other materials helps to decrease the size of machine and increase efficiency.

The rapid development in the area of permanent magnet synchronous machine began in 1983 when Neodymium-Iron-Boron (Nd-Fe-B) magnetic material was invented.

Asynchronous machines with gearbox can be also used for such needs. However, a machine without gearbox demands less space, reduces the costs of maintenance and increases the reliability of the system. Modern control methods such as the direct torque control or other high performance vector control methods used in permanent magnet machines help to achieve high-quality low speed direct drives.

The main target of design engineer is to make the most appropriate electrical machine for a particular application.

Traditionally, radial-flux machines were in use widespread. But since high quality permanent magnet materials have been invented, in some cases it is clear that the usage of axial-flux permanent-magnet machines is more suitable. The benefits of such machines are that their axial length is lower and the rotor can be connected directly to the driven parts. Nowadays axial-flux machines are competitive with radial-flux machines in low-power areas. Moreover, the process of designing of axial-flux machines is still in progress and it is still possible to get new innovations and inventions in this area.

The process of designing an electrical machine is a multivariable problem. For the one initial data designer can make a series of solutions and then the most appropriate one must be chosen. The problem is that for calculating a machine a lot of additional information is needed. The designer can receive them only from the experience or literature recommendations.

The designer has to think about many factors creating a new machine. The electromagnetic loads, mechanical loads and thermal loads have interactions with each other especially when the designer tries to decrease the dimensions. That fact makes the design process not simple and usually design division works at the creation of new type of the machine. They must do series of iterations before they get an acceptable result.

One of the hardest parts in calculation is to understand how the magnetic field is distributed in the electrical machine. In principle, to understand this for a specific geometry a system of three-dimensional differential equations needs to be solved. Even nowadays it is hard but some years ago it was impossible. Of course people could calculate the fields of some small important parts but it should take a lot of time. To decrease the time of a creation of the machines manufacturers have created their analytical methodologies to calculate new products. With the experience and individual features of manufacturing included a lot of additional coefficients that make the parameters of calculated machine close to manufactured one.

For many years these methodologies were the only way of calculating the machines. For calculation the magnetic parameters a machine is assumed as a series of magnetic resistances that with some pre-determined coefficients can give precise enough results.

Briefly, the process of designing the synchronous generator has the next steps:

- Selecting the main dimensions
- Design of the stator geometry
- Determination of the type of stator winding and its parameters, determination of the stator slots dimensions
- Design of the air gap and rotor geometry
- Design of damper winding if it is needed
- Calculation of the no-load mode for the geometry chosen
- Calculation of electromagnetic and some transient parameters of the machine

- Calculation of the permanent magnets to produce excitation flux
- Calculations of the losses and efficiency
- Calculation of all the other needed parameters of the generator
- Thermal, ventilating, mechanical calculations

Problems can occur at every step so that a new iteration can be needed or new calculations from the beginning.

This methodology has a lot of assumptions and simplifications but the created generators are good enough and work properly.

A new era in machine design started when computers appeared. They greatly reduced the time spent on the calculations. Almost all paper methodologies became digital and it simplified the process of the machine developing.

Nowadays we can more and more use computers in designing the machines. Special programs that are based on finite element method can solve the differential equations of different fields. They allow checking the magnetic field, electric field, mechanical stresses and temperature of any geometry you want. It is possible to calculate parameters and loads at nominal point, transients and connected problems (for example find the losses and calculate the rise of the temperature in elements). 2D and 3D tasks can be solved but the only problem is that the speed of calculation is limited by the power of computer.

2.2 Permanent magnet materials

The unusual properties of lodestone (chemical compound Fe_3O_4) were known long centuries ago by ancient Asian and European communities. The Chinese invented a compass around 5000 years ago. The first directional study of the magnetism phenomenon was made in the beginning of 17th century by William Gilbert published his work called “De Magnete”.

According to modern knowledge, the carbon steel which was in use those days is an extremely poor magnet material with a low coersivity H_c less than 4 kA/m and also a low energy product of maximum *BH* which is less than 2 kJ/m^3. Only after 1880 systematic research of alloy properties began.

With addition of such materials as cobalt, tungsten and chromium H_c increased to some level.

In 1917 Japanese scientist Honda achieved the final properties of magnetic steel by making the alloy with 35 per cent of cobalt. The features of this material were: maximum energy product – 8 kJ/m^3, coersivity – 20 kA/m [15, 16]. In 1931 the first hard magnetic alloy which contained iron, nickel and aluminum, was patented by T. Mishima. That moment was the starting point of the development of new magnet family known as AlNiCo. Because of the remarkably improved magnet properties of those magnets are still used for a wide range of electrical applications.

Getting this impact, scientists began to work harder in the field of permanent magnets and soon, in 1950s, another family of permanent magnet – ferrites – was invented. Due to their better properties and lower price the ferrites became very popular in manufacture of DC machines.

Lately, rare earth permanent magnet materials were developing with the Samarium-Cobalt alloys. Properties of $SmCo_5$ and Sm_2Co_{17} make these materials suitable for electric machines, however because of the usage of rare raw materials, they are more expensive. The last significant innovation in permanent magnet materials was made in 1983, when the high quality material Neodymium-Iron-Boron was created. Compared to Sm-Co family, Nd-Fe-B magnets offer similar properties but they are much cheaper.

Nd-Fe-B permanent magnet materials caused a tendency to use magnet machines in large industrial applications.

Since the permanent-magnet machine design is discussed, it is relevant to concern some properties of the magnetic materials. The main features of them are mentioned below. [9]

Soft magnetic materials are commonly used electrical technologies. The main difference between soft and hard magnetic materials is strength of coercive field H_c; in soft magnets it is less than 1 kA/m. Some other features of soft those materials are low shape anisotropy, magnetostriction, mechanical hardness and crystal anisotropy [17].

Soft magnetic materials can be divided into groups:

-Electrical steels

- Non-oriented
- Grain-oriented

-Nickel-Iron alloys

-Soft ferrites

- NiZn
- MnZn

-Amorphous metals

-Soft magnetic composites

-Construction steels

2.2.1 Magnetization and coercivity

Present-day knowledge explains that the origin of magnetism is related to the magnetic dipole moments μ_m of the electrons. Based on the concept of the magnetic dipole moments available in a volume *V*, it is possible to form the sum of all magnetic dipole moments giving a quantity called magnetization *M*, which is defined as [13]

$$M = \lim_{V\to 0} \frac{\sum \mu_\mathrm{m}}{V} = n\mu_\mathrm{m} \qquad (1)$$

In some materials exists the tendency to align the axes of the magnetic dipoles due to their own internal field. This process is called exchange interaction.

Spontaneous magnetization is the phenomenon which describes the existence of the internal field without external field. Spontaneous magnetization alone may be a reason of polarisation *J* inside the material. *J* is equal to the flux density *B* when the external field strength *H* is zero.

$$J = \mu_0 \cdot M = B - \mu_0 \cdot H \qquad (2)$$

Rewriting previous equation, the possible impact of the external field strength H is considered which leads to the equation

$$B = \mu_0 \cdot (M + H) \tag{3}$$

The intrinsic coercivity H_{ci} is the evaluation of magnetism in a material and it is very important feature of the magnetic material. It can be calculated from the equation

$$H_{ci} = \frac{2K}{\mu_m M_{sat}} \text{, where} \tag{4}$$

Usually, information is given in a form of the magnetic flux density B plotted against H. This graph is given below.

When the magnetizing field strength is zero, the value of B is called remanent flux density B_r (equal to polarisation) and it can be calculated from the formula

$$B_r = \mu_0 M_{sat} \tag{5}$$

The value of H, that is needed to decrease the flux density in material into zero, is called coercivity H_c. This means that a weaker magnetizing force is required to remove B than is needed to reduce M to zero in a material. If the coercive force is smaller than the peculiar coercivity H_{ci}, the portion of the B-H loop in the second quadrant is entirely linear since the knee, which occurs at $-H_{ci}$, is moved into the third quadrant.

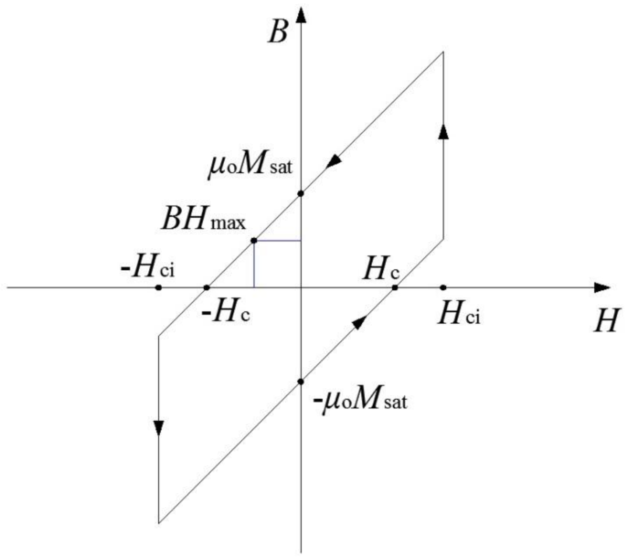

Fig.4. *B*-*H* loop

The above explanation of the permanent magnets behavior is idealized. In reality, there is no sudden reverse in magnetization. Thus, the knee of the *B*-*H* loop is in practice smoother. Moreover, the connection between magnetization and temperature was neglected. [9]

Table 2. Magnetic properties of some materials [10]

Alloy’s name	Maximum energy product (BH_{max})	Residual flux density (B_r)	Coercive force (H_c)	Working temperature, °C
Ceramic 5	3.4	3950	2400	400
Sintered Alnico 5	3.9	10900	620	540
Cast Alnico 8	5.3	8200	1650	540
Samarium Cobalt 20 (1.5)	20	9000	8000	260
Samarium Cobalt 28 (2.17)	28	10500	9500	350
Neodymium N45	45	13500	10800	80
Neodymium 33UH	33	11500	10700	180

2.2.2 Neodymium-iron-boron permanent magnets

Magnetic material Nd-Fe-B became available in the market in the beginning of the 21st century with flux density B_r of 1.52 T and a maximum energy product of 440 kJ/m^3. These values are very high but the magnet has a disadvantage of poor thermal behavior. The highest operating temperature is around 100 °C. Adding dysprosium and cobalt it is possible to improve the temperature behavior however an anti-ferromagnetic coupling appears which means that magnetization and maximum energy product is reduced. The best Nd-Fe-B properties are remanent flux densities is 1.2 T and maximum energy product is 300 kJ/m^3 at temperature of 20 °C with tolerating temperature around 200 °C.

Another disadvantage of those magnets is high sensitivity to corrosion which causes the decreasing of magnetic properties. It can be improved by alloy combinations or shielding with coating. Nd-Fe-B materials have resistivity of 1.5 μΩm at temperature of 20 °C.

