Permanent Magnet Axial Length Optimization for Transverse Magnetic Flux Generator with Disk Rotor

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Abstract. Based on the analysis of the transverse flux machine designs, they were found to have a relative design simplicity and a high-power density. The purpose of this work is to determine the optimal height of a permanent magnet and to define its effect on the induced EMF value in the stator coils and the cogging torque, as well as to define the picture of the magnetic flux leakage between the stator poles. To achieve these goals, the 3D model of a low speed generator was studied. The electromagnetic analysis was carried out using a modern software, which allows us to determine the magnetic field distribution in the 3D, as well as the induced EMF value and the rotor cogging torque. The criterion for the optimal calculation is the highest EMF value at the minimum value of the rotor cogging torque. The parameters of the permanent magnets, such as the width and length, remained unchanged, whereas, the height varied from 1 to 8 mm at a 1-mm step. The corresponding dependencies are obtained for each height. The most significant result of the work is the conclusion that the height of the permanent magnet should not exceed the 3-mm value. The significance of the obtained results is that the used methodology allowed finding the optimal height of the permanent magnet, since a further increase in its height leads to no growth in the EMF value, but rather significantly enhances the negative effect from the rotor cogging torque. In addition, the simulation results were supported experimentally.
Keywords**:** transverse flux machine, permanent magnet, electromotive force, torque, electromagnetic analysis, magnetic flux density.
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Determinarea dimensiunii optime a magneților permanenți pentru generatorul de câmp magnetic transversal cu rotor de disc

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Rezumat. În baza analizei proiectelor de mașini cu câmp magnetic transversal, s-a constatat că acestea au o simplitate relativă de proiectare și o densitate mare de putere. Scopul acestei lucrări este de a determina înălțimea optimă a unui magnet permanent și de a determina efectul acestuia asupra magnitudinii tensiunei electromotoare (EMF) induse în bobinele statorului și a cuplu cogging, precum și de a determina modelul de dispersie a câmpului magnetic între stâlpi de stator. Pentru a atinge acest obiectiv, s-au efectuat studii pe un model tridimensional al unui generator cu viteză redusă cu câmp magnetic transversal. Analiza electromagnetică a fost efectuată folosind un soft modern care permite determinarea distribuției câmpului magnetic în 3D în nuclee și în spațiul de aer al mașinii, precum și magnitudinea EMF indusă și a cuplurilor de frânare. Criteriul pentru calculul optim este cea mai mare valoare a EMF la valoarea minimă a momentului dinților rotorului. Rezultatul cel mai semnificativ al lucrării este stabilirea faptului că înălțimea magnetului permanent nu trebuie să depășească 3 mm, la care inducția magnetică în golul de aer corespunde cu 0,75 T. Semnificația rezultatelor obținute constă în faptul că tehnica utilizată a făcut posibilă determinarea înălțimii optime a magnetului permanent, deoarece o creștere suplimentară a înălțimii sale nu duce la o creștere semnificativă a valorii EMF în bobină, iar crește

semnificativ momentul dinților rotorului, care afectează negativ mecanismul de acționare. Rezultatele simulării sunt confirmate experimental pe un prototip de lucru al unui generator cu câmp magnetic transversal.
Cuvinte-cheie: mașină cu flux magnetic transversal, magnet permanent, cuplu, analiză electromagnetică, tensiune electromotoare.

Оптимизация аксиальной длины постоянных магнитов для генератора поперечного магнитного поля с дисковым ротором