2.3 Stator and stator winding

The stator is air-cored and windings are not placed into slots but fixed to the non-magnetic surface. Without stator teeth there is no cogging torque and iron losses are eliminated. In addition, the weight and material cost of the machine become lower.

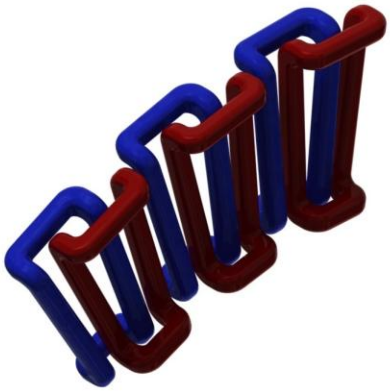

Fig.5. Coil profile [18]

Trapezoidal coil is the most popular coil shape for such machines. This type allows the maximum coil flux linkage. The end-winding length of the coil is comparable to the active length while it is better to possibly reduce the dimensions of ending parts to decrease the resistive losses of the coil.

Overlapping coils are winding components that are specially bent to overlap each other. Non-overlapping coils are used when the winding coils lie in the same plane next to each other.

The winding contains two coil-connected systems that are placed on 90 electrical degrees and belong to different phases.

The speed of rotation is considerably low and that mean that we have to use better insulation to protect the winding because the self-cooling of the generator is not perfect. The volume of air which goes through the rotor and stator is low and the parts of machine become hotter.

That is why it is advised to use the class 180 °C insulation which can protect the winding with a constant operating temperature up to 155 °C.

2.4 Magnets in the rotor

Iron rotors are connected to the shaft. The width of iron plate should be rigid to stand sustainable during rotations and not bend under the weight of magnets.

Low-speed generator requires high pole number and large diameter because a high torque is needed. However, the diameter also has limits and if it is too big it can cause disturbance of the airflow around the hub. Moreover, the bigger the diameter of the machine is, the worse its cooling capabilities will be. Big number of poles may become a reason of excessive leakage flux between neighboring magnets.

Permanent magnets can be mounted on the surface of the rotor or embedded inside the steel. The first way is preferable because it is much easier. Rotor surface mounted magnets act as a fan, additionally cooling the stator.

There are many different types of magnet's shapes that are used but it is possible to define the three most popular:

- Circular
- Rectangular
- Sector-shaped

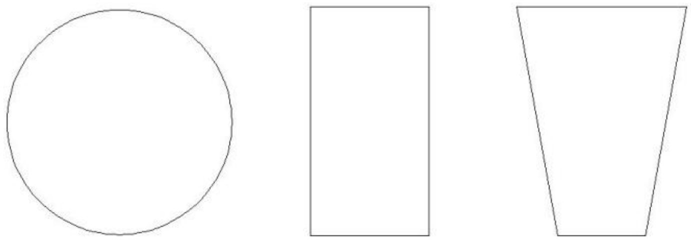

Fig.6. Types of magnet's shape (circular, rectangular and sector-shaped)

The type is the best choice because, even using more material, it produces more useful flux per pole and creates more rectangular flux distribution. [11]

3 Calculations and finite elements analysis

Axial-flux PMSM has quite a straight-forward design and simple structure. The force of wind rotates the shaft and rotor equipped with magnets. The magnetic field of the magnets crosses the winding of the stator and produces EMF which causes a current in the coil if suitable circuit is provided. The main target in the design of such a machine is often to find the minimum amount of magnets and copper that produce the output power desired.

To calculate the machine some initial data is required. Firstly, we should know the output power. In addition, the speed of the machine is required and some other parameters. Knowing the configuration of the machine, we can start selection of the most appropriate dimensions, which can give required output values, proper efficiency and economy of materials and consequently cost.

3.1 Initial values of the generator

Nominal power	$P_n = 1000$ W
Phase RMS voltage	$U_{ph} = 55$ V
Nominal rotational speed	$n = 150$ rpm
Number of phases	$m = 2$
Frequency	$f = 50$ Hz

Flux density in the middle of the air gap is selected as $B_\delta = 0.5 \cdot B_r = 0.5 \cdot 1.2 = 0.6$ T to guarantee the smallest possible usage of permanent-magnet materials.

3.2.1 Geometry of the rotor

Knowing the required frequency and nominal speed of the generator we can find the number of pole pairs p

$$p = 60 \cdot \frac{f}{n} = 20 \qquad (6)$$

The number of poles equals to the number of permanent magnets pieces in this case. In this generator 40 magnets are required.

The determination of the main dimensions starts with choosing the appropriate tangential stress [11]

$\sigma_{\mathrm{Ftan}} = 3350$ Pa

The rotor volume

$$V_{\mathrm{r}} = \frac{T}{2 \cdot \sigma_{\mathrm{Ftan}}} = 0.0095\ \mathrm{m}^3 \qquad (7)$$

The ratio χ of equivalent core length and air-gap diameter [11]

$$\chi = \frac{\pi \cdot \sqrt{p}}{4 \cdot p} = 0.0176 \qquad (8)$$

The rotor diameter D_{r}

$$D_{\mathrm{r}} = \sqrt[3]{\frac{4 \cdot V_{\mathrm{r}}}{\pi \cdot \chi}} = 0.4099\ \mathrm{m} \qquad (9)$$

We select outer radius of the rotor r_{out}

$r_{\mathrm{out}} = 0.21$ m

In this case, equivalent core length l is

$$l = \chi \cdot \mathrm{D_r} = 0.0176 \cdot 0.42 = 0.072\ \mathrm{m} \qquad (10)$$

In some literature [26], the optimal value of coefficient K_{D} is considered $\frac{1}{\sqrt{3}}$

$$K_{\mathrm{D}} = \frac{r_{\mathrm{in}}}{r_{\mathrm{out}}} \qquad (11)$$

Inner radius of the rotor r_{in}

$$r_{\mathrm{in}} = r_{\mathrm{out}} K_{\mathrm{D}} = \frac{0.21}{\sqrt{3}} = 0.12\ \mathrm{m}$$

Average radius of the rotor r_{av}

$$r_{av} = \frac{r_{in}+r_{out}}{2} = 0.165\text{m} \tag{12}$$

Outer perimeter of the rotor Π_{out}

$$\Pi_{out} = 2\pi \cdot r_{out} = 1.3195 \text{ m} \tag{13}$$

Inner perimeter of the rotor Π_{in}

$$\Pi_{in} = 2\pi \cdot r_{in} = 0.754 \text{ m} \tag{14}$$

Average perimeter of the rotor Π_{av}

$$\Pi_{av} = \frac{\Pi_{in}+\Pi_{out}}{2} = 1.037 \text{ m} \tag{15}$$

Pole pitches for different parts of the coil

- outer $\tau_{p,max} = \frac{\Pi_{out}}{2p} = 0.033 \text{ m}$ (16)
- inner $\tau_{p,min} = \frac{\Pi_{in}}{2p} = 0.0189 \text{ m}$ (17)
- average $\tau_{p,av} = \frac{\tau_{p,max}+\tau_{p,min}}{2} = 0.026 \text{ m}$ (18)

Magnet's length l_a is a difference between outer and inner radius of the rotor and it is equal to the active length of the coil, because there is no need to have an active length of the coil longer the magnet's length. This dimension is very important because it influences the price of the generator significantly. In the next iterations it is required to decrease the length of the magnet (active length of the coil)

$$l_a = r_{out} - r_{in} = 0.09 \text{ m} \tag{19}$$

3.2.2 Geometry of one magnet

Distance between magnets is chosen as

$\Delta\tau$ = 0.004 m

Maximum width of the magnet $w_{PM,max}$

$$w_{PM,max} = \tau_{p,max} - \Delta\tau = 0.029 \text{ m} \tag{20}$$

Minimum width of the magnet $w_{PM,min}$

$$w_{PM,min} = \tau_{p,min} - \Delta\tau = 0.015 \text{ m} \tag{21}$$

The average width of the magnet $w_{\mathrm{PM,av}}$

$$w_{\mathrm{PM,av}} = \frac{w_{\mathrm{PM,max}} + w_{\mathrm{PM,min}}}{2} = 0.022\ \mathrm{m} \qquad (22)$$

3.2.3 Geometry of the stator winding

As it was declared above, the machine is slotless. But a number of virtual slots is required for following calculations.

Number of virtual slots Z

$$Z = 2pm = 80 \qquad (23)$$

Number of slots per pole and phase q

$$q = \frac{Z}{2p \cdot m} = 1 \qquad (24)$$

As a result of using $q = 1$ the winding factor of the fundamental is $k_{\mathrm{w}} = 1$.

Average rotor diameter D_{av}

$$D_{\mathrm{av}} = 2 \cdot r_{\mathrm{av}} = 0.33\ \mathrm{m} \qquad (25)$$

Average linear velocity v_{av} for nominal speed

$$v_{\mathrm{av}} = \frac{\pi \cdot D_{\mathrm{av}} \cdot n}{60} = 2.6\ \mathrm{m/s} \qquad (26)$$

Maximum electromotive force (EMF) of a single conductor can be found as product of the flux density in the air gap, active length of the magnet and rotation speed of the magnets (magnetic field)

$$E_{\mathrm{cond,max}} = B_{\delta} \cdot l_{\mathrm{a}} \cdot v_{\mathrm{av}} = 0.14\ \mathrm{V} \qquad (27)$$

Since one coil turn consist of two conductors, maximum EMF of the turn is

$$E_{\mathrm{turn,max}} = 2 \cdot E_{\mathrm{cond,max}} = 0.28\ \mathrm{V} \qquad (28)$$

The maximum value of EMF which is required can be found from the nominal phase voltage

$$E_{\mathrm{ph,max}} = \sqrt{2} \cdot U_{\mathrm{ph}} = 77.8\ \mathrm{V} \qquad (29)$$

Thereby, to reach the nominal voltage, the number of turns in one phase should be N_{ph}

$$N_{\mathrm{ph}} = \frac{E_{\mathrm{ph,max}}}{E_{\mathrm{turn,max}}} = 277.9\ \mathrm{turns} \qquad (30)$$

And in one coil it is required number of turns N in one coil

$$N = \frac{N_{\mathrm{ph}}}{a \cdot p} = \frac{\sqrt{2} \cdot U_{\mathrm{ph}}}{a \cdot p \cdot 2 \cdot B_{\delta} \cdot l_{\mathrm{a}} \cdot \mathrm{v}_{\mathrm{av}}} = 13.9 \text{ turns} \tag{31}$$

Number of parallel branches $a = 1$

Number of turns in one coil is rounded $N = 14$ and the total number of turns in one phase

$$N_{\mathrm{ph}} = a \cdot p \cdot N = 280 \text{ turns} \tag{32}$$

Suppose, that load is purely resistive and power factor $\cos\varphi = 1$

Thereby, the phase current I_{ph} can be found

$$I_{\mathrm{ph}} = \frac{P}{m \cdot U_{\mathrm{ph}} \cdot \cos\varphi} = 9.1 \text{ A} \tag{33}$$

Assume, current density $J_{\mathrm{a}} = 5$ A/mm^2

Now the cross-sectional area of one turn S_{turn} should be

$$S_{\mathrm{turn}} = \frac{I_{\mathrm{ph}}}{J_{\mathrm{a}}} = 1.82 \text{ mm}^2 \tag{34}$$

We can choose the rectangle conductor with cross-section of 1.8 mm2 [19] because it is easier to form a coil with such conductor configuration. Conductor's dimensions 0.9×2 mm×mm.

Form a two-layer coil with 7 turns along the height and have the dimensions of that coil $b_{\mathrm{c}} = 0.004$ m, $h_{\mathrm{c}} = 0.0063$ m

Total cross-sectional area of one coil S_{c}

$$S_{\mathrm{c}} = b_{\mathrm{c}} \cdot h_{\mathrm{c}} = 4 \cdot 6.3 = 25.2 \text{ mm}^2 \tag{35}$$

Average length of one turn in the coil l_{turn}

$$l_{\mathrm{turn}} = 2 \cdot l_{\mathrm{a}} + \tau_{\mathrm{p,max}} + \tau_{\mathrm{p,min}} + 2\pi \cdot b_{\mathrm{c}} = 0.257 \text{ m} \tag{36}$$

Resistance of the winding at 20 °C with 57 MS/m conductivity

$$R_{\mathrm{a,20°C}} = \frac{1}{57} \cdot \frac{l_{\mathrm{turn}}}{S_{\mathrm{turn}}} \cdot N_{\mathrm{ph}} = 0.7 \text{ Ohm} \quad (37)$$

For ambient temperature of 80 °C the resistance of the winding will become

$$R_{\mathrm{a,80°C}} = R_{\mathrm{a,20°C}}\big(1 + \alpha(80 - 20)\big) = 0.87 \text{ Ohm} \quad (38)$$

Temperature coefficient for copper $\alpha = 0.04$

Losses in all phases of the stator winding are defined by resistance of the winding in hot conditions and phase current

$$P_{\mathrm{Cu}} = m \cdot {I_{\mathrm{ph}}}^2 \cdot R_{\mathrm{a,80°C}} = 143.7 \text{ W} \quad (39)$$

Suppose, the mechanical air gap between rotor and stator Δ = 0.001 m

Then, the gap between rotors will be

$$\delta = h_{\mathrm{C}} + 2 \cdot \Delta = 0.0083 \text{ m} \quad (40)$$

Usually, air gap δ means the distance between rotor and stator but in case when stator is ironless and almost the whole space between rotors has permeability of air, it is possible to call this distance the air gap.

Suppose, the air gap δ = 0.009 m

Height of the magnet may be taken as half of the gap between rotors.

$$h_{\mathrm{PM}} = 0.5 \cdot \delta = 0.0045 \text{ m} \quad (41)$$

Rounding this value we are getting $h_{\mathrm{PM}} = 0.005$ m

3.2.4 Mass and cost of permanent magnets

Mass and cost of permanent magnets

The evaluation of the cost-mass features of the generator may help to decide was the iteration successful or not.

Volume of all magnets

$$V_{\mathrm{PM}} = 2 \cdot 2 \cdot p \cdot l_{\mathrm{a}} \cdot \tau_{\mathrm{av}} \cdot h_{\mathrm{PM}} = 9.33 \cdot 10^{-4}\ \mathrm{m}^3 \tag{42}$$

Mass of all magnets

$$m_{\mathrm{PM}} = 7.4 \cdot 10^3 \cdot V_{\mathrm{PM}} = 6.905\ \mathrm{kg} \tag{43}$$

Cost of the magnets

The cost of 1 mm^3 of permanent magnet is around 0.04 ruble [21]

The rate of exchange is approximately 1 euro=50 ruble (by May 2014) [25]

$$C_{\mathrm{PM}} = 0.04 \cdot V_{\mathrm{PM}} \cdot 10^9 = 37320\ \text{rubles} = 746.4\ \text{euro} \tag{44}$$

<u>Mass and cost of copper winding</u>

Mass of copper winding

$$m_{\mathrm{Cu}} = m \cdot \rho_{\mathrm{Cu}} \cdot l_{\mathrm{turn}} \cdot N_{\mathrm{ph}} \cdot S_{\mathrm{turn}} = 2.305\ \mathrm{kg} \tag{45}$$

Density of the copper $\rho_{\mathrm{Cu}} = 8.9 \cdot 10^{-3}\ \mathrm{g/mm}^3$

The cost of copper winding is around 418 rubles (8.36 euro) per 1 kg [19]

The cost of the copper winding of the generator

$$C_{\mathrm{Cu}} = 418 \cdot m_{\mathrm{Cu}} = 963.6\ \text{rubles} = 19.3\ \text{euro} \tag{46}$$

<u>Total mass and cost of the active materials</u>

Total mass of the active materials

$$m_{\Sigma} = m_{\mathrm{PM}} + m_{\mathrm{Cu}} = 9.21\ \mathrm{kg} \tag{47}$$

Total cost of the active materials

$$C_{\Sigma} = C_{\mathrm{PM}} + C_{\mathrm{Cu}} = 765.7\ \text{euro} \tag{48}$$

Knowing the mass and cost of active materials, we can conclude that it is required to decrease active length of the magnets. However, this value is limited because increasing number of turns and its cross-sectional aria, it is also demanded to increase the air gap.

3.3 Finite-Element Analysis

After that, with a help of Finite-Element Analysis, the definition and optimization of the permanent magnets dimensions is possible.

The no-load model was solved in finite-element program which is called “Elcut” [20].

2D magneto-static task was chosen. The outer geometry dimensions were taken from the figure on web-site for 1000 W generator [18]. The width of the machine contains frame, two rotors, stator and four air gaps.

Firstly, the distance between magnets δ and the height of magnets h_{PM} was variable.

<u>Parameters of the magnets</u>

Coercitivity H_c = 900000A/m

Remanent flux density B_r = 1.2 T

Relative magnetic permeability of the magnets μ_r=1.06μ_0

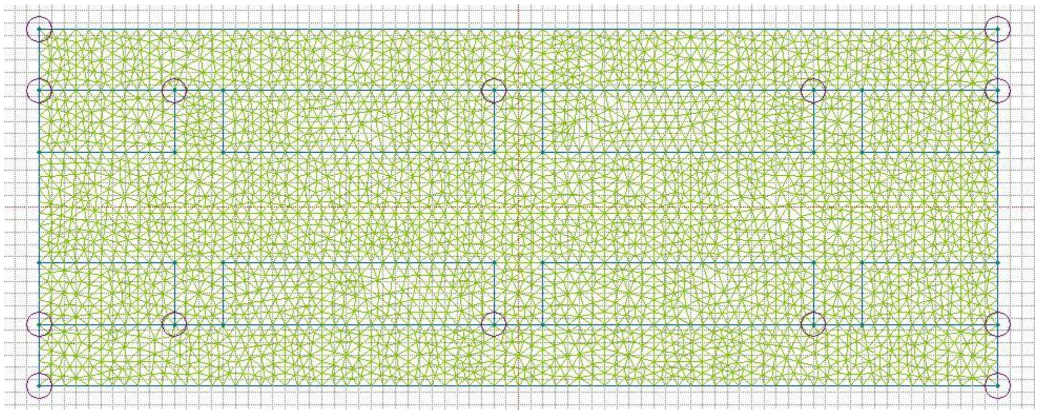

Fig.7. Geometry and mesh ($\delta = 9$ mm, $h_{PM} = 5$ mm)

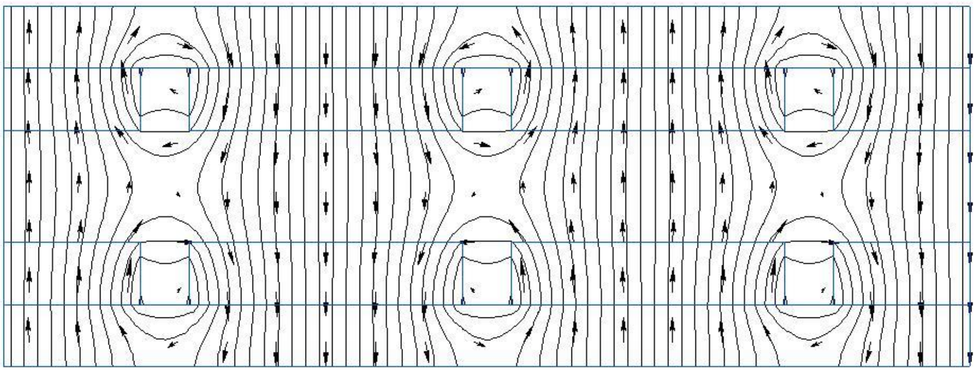

Fig.8. Flux lines ($\delta = 9$ mm, $h_{PM} = 5$ mm)

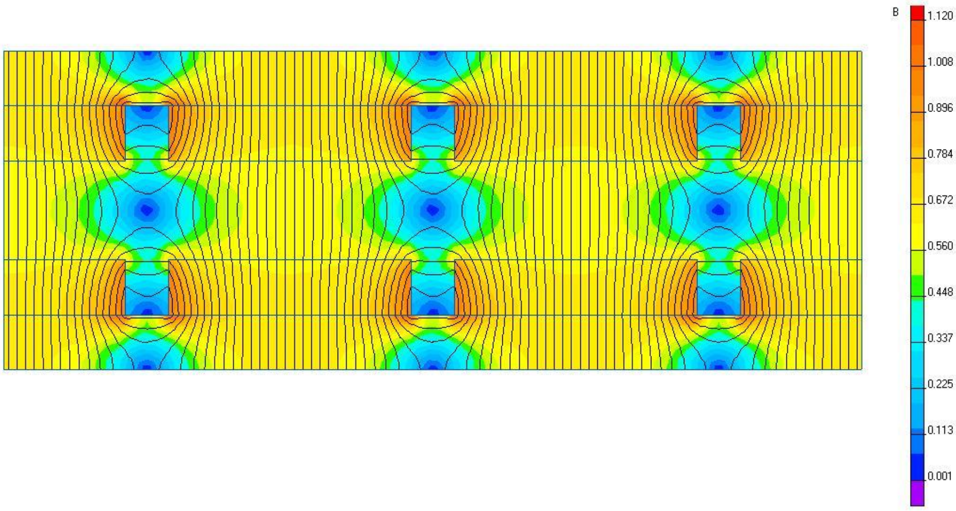

Fig.9. Flux density ($\delta = 9$ mm, $h_{PM} = 5$ mm)