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Аннотация. На основании анализа конструкций машин с поперечным магнитным полем установлено, что они обладают относительной простотой конструкции и высокими показателями удельной мощности. Целью данной работы является определение оптимальной высоты постоянного магнита и определение ее влияния на величины наводимых ЭДС в катушках статора и зубцового момента, а также определение картины рассеяния магнитного поля между полюсами статора. Для достижения поставленной цели проведены исследования на трехмерной модели низкооборотного генератора с поперечным магнитным полем. Электромагнитный анализ проведен с помощью современного программного обеспечения, позволяющего определить распределение магнитного поля в 3D в сердечниках и в воздушном зазоре машины, а также величины наводимых ЭДС и тормозных моментов. Критерием оптимальности расчета служит наибольшее значение ЭДС при минимальном значении зубцового момента ротора. При моделировании использовались параметры постоянного магнита марки Nd-Fe-B-35, его ширина и длина оставались неизменными, а высота варьировалась от 1 до 8 мм с шагом 1 мм. Для каждого значения получены соответствующие графики и зависимости. Среднее значение магнитной индукции в воздушном зазоре составило 0,43 Тл для высоты постоянного магнита 1 мм и 0,821 Тл – для высоты 8 мм. Наиболее существенным результатом работы является установление того, что высота постоянного магнита не должна превышать 3 мм, при которой магнитная индукция в воздушном зазоре соответствует 0,75 Тл. Значимость полученных результатов состоит в том, что использованная методика позволила определить оптимальную высоту постоянного магнита, поскольку дальнейшее увеличение его высоты не приводит к значительному увеличению величины ЭДС в катушке, но значительно усиливает зубцовый момент ротора, что отрицательно сказывается на приводном механизме. Результаты моделирования подтверждены экспериментально на рабочем прототипе генератора с поперечным магнитным полем.
***Ключевые слова*:** машина с поперечным магнитным потоком, постоянный магнит, электродвижущая сила, момент, электромагнитный анализ, магнитная индукция.

INTRODUCTION

It is commonly known that the electrical machines with permanent magnets (PMs) demonstrate higher efficiency, greater reliability than machines with electromagnetic excitation. Among the electric machines with the PMs, there is a separate class of transverse magnetic flux machines (TFM). Due to the design features of this TFM magnetic system, the relatively simple design and creation of the best indicators of the specific power TFM find wide interest in the scientific community.

For the first time the TFM was proposed by V. M. Mordy in 1895 [1].

However, unfortunately, at that time there were no possibilities for the computer-aided design systems and production. In recent decades in connection with the development of the CAD simulations based on numerical methods, as well as modern technologies in production, the TFM becomes increasingly important [2–5]. Over the past 50 years a large number of designs and modifications have been presented in this class of the electrical machines. The main designs of the TFM are the external, internal or disk modification of the rotor, and the stator winding is mainly manufactured in one-, two- and three-phase [6–17].

Recently, there has been a tendency to reduce the size of the electrical machines and increase their specific power. Also, with the development of robotics, private vehicles and private low-speed river and wind generators, the design and the right choice of the PMs size is very important for maximum efficiency and successful use of the electrical machines with the PMs [18, 19].

It is a well-known fact, that China is a monopolist in the market of rare-earth permanent magnets, such as Nd-Fe-B, so the task to find their optimal size is very important and is closely related to the price of the electrical machine in general. Since the TFM has a very large number of the PMs on the rotor, each additional millimeter of their size will necessarily lead to an increase in the total price of the whole electrical machine. Therefore, finding the optimal size of the PMs without unnecessary overpayments is an important task [20, 21].

Today several research groups are actively involved in the design and production of these machines. These works showed a high potential of TFM in terms of energy efficiency with high specific torque and good weight-to-size dimensions. In addition, the TFM allows to implement a multi-pole design (20–60 U-cores and more), which opens the way to design a low-speed and high-torque gearless electrical machines. This type of machines allows us to use stator windings that are simple, economical and reliable today [22, 23].

During the design of different TFM constructions it becomes a matter of getting the maximum power of the same machine size. The number of pole pairs is easy to modify in the TFM, which is a feature for such machines. However, an increasing number of U-cores in the stator with a constant diameter leads to a proportional reduction of the pole width and therefore to an increase in the magnetic flux leakage [24].

A study of the TFM in the generator mode was carried out, and it was determined that the number of U-cores from 32 to 38 is the best result for the maximum value of electromotive force (EMF) in the stator coils. For the motor mode the number of U-cores must be in the range from 28 to 34 for the most efficient energy conversion process. Thus, the TFM design with 32 stator U-cores for one phase is the most optimal design from the technological and energy points of view for both generator and motor modes [25].