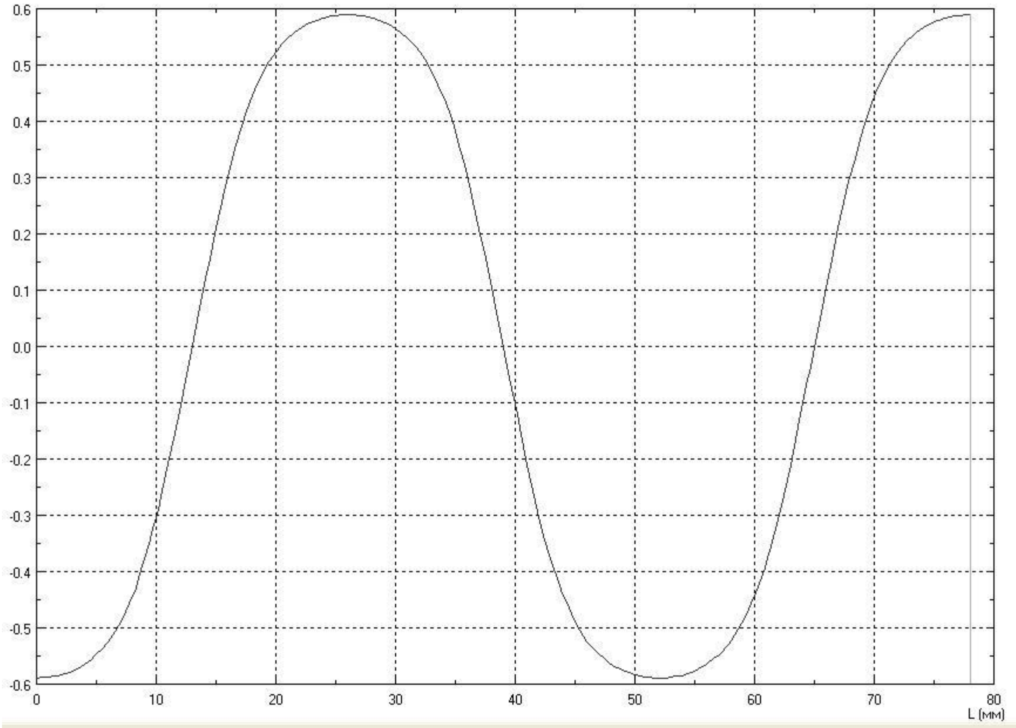

Fig.10. Flux density distribution in the middle of air gap (δ = 9 mm, h_{PM} = 5 mm)

Changing the air gap δ from 7 to 13 mm and height of the magnets h_{PM} from 2 to 12 mm we are getting the following results (Table 3). There is no point to increase these parameters later because of economic reasons.

Table 3. Flux density B depends on height of magnets h_{PM} and air gap length δ

	magnet's height h_{PM}, mm										
air gap δ, mm	2	3	4	5	6	7	8	9	10	11	12
7	0.419	0.532	0.614	0.674	0.718	0.752	0.778	0.798	0.813	0.824	0.833
8	0.382	0.491	**0.57**	0,629	0.674	0.707	0.733	0.753	0.768	0.78	0.789
9	0.351	0.455	0.532	**0.59**	0.633	0.667	0.692	0.712	0.727	0.739	0.748
10	0.324	0.423	0.497	0.553	**0.595**	0.628	0.653	0.672	0.687	0.699	0.708
11		0.394	0.465	0.519	0.56	0.592	0.616	0.635	0.65	0.661	0.67
12			0.436	0.487	0.527	0.557	0.581	0.599	0.614	0.625	0.634
13				0.458	0.497	0.526	0.549	0.567	0.581	0.591	0.6
14					0.467	0.495	0.517	0.534	0.548	0.558	0.566
15						0.467	0.488	0.505	0.518	0.528	0.536

It is easy to see that increasing both dimensions (air gap and magnet's height) we are getting a higher flux density. The remanent flux density B_r is 1.2 T and it is clever to work at the point of maximum energy $(BH)_{max}$ on *B-H* loop (Fig.4). Therefore we should choose the flux density around 0.6 T. Such values are bold in Table 3.

Another condition is the price. It is not necessary to have very high magnet if it is possible to use the same flux density with thinner magnet. Money saving is one of the main principles of optimization. Reducing the price of the machine, we make it competitive in the market.

No-teeth solution of the stator in the machine design can offer some benefits.

"The technology of the magnetic field focusing is intended to increase the generator's efficiency by reducing the parasitic scattering of magnetic fields between adjoining magnets on the rotor disc and therefore allows increasing the magnetic field strength in the running clearance of the generator." [18]

Also, changing steel material of the stator into plastic, we lighten the generator and exclude the losses in the stator core.

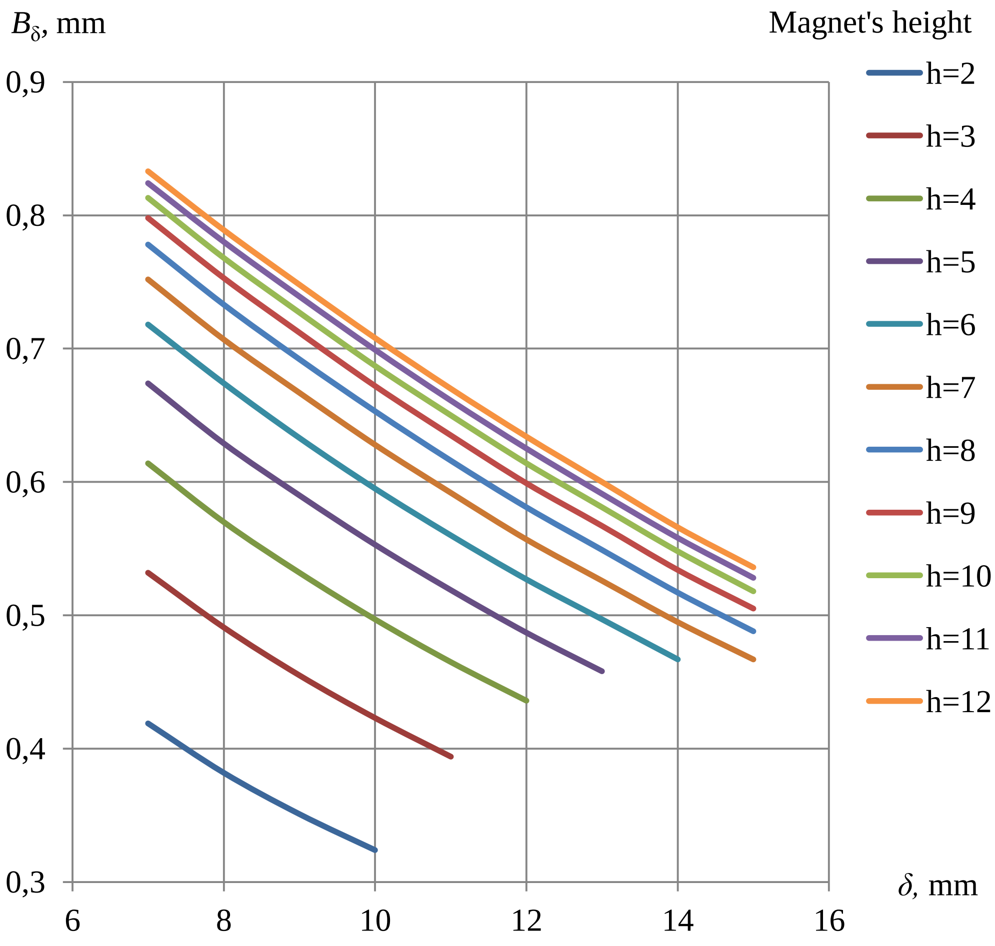

Fig.11. Maximum flux density in the air gap B_{δ} versus air gap δ

The flux density goes higher when the magnets are filling a larger proportion of the total air gap. In the theoretical case where the magnets fill the whole air gap, they operate very close to their remanent flux density. The function is almost linear. Since some value of magnet’s height, the increase in flux density is low.

From the plots above it is obvious that the flux density is bigger when the magnets are higher and the distance between them is lower. However, we may also analyze the energy that is hidden in the air gap.

The relative energy is depending on flux density and coercitivity

$$W' = \frac{B \cdot H}{2} = \frac{B^2}{2 \cdot \mu_0} \tag{49}$$

The energy is a product of relative energy and volume where the energy exists. Then, energy is proportional to the square of flux density and air gap

$$W = W' \cdot V \propto B^2 \cdot \delta \tag{50}$$

Table 4. Product of $B^2\delta$ depends on height of magnets h_{PM} and air gap length δ

	magnet's height h_{PM}, mm										
air gap δ, mm	2	3	4	5	6	7	8	9	10	11	12
7	**1.229**	**1.981**	**2.639**	**3.180**	3.609	3.959	4.237	4.458	4.627	4.753	4.857
8	1.167	1.929	2.599	3.165	**3.634**	3.999	4.298	4.536	4.719	4.867	4.980
9	1.109	1.863	2.547	3.133	3.606	**4.004**	**4.310**	**4.562**	**4.757**	**4.915**	**5.036**
10	1.050	1.789	2.470	3.058	3.540	3.944	4.264	4.516	4.720	4.886	5.013
11		1.708	2.378	2.963	3.450	3.855	4.174	4.435	4.648	4.806	4.938
12			2.281	2.846	3.333	3.723	4.051	4.306	4.524	4.688	4.823
13				2.727	3.211	3.597	3.918	4.179	4.388	4.541	4.680
14					3.053	3.430	3.742	3.992	4.204	4.359	4.485
15						3.271	3.572	3.825	4.025	4.182	4.309

In Table 4 the maximum energy for each magnet’s height is in bold type. It can be seen that the maximum energy is response to the air gap δ of 7-9 mm.

Looking at Table 4 again we may assume that for air gap of 9 mm, it is better to take magnets of 7–12 mm height to get the desired flux density. However, as we are thinking about the price of this machine, we should choose smaller magnets. For magnets with height of 5 mm, it is not a big difference between energy in cases of 7 and 9 mm air gap, and it is possible to use magnets with h_{PM} = 5 mm and air gap δ = 9 mm.