An important criterion for selecting the type of the TFM design for the research is, first of all, the efficiency and manufacturability of the design. Therefore, this work will pay attention to the design with a disk rotor and the PMs based on Nd-Fe-B type.

However, it is necessary to take into account the fact that the disk rotor with the shaft must be rigidly fixed in the bearings. It is important to avoid skewing and air-gap irregularity caused by the attraction forces of the PMs on the disk rotor. This issue is poorly considered in the works described above, therefore it is relevant, since it will reduce the effect of the cogging torque caused by these forces.

However, despite the successful experience in the simulation and implementation of such generators in real designs, there are a number of issues related to the correct choice of the type and size of permanent magnets, as well as the scientific substantiation of their application possibility. These problems have not been previously considered in the literature and they are the subject of study in this article.

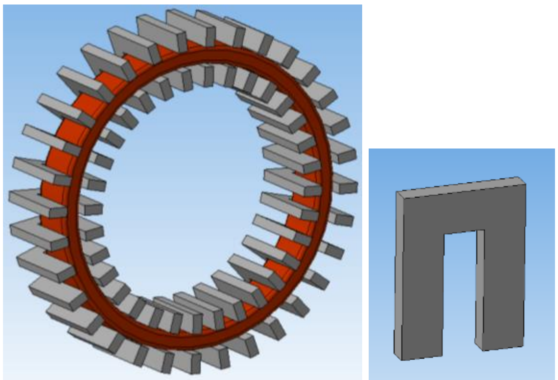
The purpose of this work was to investigate the tendency of the influence of the permanent magnet thickness on the induced EMF value in the stator coils and the cogging torque value, as well as to determine the picture of the magnetic flux leakage between the stator poles.

I. OBJECT, SUBJECT, AND METHODS FOR RESEARCH

As an object for the research to find the optimal size of the PMs, the TFM with an internal disk rotor was chosen. This design has an aluminum housing, inside which the two stator phases were located. Each phase consists of 32 poles, which ensures a rotor speed at 60 rpm. The stator phase magnetic system is made of M350 electrical laminated steel, its external diameter is 360 mm, and its axial length is 180 mm. The stator phase winding is a multi-turn coil made of insulated copper wire with 207 turns. The disk rotor is located in the middle of the machine between the stator phases. The air gap between the stator poles and the PMs of the rotor is 1.5 mm. The rotor disk is made of St3 type solid steel; 128 permanent magnets are located on the disk rotor surface and have the Nd-Fe-B-35 type.

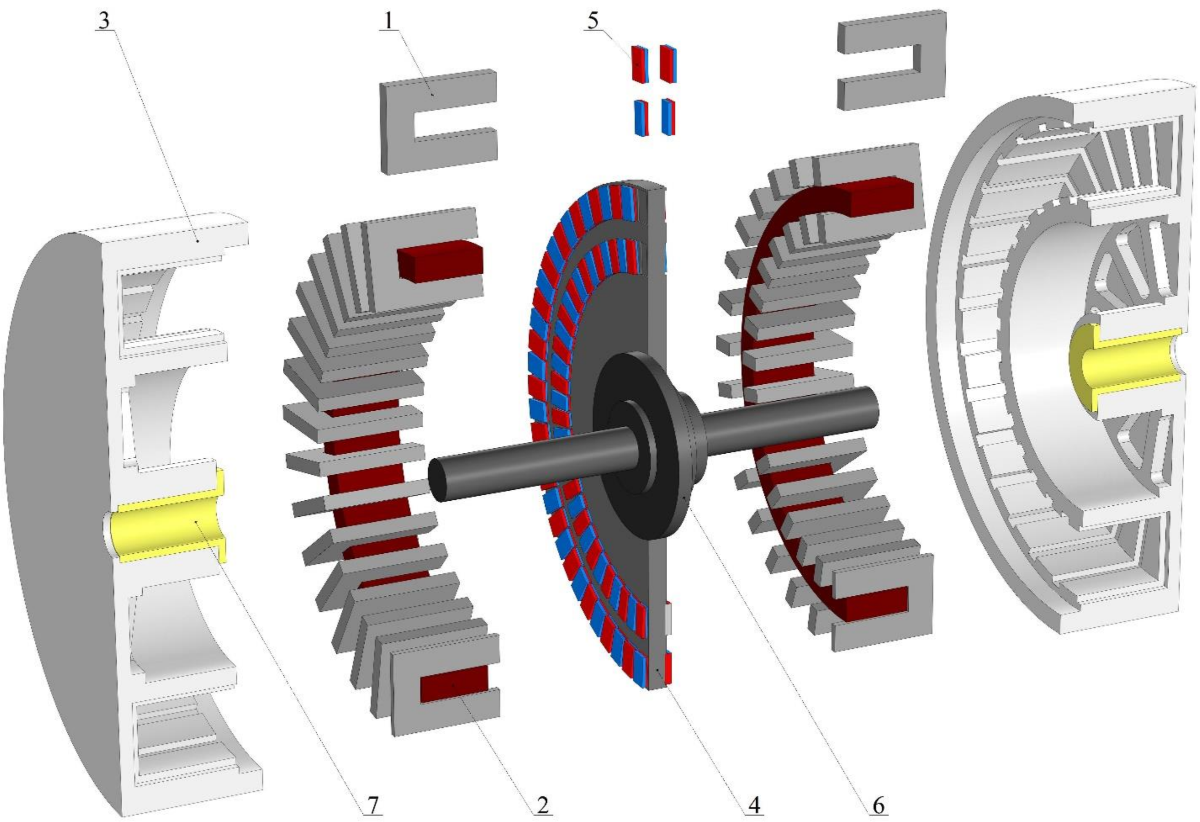
The stator of the machine consists of two pieces (phases), each phase consists of U-shaped cores that are evenly located around the stator and act as magnetic cores (Fig. 1, a). Each magnetic core consists of two teeth, which are connected by a yoke (Fig. 1, b). The PMs number, which are located on the surface of the rotor, is twice as many as the number of U-shaped magnetic cores. Their direction of magnetization is interchanged in a chess order, perpendicular to the surface of the rotor (Fig. 2). This is due to the necessity of a change in the magnetic field in order to satisfy the electromagnetic induction law in the generator mode for the TFM. Figure 2 shows the assembled design of the TFM with a disk rotor and its housing.

The working principle of this electrical machine is similar to a permanent magnet synchronous machine. By connecting the TFM to the alternative current in the motor mode, will make a current flow in the stator winding and a stator magnetic field will be created. The created magnetic field of the stator will begin to interact with the magnetic field of the PMs of the rotor and move them to a position with a minimum magnetic resistance. Thus, the PMs of the rotor will be located opposite the teeth of the stator cores. This process will lead to a torque creating and to the rotor rotation.



a b

a – *one phase of the stator*; b – *stator pole*.
Fig. 1. Design of one phase of the TFM stator.



1 – *stator pole*; 2 – *stator coil*; 3 – *aluminum stator body*; 4 – *rotor disk made of solid steel*; 5 – *permanent magnets with the chess order magnetization*; 6 – *machine shaft*; 7 – *friction type bearings.*
Fig. 2. Design of 32-cores TFM with a disk rotor, its housing and the shaft.

Regarding the working principle of this machine in a generator mode: the magnets on the disk rotor move at a certain speed relative to the stator poles, and magnetizing them with a magnetic flux of alternating polarity. Since the magnets are located in a chess order polarity on the rotor, the alternating magnetic flux, according to Faraday's law of electromagnetic induction, induces the EMF in the stator coil. It is directly proportional to the number of turns of the coil and to the frequency of the magnetic field changing, namely, to the speed of the rotor.

II. Analysis of the TFM Model and the Methodology of its Research

Obviously, for maximum TFM efficiency it is very important to have optimal pole sizes, their number, and the size of the PMs in order to use all the resources of the machine rationally. The size and number of poles are closely related to each other in the same size of the machine, but the optimal PMs size was not considered.

As for the width and length of the PMs – these are dependent parameters and they are associated with the number of stator poles and their size. However, the height of the PMs can be changed, which will affect the residual flux density of the magnetic field on the surface of the magnet.