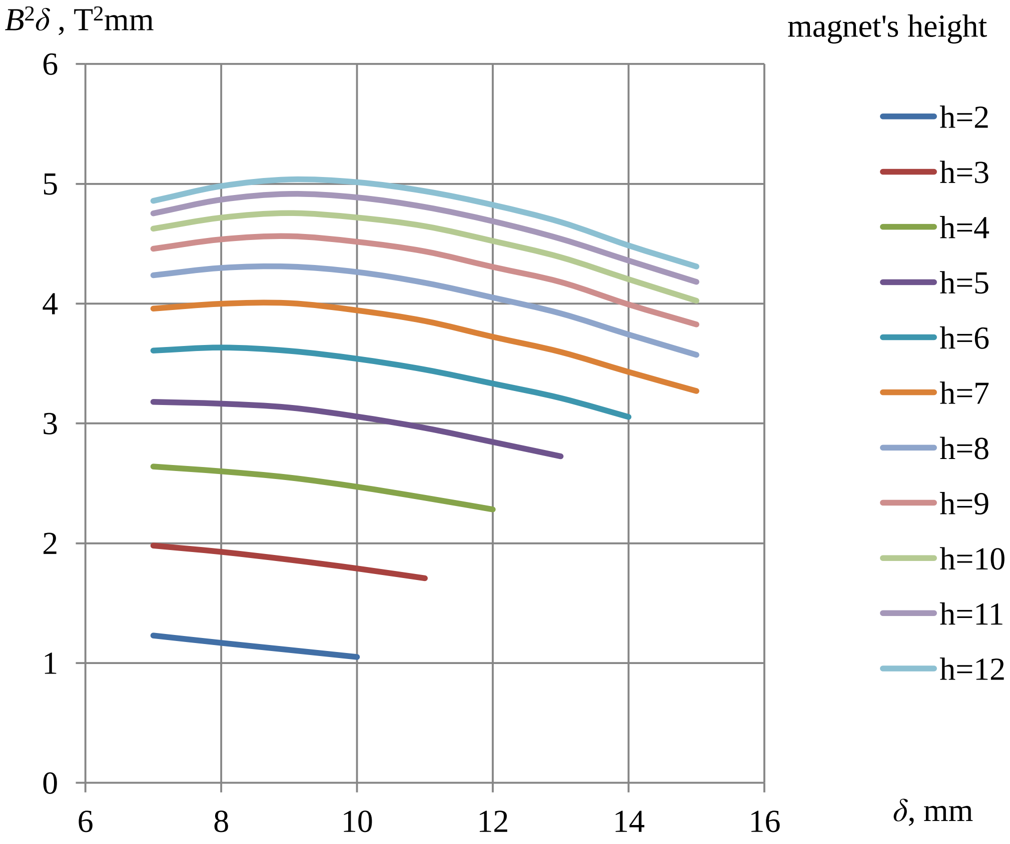

Fig.12. Product of $B^2\delta$ versus air gap δ

In thin magnets the functional dependence is linear but increasing the width we can find the maximum of the function.

At first steps changing the height of magnets we can see the same significant change in the product of $B^2\delta$ (h_{PM} = 2–5), however, since some value of magnet's width (h_{PM} = 10–11) the product of $B^2\delta$ changes slightly.

After “Elcut” modulation we can approve the magnets height h_{PM} = 5 mm and the air gap δ = 9 mm.

3.4.1 Geometry of the rotor

After varying values, some possible solutions were found. Most successful are presented at table 5.

Table 5. Parameters of different machines

Active length l_a, m	Number of turns in one coil N	Coil dimensions ($b_c \times h_c$)	Efficiency, %	Mass of active materials m, kg	Price of active materials C, euro
0.048	28	6.3×8	80.3	7.82	479.5
0.045	32	7.2×8	79.6	8.01	458.3
0.040	35	6.3×10	76.9	8.08	420

The calculations of second machine are presented below because it has average parameters between all of those generators.

It was decided to change the inner rotor radius to

$r_{\text{in}} = 0.165$ m

Outer radius of rotor r_{out} remains

$r_{\text{out}} = 0.21$ m

Average radius of rotor r_{av}

$$r_{\text{av}} = \frac{r_{\text{in}}+r_{\text{out}}}{2} = 0.1875 \text{ m} \tag{45}$$

Outer perimeter of the rotor Π_{out}

$$\Pi_{\text{out}} = 2\pi \cdot r_{\text{out}} = 1.3195 \text{ m} \tag{46}$$

Inner perimeter of the rotor remains Π_{in}=1.037 m

Average perimeter of the rotor Π_{av}

$$\Pi_{\text{av}} = \frac{\Pi_{\text{in}}+\Pi_{\text{out}}}{2} = 1.178 \text{ m} \tag{47}$$

Pole pitches

- outer $\tau_{\mathrm{p,max}} = 0.033$ m
- inner $\tau_{\mathrm{p,min}} = \frac{\Pi_{\mathrm{in}}}{2p} = 0.0259$ m (48)
- average $\tau_{\mathrm{p,av}} = \frac{\tau_{\mathrm{p,max}} + \tau_{\mathrm{p,min}}}{2} = 0.029$ m (49)

Magnet's length and active length of the coil are decided to be decreased significantly

$$l_{\mathrm{a}} = r_{\mathrm{out}} - r_{\mathrm{in}} = 0.045\ \mathrm{m} \tag{50}$$

3.4.2 Geometry of one magnet

Distance between magnets $\Delta\tau$ = 0.004 m

Maximum width of the magnet $w_{\mathrm{PM,max}}$

$$w_{\mathrm{PM,max}} = 0.029\ \mathrm{m}$$

Minimum width of the magnet $w_{\mathrm{PM,min}}$

$$w_{\mathrm{PM,min}} = \tau_{\mathrm{p,min}} - \Delta\tau = 0.022\ \mathrm{m} \tag{51}$$

The average width of the magnet $w_{\mathrm{pm,av}}$

$$w_{\mathrm{PM,av}} = \frac{w_{\mathrm{PM,max}} + w_{\mathrm{PM,min}}}{2} = 0.025\ \mathrm{m} \tag{52}$$

3.4.3 Geometry of the stator winding

Number of virtual slots remains $Z = 80$

Average rotor diameter

$$D_{\mathrm{av}} = 2 \cdot r_{\mathrm{av}} = 0.38\ \mathrm{m} \tag{53}$$

Average linear velocity *v*

$$v_{\mathrm{av}} = \frac{\pi \cdot D_{\mathrm{av}} \cdot n}{60} = 2.98\ \mathrm{m/s} \tag{54}$$

Maximum electromotive force (EMF) of a single conductor

$$E_{\mathrm{cond,max}} = B_{\delta} \cdot l_{\mathrm{a}} \cdot v_{\mathrm{av}} = 0.079\ \mathrm{V} \tag{55}$$

Maximum EMF of the turn is

$$E_{\text{turn,max}} = 2 \cdot E_{\text{cond,max}} = 0.158\ \text{V} \tag{56}$$

The maximum value of EMF is increased because the copper losses are very high and the output voltage of the machine becomes lower than required. To get the nominal output voltage, we should increase the EMF in the winding

$$E_{\text{ph,max}} = 99\ \text{V}$$

To reach the nominal voltage, the number of turns in one phase should be N_{ph}

$$N_{\text{ph}} = \frac{E_{\text{ph,max}}}{E_{\text{turn,max}}} = 625.7\ \text{turns} \tag{57}$$

And in one coil it is required number of turns N in one coil

$$N = \frac{N_{\text{ph}}}{a \cdot p} = \frac{E_{\text{ph,max}}}{a \cdot p \cdot 2 \cdot B_{\delta} \cdot l_{\text{a}} \cdot v_{\text{av}}} = 31.7\ \text{turns} \tag{58}$$

Number of parallel branches $a = 1$

The number of turns in one coil is rounded $N = 28$ and the total number of turns in one phase

$$N_{\text{ph}} = a \cdot p \cdot N = 32\ \text{turns} \tag{59}$$

The phase current remains $I_{\text{ph}} = 9.1$ A and power factor $\cos\varphi = 1$

Current density is $J_{\text{a}} = 5\ \text{A/mm}^2$

And cross-sectional area of one turn S_{turn} should be

$$S_{\text{turn}} = 1.82\ \text{mm}^2$$

The cable with cross-section of 1.8 mm^2 is chosen [19].

Form a four-layer coil with 8 turns along the height $b_{\text{c}} = 0.008$ m, $h_{\text{c}} = 0.0072$ m

Total cross-sectional area of one coil S_{c}

$$S_{\text{c}} = b_{\text{c}} \cdot h_{\text{c}} = 8 \cdot 7.2 = 57.6\ \text{mm}^2 \tag{60}$$

Average length of one turn in the coil

$$l_{\text{turn}} = 2 \cdot l_{\text{a}} + \tau_{\text{p,max}} + \tau_{\text{p,min}} + 2\pi \cdot b_{\text{c}} = 0.199\ \text{m} \tag{61}$$

It should be mentioned that because the end coil is not straight, the length of the coil changes not proportionally and therefore the resistance also is not proportionally changed.

Resistance of the winding at 20 °C with 57 MS/m conductivity

$$R_{\mathrm{a,20°C}} = \frac{1}{57} \cdot \frac{l_{\mathrm{turn}}}{S_{\mathrm{turn}}} \cdot N_{\mathrm{ph}} = 1.242 \text{ Ohm} \quad (62)$$

For ambient temperature of 80 °C the resistance of the winding will become

$$R_{\mathrm{a,80°C}} = R_{\mathrm{a,20°C}}\big(1 + \alpha(80 - 20)\big) = 1.541 \text{ Ohm} \quad (63)$$

Losses in all phases of the stator winding are defined by resistance of the winding in hot conditions and phase current

$$P_{\mathrm{Cu}} = m \cdot {I_{\mathrm{ph}}}^2 \cdot R_{\mathrm{a,80°C}} = 255.1 \text{ W} \quad (64)$$

3.4.4 Mass and cost of the active materials

Mass and cost of permanent magnets

Volume of all magnets

$$V_{\mathrm{PM}} = 2 \cdot 2 \cdot p \cdot l_{\mathrm{a}} \cdot \tau_{\mathrm{av}} \cdot h_{\mathrm{PM}} = 5.3 \cdot 10^{-4} \text{ m}^3 \quad (65)$$

Mass of all magnets

$$m_{\mathrm{PM}} = 7.4 \cdot 10^3 \cdot V_{\mathrm{PM}} = 3.92 \text{ kg} \quad (66)$$

Cost of the magnets

$$C_{\mathrm{PM}} = 0.04 \cdot V_{\mathrm{PM}} \cdot 10^9 = 21210 \text{ rubles} = 424.1 \text{ euro} \quad (67)$$

Mass and cost of copper winding

Mass of copper winding

$$m_{\mathrm{Cu}} = m \cdot \rho_{\mathrm{Cu}} \cdot l_{\mathrm{turn}} \cdot N_{\mathrm{ph}} \cdot S_{\mathrm{turn}} = 4.09 \text{ kg} \quad (68)$$

Cost of copper

$$C_{\mathrm{Cu}} = 418 \cdot m_{\mathrm{Cu}} = 1707 \text{ rubles} = 34.2 \text{ euro} \quad (69)$$

<u>Total mass and cost of the active materials</u>

Total mass of the active materials

$$m_{\Sigma} = m_{\mathrm{PM}} + m_{\mathrm{Cu}} = 8.01 \text{ kg} \tag{70}$$

Total cost of the active materials

$$C_{\Sigma} = C_{\mathrm{PM}} + C_{\mathrm{Cu}} = 458.3 \text{ euro} \tag{71}$$

The mass of the magnet decreased while mass of the winding increased. However, the cost of magnets is higher and density of copper is lower. Therefore, the total price and weight of these components is lower.