During the research, the width and length of the magnet remained unchanged, as the main dimensions of the poles and the diameter of the magnetic system. However, the height of the PMs – varied from 1 to 8 mm (Fig. 3) with the preservation of the air gap value between the PMs and the stator poles – 1.5 mm.

To carry out this research it was necessary to analyze the magnetic system of the machine with variable parameters of the PM height.

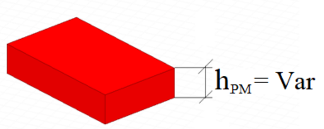


Fig. 3. The height of the permanent magnet, which was varied during the research.

As we know, each serially produced electrical machine has its own methods for calculation its characteristics and geometric dimensions, based on a large number of experimental studies, empirical coefficients and simplifications. TFM calculations use existing methods for the analysis of the magnetic field: numerical-field, total current law, equivalent circuits. The last two methods have several simplifications in the distribution of the magnetic field and saturation of the magnetic system, but they give a picture of the overall dimensions of the TFM, which are refined using the numerical-field methods. This method for calculation the magnetic circuit is implemented in such programs as the FEMM, ANSYS Maxwell, COMSOL and others.

These programs allow us in a short period of time to determine the optimal magnetomotive force (MMF), to analyze the saturation of the magnetic system of the stator and rotor cores, and to make parameterization and optimization of permanent magnets with a preset criterion. This vastly simplifies the design process for any electrical machines.

Firstly, in our research a three-dimensional model of the TFM magnetic system with the appropriate dimensions was created by using the KOMPAS-3D software [26]. Further, this model had to be transferred for the numerical-field analysis. For this purpose, ANSYS Maxwell software was chosen. And an electromagnetic analysis of the TFM was carried out there [27].

In this software, the main properties of magnetic conductive materials were set, namely: the magnetization B(H) curve of the materials of the stator and rotor cores, the direction of the stator poles stacking factor, winding data, the direction of the PMs magnetization, their type and magnetic properties, and other features of the model.

It should be noted that a very large part of the time and computer resources is spent for creation and calculation a model in 3D to find the optimal PMs value. Therefore, in order to optimally allocate computer resources and save the time for three-dimensional calculations, without reducing the simulation accuracy, it was decided to use the symmetry conditions for this machine. Therefore, the analysis was carried out only for 1/8 part of the model, for one phase of the stator (Fig. 4). The results of such calculation can be positioned further for the full TFM model using the appropriate symmetry multiplier.

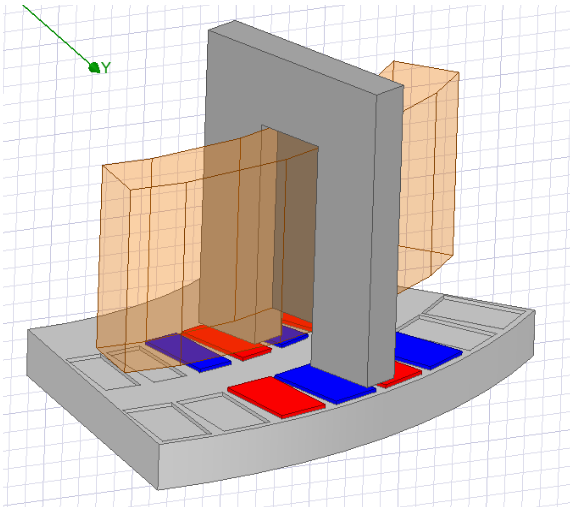


Fig. 4. 1/8 part of 3D TFM model for analysis.

III. THE RESEARCH RESULTS

Magnetic system analysis to find the optimal height of the PMs was carried out with the preservation of all the main dimensions of the machine and the air gap. The rotor speed in the generator mode was constant and had a value of 60 rpm.

A large number of calculations were carried out with the 3D model of the TFM and with different PMs height ranging from 1 to 8 mm. The initial controlled parameters were: the EMF generated in the stator phase coil and the cogging torque from the PMs attraction force of the rotor, which fundamentally affects the power of the rotating machine and the amplitude of its pulsations. This cogging torque is negative and it will be a holding torque of the rotor, so the smaller it is, the easier it will be to rotate the generator using an external drive mechanism.

Therefore, the purpose of the calculation is to find the optimal height of the PMs, which corresponds to the maximum possible value of the EMF in the coil and with a minimum negative value of the cogging torque for the PMs attraction of the rotor. The results of calculations in the form of the graphs for the EMF value and cogging torque value depending on the PMs height are shown in Figs. 5, 6. All results are given for the whole TFM model and one stator phase with corresponding symmetry multiplier.

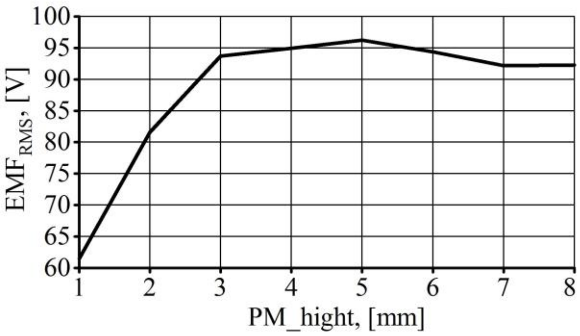


Fig. 5. Dependence of the PMs height on generated EMF value in the stator coil.

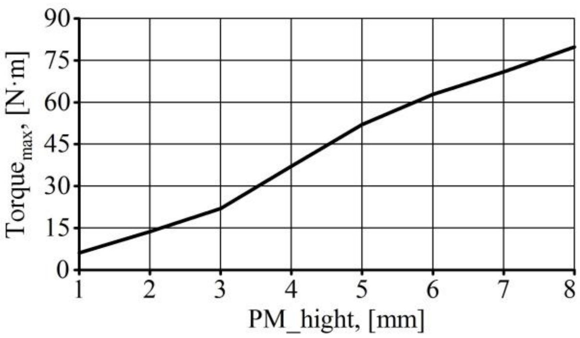


Fig. 6. Dependence of the PMs height on the maximum value of the cogging torque.

As we can see in the graphs, the value of the cogging braking torque increases almost linearly, while the value of the induced EMF in the stator coil does not grow linearly and reaches its maximum at value of 95–96 V.

The results of calculating the magnitude of the induced EMF in the coil and the cogging torque of the rotor for different values of the PMs height are given in Table 1.

Table 1.

Results of calculation of the EMF value in the coil and cogging torque of the rotor for different values of the PMs height

PM height, h_{PM}, mm	EMF, E_{rms}, V	Cogging torque, M_{cog}, N·m	Increasing (+) or decreasing (-) of E_{rms} compared to previous value, %	Increasing (+) of M_{cog} compared to previous value, %
1	61.3	6.3	–	–
2	81.5	13.9	+33 %	+120 %
3	93.8	22.2	+15 %	+59 %
4	94.9	37.4	+1.0 %	+68 %
5	96.3	52.4	+1.4 %	+40 %
6	94.4	63.4	-0.9 %	+21 %
7	92.2	71.5	-2.4 %	+12.7 %
8	92.3	80.4	+0.1 %	+12.5 %