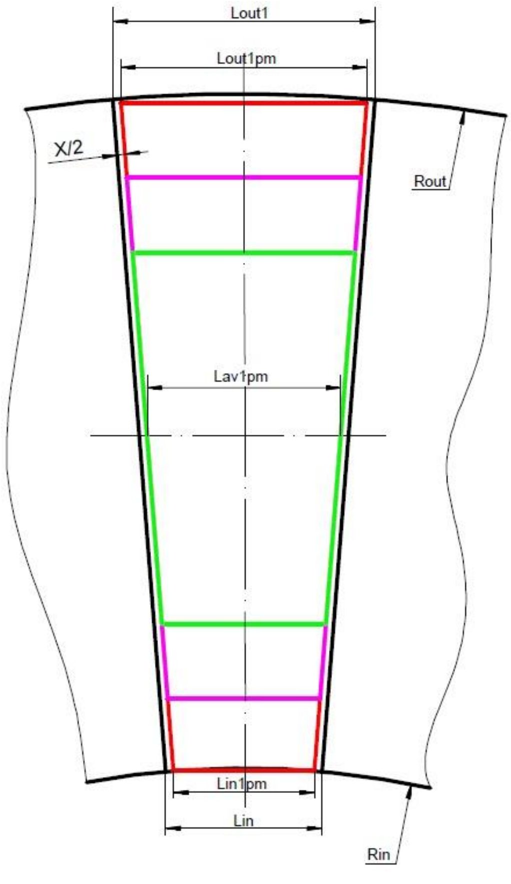

Fig.13. Sector of the rotor with magnet

Different colors at Fig.13 mean different dimensions of magnets.

It is better to have a high flux density to get less turns but it is not demanded to have maximum active length of the coil because the total length of coil remains almost the same with low number of turns with long active cable and vice versa.

For instance, if $B = 0.6$ T, the length of the active winding in one coil is

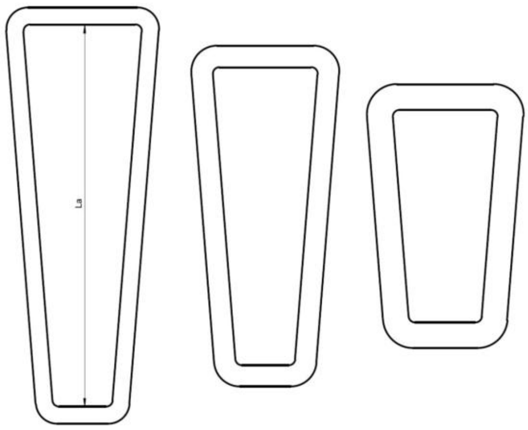

Fig.14. Geometry of coil depends on the geometry of magnet

Decreasing the length of magnets, we should decrease the active length of the coil. However, remaining the same number of turns, it increases in width and needs more space in the air-gap. The air-gap is limited and width of the coil cannot be increased significantly.

3.5 Armature reaction

Put the current source with maximum phase current $I_{\mathrm{ph,max}} = 12.8$ A in one phase of the winding.

Without magnets the winding create quite weak magnetic field.

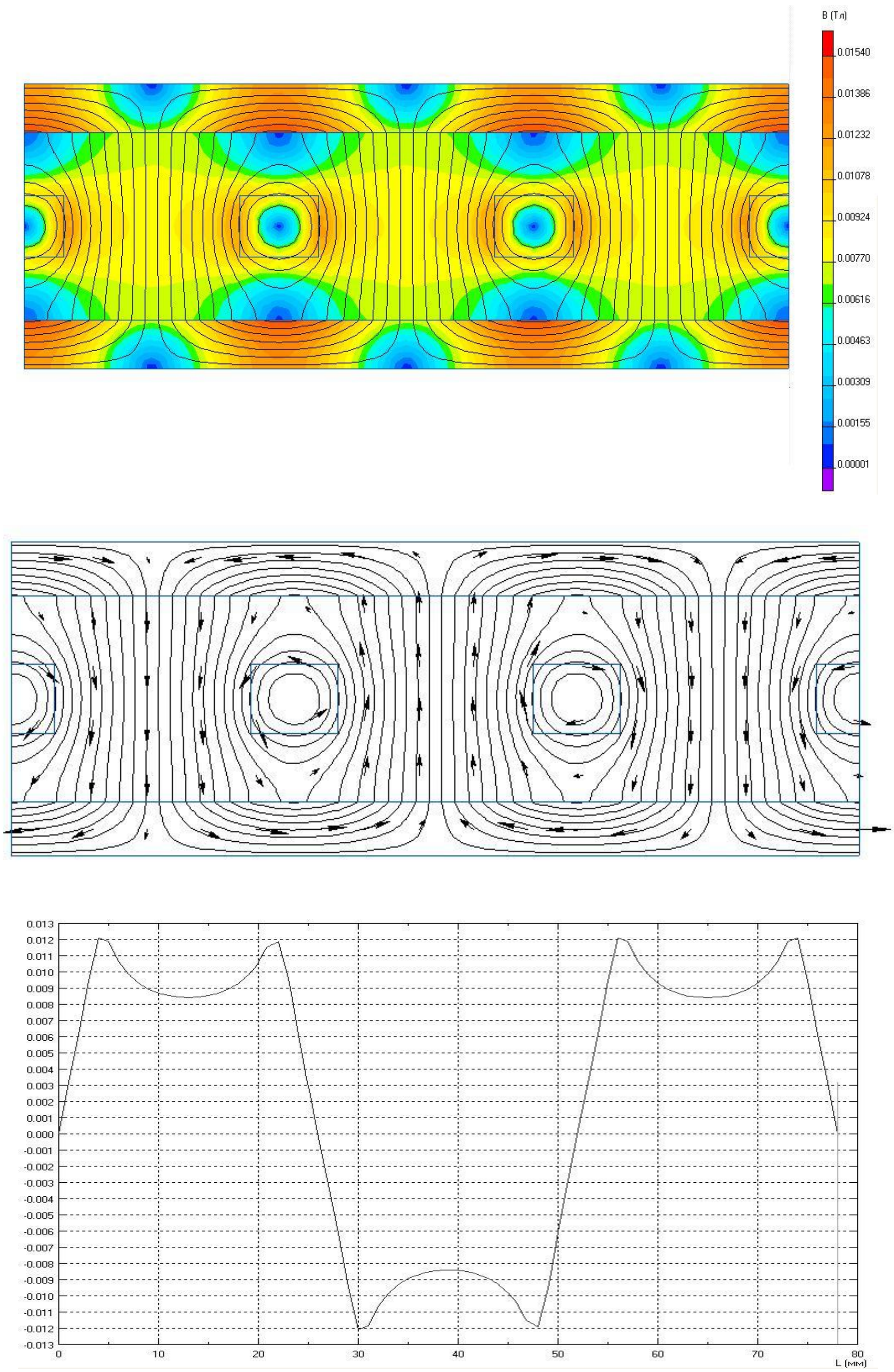

Fig.15. Flux density and flux lines produced by the winding with maximum phase current $I_{\mathrm{ph,max}}$

Knowing the flux linkage ψ (from "Elcut") and current in the winding, we may find the inductance and inductive impedance in the phase.

Flux linkage of the coil $\psi = 8.795 \cdot 10^{-4}$ Vs

Inductance of the coil

$$L_a = \frac{p \cdot \psi}{I_{ph,max}} = \frac{20 \cdot 8.795 \cdot 10^{-4}}{12.8} = 1.37 \cdot 10^{-3} \text{ H} \quad (72)$$

Angular velocity

$$\omega = 2\pi \cdot f = 314.2 \text{ rad/sec} \quad (73)$$

Reactance of the phase

$$x_a = \omega \cdot L_a = 314.2 \cdot 1.37 \cdot 10^{-3} = 0.43 \text{ Ohm} \quad (74)$$

Impedance of the phase in the hot conditions

$$Z_a = \sqrt{R_{a,80°C}^2 + x_a^2} = \sqrt{1.541^2 + 0.43^2} = 1.6 \text{ Ohm} \quad (75)$$

Since the magnetic field strength caused by the winding is very weak, it almost does not cause any changes in the total field and armature reaction is insignificant.

The flux density and flux distribution from magnets and winding are presented below

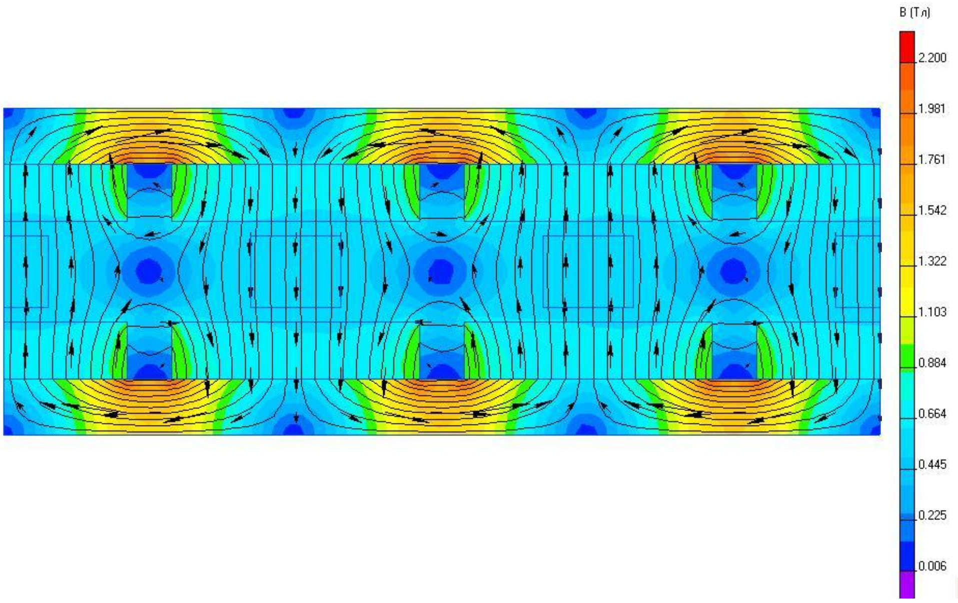

Fig.16. Flux density produced by the winding with maximum phase current $I_{ph,max}$ and magnets

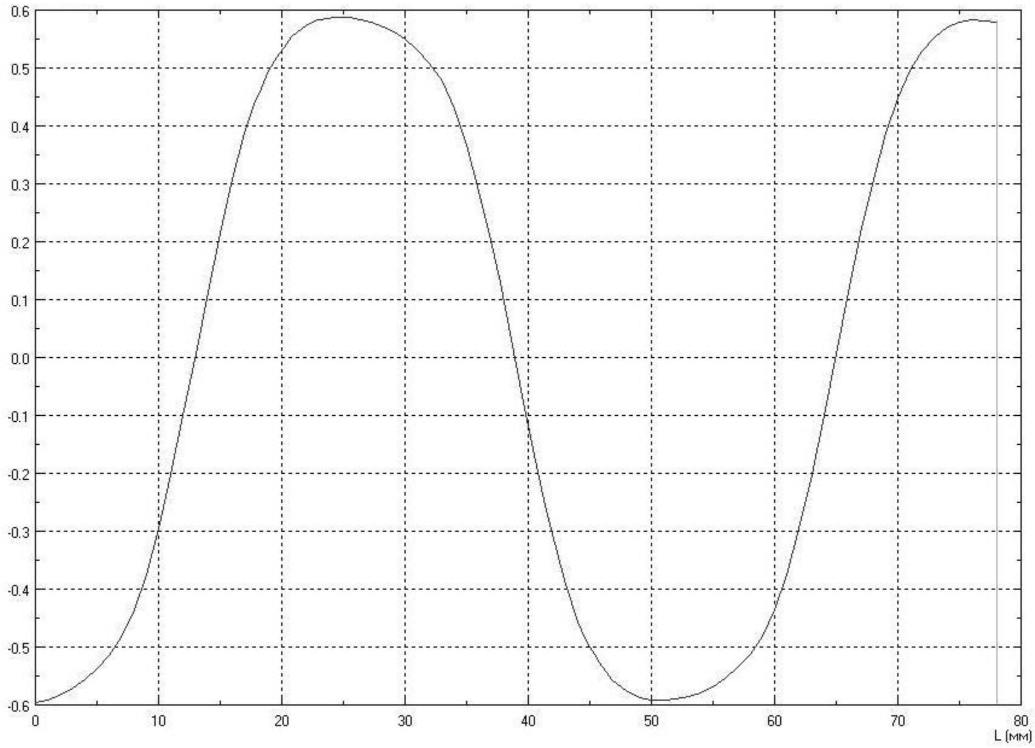

Fig.17. Flux density distribution in the air gap

The maximum flux density of the field with current in the winding is B_{max} = 0.594 T while maximum flux density of the field without current in the winding is B_{max} = 0.589 T.

3.6 Per unit values of the generator equivalent circuit

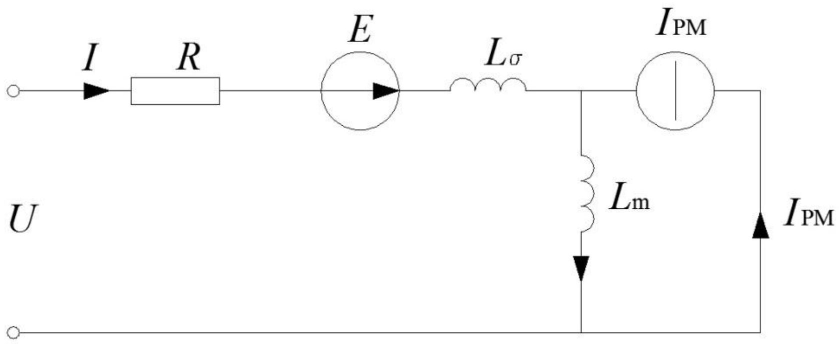

Fig.18. Generator equivalent circuit [28]

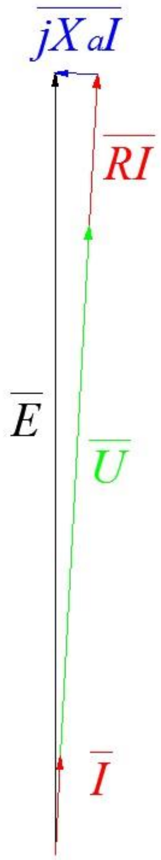

Fig.19. Vector diagram

Knowing EMF (E_{ph} = 72.2 V), current (I_{ph} = 9.1 A), power factor ($\cos\varphi$ = 1), resistance (R_a = 1.541 Ohm) and reactance (x_a = 0.43 Ohm) of the winding, it is possible to find the output voltage.

Since the magnets are on the surface of the machine and the relative magnetic permeability of the magnets is almost equal to the air, the machine has non-silent pole construction. Then, inductances along the d- and q- axis are also equal.

Synchronous reactance of the winding x_a = 0.43 Ohm

Winding inductance L_a = 0.00135 H

Angular frequency $\omega_n = 2\pi \cdot f_n = 314.2$ Hz (76)

The base value for impedance $Z_b = \frac{U_{n,max}}{I_{n,max}} = \frac{\frac{\sqrt{2}\cdot 55}{\sqrt{3}}}{\sqrt{2}\cdot 9.1} = 3.5$ Ohm (77)

The base value for inductance $L_b = \frac{Z_b}{\omega_n} = \frac{3.5}{314.2} = 0.0111$ Ohm (78)

The relative values of inductance is the same as the relative value of reactance

$$L_{a,pu} = x_{a,pu} = \frac{L_a}{L_b} = \frac{0.00135}{0.0111} = 0.012 \text{ p.u.} \quad (79)$$

The relative values of resistance

$$R_{a,pu} = \frac{R_a}{Z_b} = \frac{1.541}{3.5} = 0.44 \text{ p.u.} \quad (80)$$

The active resistance of this generator is much bigger than reactive resistance.

3.7 Velocity characteristic of the loaded machine

Output power

$$P_{\text{out}} = m \cdot U_{\text{ph}} \cdot I_{\text{ph}} \cdot \cos\varphi \tag{81}$$

Generated power

$$P_{\text{in}} = m \cdot U_{\text{ph}} \cdot I_{\text{ph}} \cdot \cos\varphi + P_{\text{Cu}} + P_{\text{mech}} + P_{\text{add}} \tag{82}$$

Copper losses (equation 64)

$$P_{\text{Cu}} = m \cdot {I_{\text{ph}}}^2 \cdot R_{\text{a,80°C}} = 255.1 \text{ W}$$

Mechanical losses

$$P_{\text{mech}} = 0.105 \cdot T \cdot \frac{n}{60} \tag{83}$$

Additional losses

$$P_{\text{add}} = 0.005 \cdot m \cdot U_{\text{ph}} \cdot I_{\text{ph}} \cdot cos\varphi \tag{84}$$

Efficiency

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \cdot 100\% = \frac{m \cdot U_{\text{ph}} \cdot I_{\text{ph}} \cdot \cos\varphi}{m \cdot U_{\text{ph}} \cdot I_{\text{ph}} \cdot \cos\varphi + P_{\text{Cu}} + P_{\text{mech}} + P_{\text{add}}} \cdot 100\% \tag{85}$$

Table 6. Power, losses and efficiency depending on speed *n*

n, rpm	50	100	150	200	250	300
P_{Cu}, W	255.1	255.1	255.1	255.1	255.1	255.1
P_{mech}, W	3.3	6.7	10	13.3	16.7	20
P_{add}, W	0.9	3.1	5.3	7.5	9.7	11.9
P_{out}, W	177.1	618	1057.1	1495.6	1933.9	2372.2
η, %	40.6	70	79.6	84.4	87.3	89.2

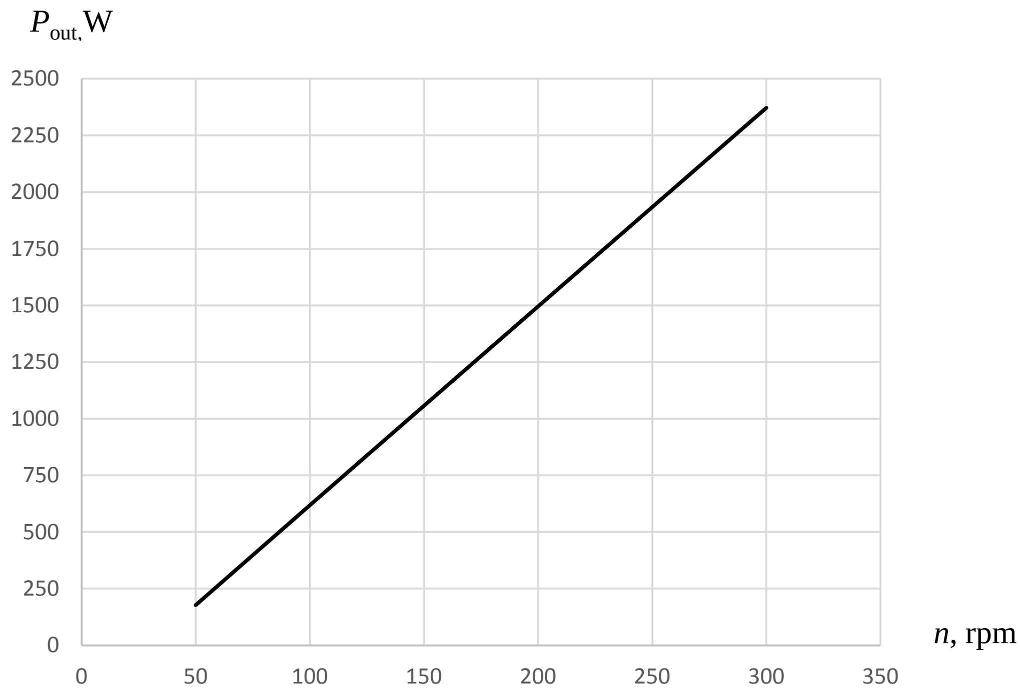

Fig.20. Output power of the generator P depending on the speed n

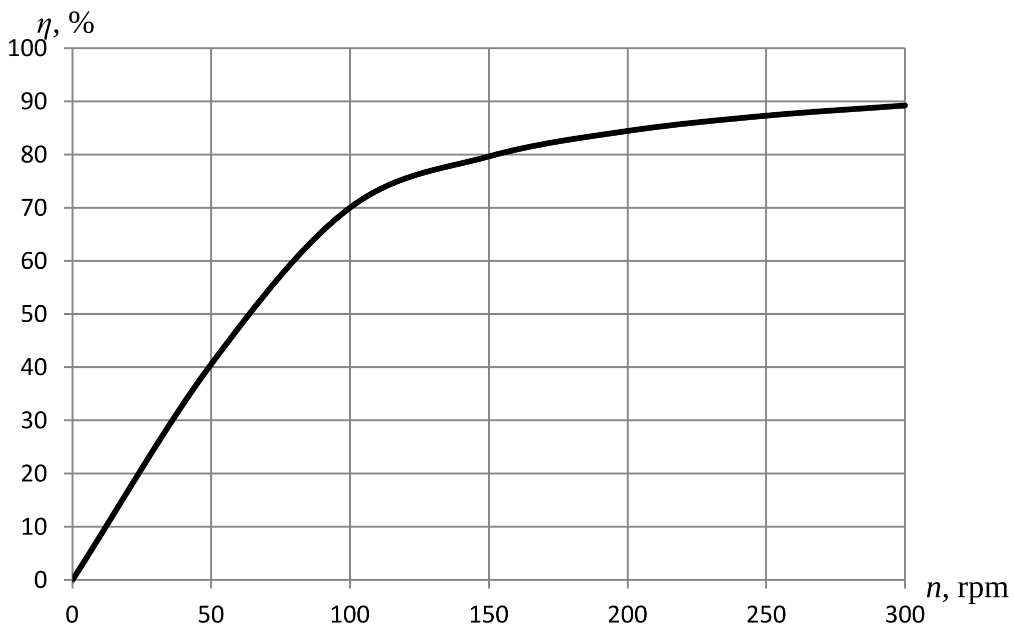

Fig.21. Efficiency η depending on the speed n

3.8 Output characteristic of the loaded generator

If cosφ=1, then from the vector diagram

$$U_{\mathrm{ph}} = \sqrt{{E_{\mathrm{ph}}}^2 - x_{\mathrm{a}} \cdot {I_{\mathrm{ph}}}^2} - R_{\mathrm{a,80°C}} \cdot I_{\mathrm{ph}} \quad (86)$$