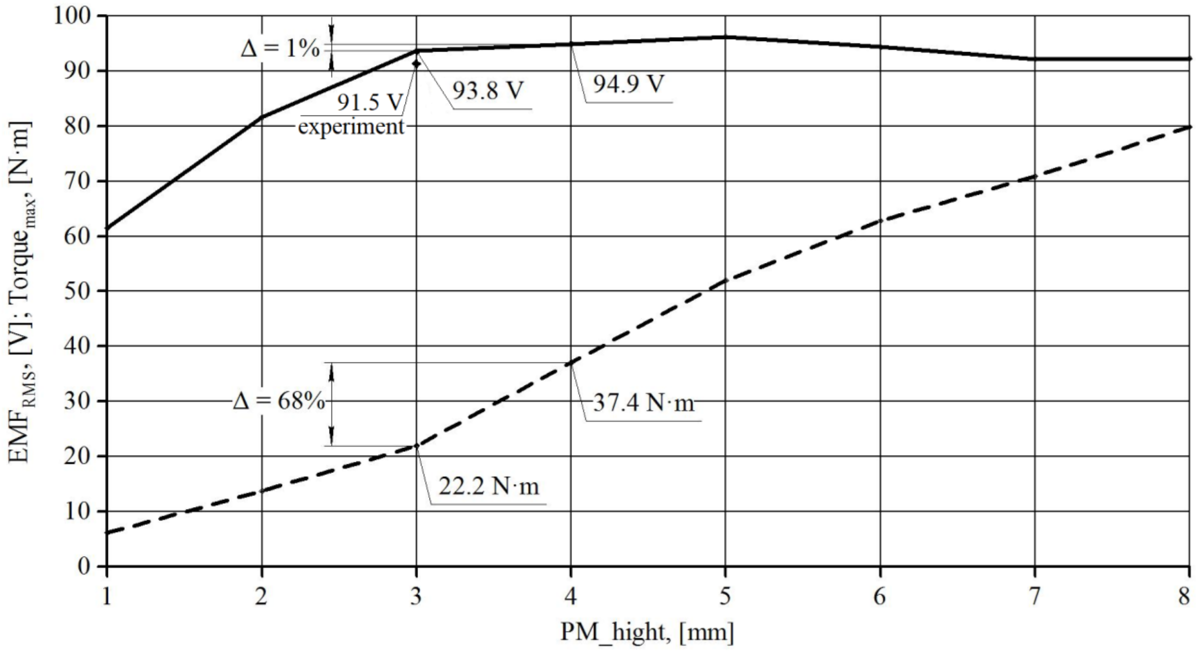
The dependence described above is explained by the fact that with increasing the PMs height, the stator pole, with the magnetic flux density, reaches its saturation state, and further increase in the PMs height leads only to an increasing the magnetic losses and magnetic flux leakage. Also, with an increase in the PMs value in the space between the stator poles near the coil, magnetic field leakage creates a back-EMF in the stator coil, reflected in the graphs as a small drop in the EMF value at 6–8 mm of the PMs height.

The dependence of the linear growth of the cogging torque on the PMs height is explained by the fact that at a higher PM height, the PMs attraction force with the stator pole also increases. Mainly it happens at the edges of the magnet and between the stator poles space. And, the highest torque value is reached at the maximum tension of the magnetic field lines in the position, when the stator pole is situated between two magnets of the rotor.

Summing up all of the above, we can conclude that the optimal values of the PMs height from the point of view of the induced EMF in the coil – are 3 and 4 mm. However, if they are compared with the obtained value of the cogging torque, then the difference between the PMs height of 3 and 4 mm is significantly greater than the difference between the EMF value in the stator coil (68% vs. 1% difference). Thus, the increase in the PMs height to 4 mm is not rational from the point of view of the cogging torque value. More illustrative results of comparing the differences between 3 and

4 mm of PMs height is shown in Fig. 7.

Experimental data of this 32-poles TFM design with the 360-mm external diameter of the magnetic system was obtained in the laboratory and compared with the theoretical data: 91.5 V – is the experimental value of EMF (Fig.7), 93.8 V – is calculated EMF value for this TFM design with the 3-mm PMs height and at the specific speed of the rotor (60 rpm).



— – *dependence of the EMF (RMS) value on the height of the PMs*;
- - - – *dependence of the cogging torque value on the height of the PMs*.

Fig. 7. Comparison of obtained results between PMs height 3 mm and 4 mm.

The calculated error is about 2%, which indicates the high accuracy of the 3D simulation.

In addition, the average magnetic flux density value in the TFM air gap for all the PMs heights were obtained. The results of dependence of the average magnetic flux density in the air gap on the PMs height are given in Table 2 and in Fig. 8.

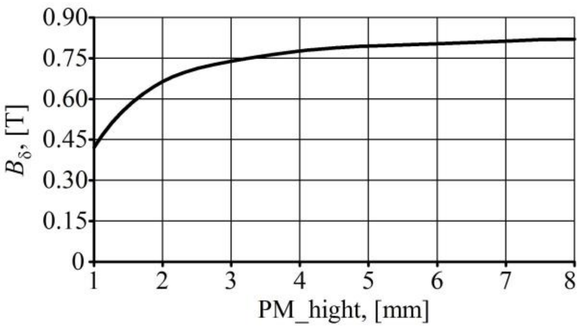


Fig. 8. Dependence of magnetic flux density in the generator air gap on the PM height.

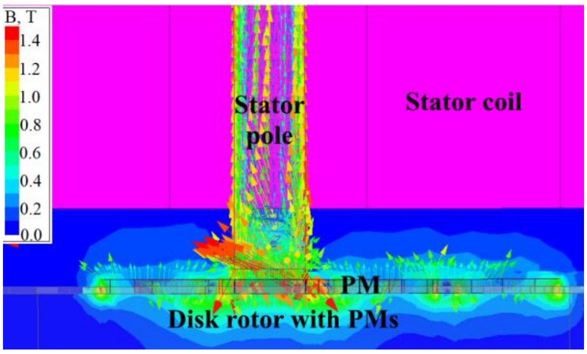
As we can see in the graph (Fig. 9), the magnetic flux density increases nonlinearly as the magnitude of the generated EMF in the stator coil. Slight decrease in the EMF at 6–8-mm PMs height is connected with the increasing activity of the flux leakage in the space between the stator poles.

Table 2.

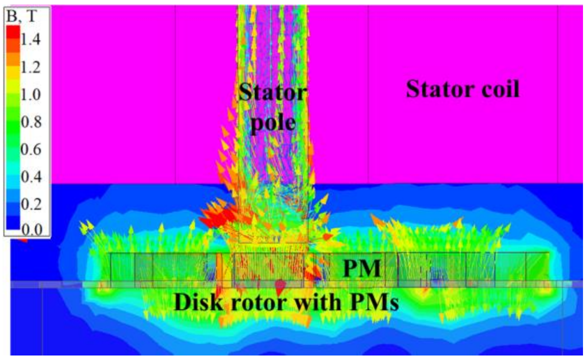
Average magnetic flux density in the air gap

PM height, h_{PM}, mm	Averaged magnetic flux density in the air gap, B_δ, T
1	0.43
2	0.66
3	0.75
4	0.772
5	0.777
6	0.788
7	0.803
8	0.821

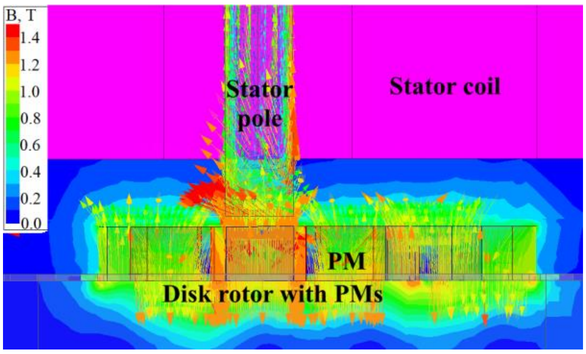
Thus, the average value of the magnetic flux density in the space between the stator poles (between PM and the coil) is 0.09 T – for 1-mm PM height, 0.18 T – for 3-mm PM height and 0.298 T – for 8-mm PM height, which are significant values of the flux leakage already. The distributions of these flux leakages between the stator poles (in the area between the PM and the coil) for comparison are shown in Fig. 9.



a



b



c

a – *PM height 2 mm;* b – *PM height 5 mm;*
c – *PM height 8 mm.*

Fig. 9. Magnetic flux density distributions

IV. Conclusions

The optimal PMs height from the point of view of the largest EMF of the stator coil and the lowest value of the rotor cogging torque – is 3 mm. In addition, an increase in the PMs height will not lead to a significant increase in the EMF value in the coil, but significantly increases the cogging torque value of the rotor, which negatively affects the drive mechanism of the generator. For this reason, the increase in the PMs height in 3 mm is not recommended.

In addition, it is necessary to pay attention to the flux leakages in the space between the stator poles and the use of the magnetic shunts for optimal magnetic field closure through the rotor and stator poles of the generator with minimal losses.

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