Table 7. Phase EMF E_{ph} and voltage U_{ph} depending on the speed *n*

n, rpm	50	100	150	200	250	300
E_{ph}, V	24.1	48.1	72.2	96.3	120.3	144.4
U_{ph}, V	9.7	34	58.1	82.2	106.3	130.3

Table 8. Phase voltage U_{ph} depending on phase current I_{ph} and speed *n*

	I_{ph}, A									
n, rpm	1	2	3	4	5	6	7	8	9	10
50	22.6	21	19.4	17.9	16.3	14.7	13.1	11.5	9.9	8.3
150	70.7	69.1	67.6	66	64.5	62.9	61.4	59.8	58.2	56.7
300	142.9	141.3	139.8	138.2	136.7	135.1	133.6	132	130.5	128.9

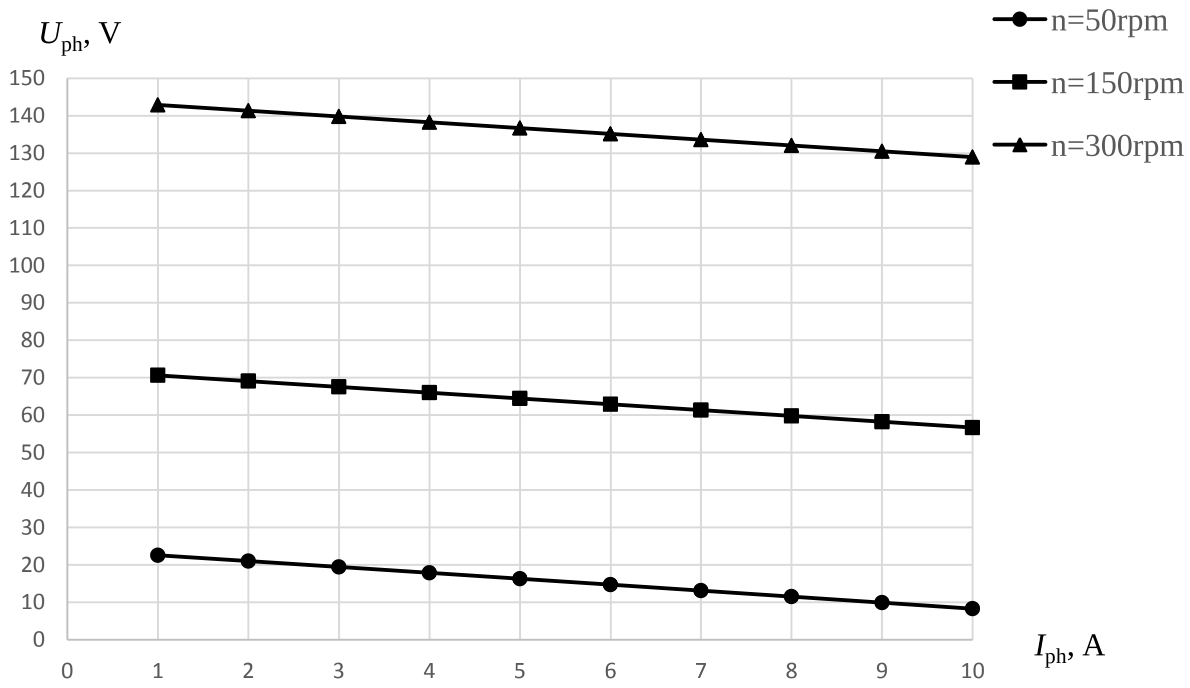

Fig.22. Terminal voltage U_{ph} depending on phase current I_{ph} for different speed *n*

3.9 Power electronics equipment

To utilize the designed generator it is possible to use single-phase diode rectifier bridges to translate AC into DC getting the DC-link. Then we may use converters to get a sine supply to the load or connect an accumulator for electricity storage.

As we have the system with two phases, it is required to use separate rectifiers for each phase consistently connected to the customer's equipment.

Since two winding of the generator are shifted on 90 electrical degrees, they are not connected inductively and it is possible to use these output wires as two separate power supply for different needs.

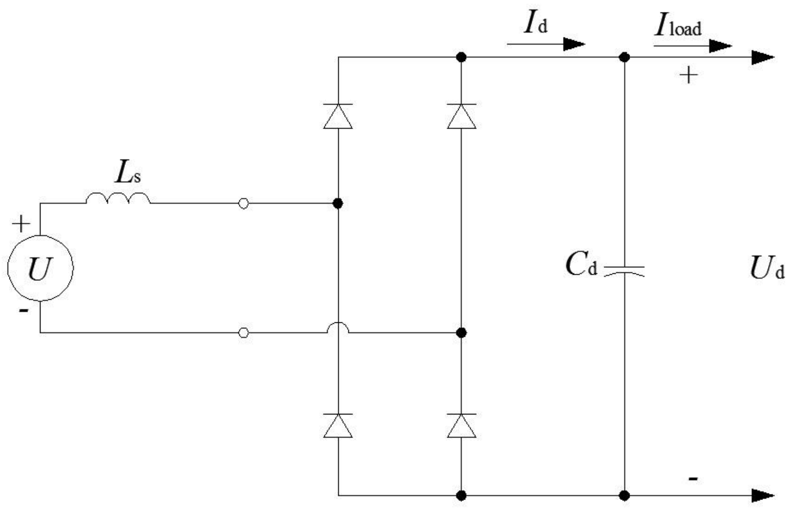

Fig.23. Single-phase diode rectifier bridge [27]

4 Conclusion

An attempt of designing an efficient low-power low-speed generator for wind power application was made. The parameters of the designed generator are presented at table 9

Table 9. Parameters of designed generator

Name	Variable	Value	Dimension
Power	P_{n}	1057.1	W
Nominal phase voltage	U_{ph}	58.1	V
Frequency	f	50	Hz
Number of phases	m	2	
Number of parallel branches	a	1	
Number of slots per pole and phase	q	1	
Number of pole pairs	p	20	
Nominal speed	n	150	rpm
Rotor outer diameter	D_{out}	0.42	m
Rotor inner diameter	D_{in}	0.33	m
Inner width of one magnet	$w_{\mathrm{PM,min}}$	0.022	m
Outer width of one magnet	$w_{\mathrm{PM,max}}$	0.029	m
Height of the magnet	h_{PM}	0.005	m

(Continued)

Table 9 (Continued)

Air gap between magnets (without rotor)	δ	0.009	m
Number of turns in coil	N	32	turns
Active length of the coil, magnets length	l_a	0.045	m
Coersivity of the magnets	H_c	900000	A/m
Remanent flux density of the magnets	B_r	1.2	T
Relative magnetic permeability of the magnets	μ_r	1.06	
Stator phase resistance at 20 °C	$R_{a,20°C}$	1.242	Ohm
Stator phase resistance at 80 °C	$R_{a,80°C}$	1.541	Ohm
Reactance of the phase	x_a	0.43	Ohm
Impedance	Z_a	1.6	Ohm
Stator phase resistance	$\underline{R_a}$	0.44	
Reactance of the phase	$\underline{x_a}$	0.012	
Copper losses	P_{Cu}	255.1	W
Mechanical losses	P_{mech}	10	W
Additional losses	P_{add}	5.3	W
Stator current density	J	5	A/mm2
Efficiency	η	79.6	%

Looking at characteristics above, we can see that the generator shows quite good output values. Efficiency is typically not high for such little machines. One of the advantages of this generator is the ability to work reliably with different types of loads and overload limit is high because the reactance of the winding is small. On the other hand, too big active resistance causes very high losses in the winding and heat the winding.

Of course, this generator can be improved. Efficiency is one of the most desirable value and the main goal is to make it higher. Some possible improvements are listed below:

- Decrease the rotor current will cause a significant decrease in copper losses. However, if the length of the magnets will be the same, it is required to increase the cross-section area of the coil. But the air gap is limited and it might be needed to increase the length of the coil and magnets also. Finally, the price of the generator will become higher but the efficiency will be also increased. In addition, cooling of the machine will be better.

- On every stage of design process use FEM programs.

- Use better electromagnetic steel for rotor core

- Decrease the mechanical losses by using better bearings with less friction

Although the created analytical program may be used for quick approximate design of the generator, deeper calculations are required. Different initial values of geometry should be checked. FEM programs must be used at every step of design.

5 Summary

Nowadays, a tendency of the renewable energy sources usage is becoming wildly spread around the world. Wind turbine is one of the possibilities to cover the electricity needs for the stand-alone applications.

A program of calculating a low-power low-speed axial-flux permanent-magnet generator for wind power application was made. The idea of two-rotor one-stator structure is used. The unusual feature of the generator is the ironless core of the stator which is supposed to decrease the mass of the machine and exclude iron losses.

Using previous researches and knowledge, the calculation and optimization methods of such machines was presented. The calculations were supported with Finite-Element Analysis. With a help of FEM program, optimization of magnet's dimensions and air gap was made and good geometry of the machine was found. The increasing of copper winding amount in the stator allowed to decrease the mass of magnets and, consequently, to decrease the total cost of the active materials.

The characteristics of the generator were calculated and they show the good features, as it was desired. The parameters and per unit values of the machine were found.

This Thesis is an attempt of finding appropriate dimensions and characteristics of a generator with a goal of getting a high efficiency, high simplicity and low cost. Of course, future development and improvement of this method and correction of the technology and materials may lead to the increase in efficiency while the project may become more expensive.

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