

*PHYSICAL AND TECHNICAL ENERGY PROBLEMS*

DIRECT-DRIVE SYNCHRONOUS GENERATORS WITH EXCITATION  
FROM STRONTIUM-FERRITE MAGNETS:  
EFFICIENCY IMPROVEMENT

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The authors consider the possibility to raise the specific power of synchronous generators with excitation from inexpensive permanent magnets. For this purpose, it is proposed to use tooth-wise windings and permanent magnets based on inexpensive magneto-hard material, e.g. strontium-ferrite. The magnets are to be placed between the rotor teeth, the alternate polarity of which is facing the air-gap. This provides a simpler and cheaper technology of making such a generator and improves its reliability. The proposed rational bevelling of the stator teeth not only raises the specific power of the generator but also reduces the level of noise and vibrations, extends the longevity of the magnets and bearings as well as facilitates the starting torque of the electric machine, e.g. if it is employed as wind generator.

**Key words:** *wind generator, permanent magnets, bevel teeth, pole overlapping.*

1. INTRODUCTION

Permanent-magnet generators are widely used in aviation, space exploration, transport, wind power production, etc.

Advantages of such electric machines are high specific power, reliability, and better efficiency owing to the absence of excitation losses. At the same time, the potentialities of such machines are far from being exhausted, especially if instead of a distributed winding a tooth-wise one is used and if the generators are annular, with a large number of pole pairs.

It is known that the multi-polar annular design provides a higher torque for the electric machine. At the same time, fastening the excitation magnets becomes more complicated, the use of magnetic flux worse; the vibration and noise levels are higher, the magnets are worn down more rapidly; starting-up proceeds slower, the maintenance becomes more difficult; the cost of repair works increases, and so on [1–4].

Under these conditions, definite design improvements are required in order to overcome the mentioned flaws, to make these machines more efficient, and to broaden the areas of their application.

2. THE MULTIPOLARITY, ANNULARITY, RATIONAL ARRANGEMENT  
OF THE WINDINGS AND MAGNETS – AN EFFECTIVE WAY TO RAISE  
THE SPECIFIC POWER OF MAGNETO-ELECTRIC GENERATORS

The electro-magnetic power of a synchronous generator is defined by the expression:

$$P_{em} = mEI = m\sqrt{2}\pi f w \Phi I k_w. \quad (1)$$

Here  $f = pn/60$  is the current frequency determined by the number of pole pairs  $p$  and rotational speed  $n$ ;  $w$  is the number of turns per phase of an  $m$ -phased electric machine;

$\Phi = B_\delta \tau l \alpha_\delta$  is the magnetic flux of a pole ( $B_\delta$  being the air-gap induction,  $\tau$  – the pole pitch,  $l$  – the axial pole length,  $\alpha_\delta$  – the pole overlap);

$I$  is the armature current, and

$k_w$  is a winding coefficient.

Substitution of corresponding  $f$  and  $\Phi$  into (1) gives the following expression:

$$P_{em} = m\sqrt{2}\pi \frac{pn}{60} B_\delta \tau l \alpha_\delta w \Phi I k_w \quad (2)$$

which, taking into account the linear load

$$A = \frac{2mwI}{\pi D} \quad (3)$$

is reduced to the finite form

$$P_{em} = 0.182 D^2 l A n \alpha_\delta k_w, \quad (4)$$

where  $D$  is the inner diameter of stator, m;

$l$  is the axial length of stator, m.

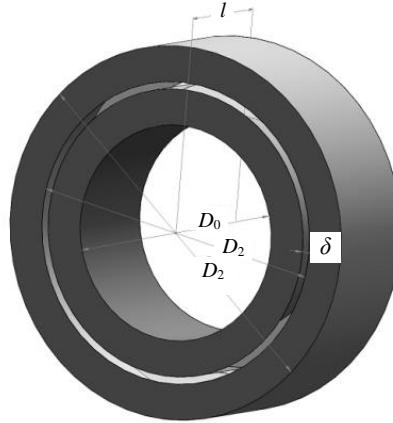


Fig. 1. Schematic design of the annular generator based on permanent magnets.

As follows from (4), the generator power does not directly depend on the number of pole pairs. This power is determined by volume ( $D^2 l$ ), electro-magnetic loads  $B_\delta$  and  $A$ , rotational speed  $n$ , pole overlap and winding coefficients  $\alpha_\delta$  and  $k_w$ , respectively. The relationship of the type is not something unusual – this is

intrinsic in synchronous machines. However, if we associate increase in the number of pole pairs with such increase in the  $D/l$  ratio, then it would follow that with a rising number of pole pairs, and, therefore, with decrease in pole pitch  $\tau$  the height of the stator and rotor yokes, respectively, is also decreasing, which means that the electric machine becomes annular in design (Fig. 1).

In this case, the inner rotor diameter,  $D_0$ , could be up to 70–80% of the outer one,  $D_2$ , which would mean that the mass of electric machine decreases  $k$  times. In the version under consideration this decrease will be:

$$K = \frac{\frac{\pi D_2^2 l}{4}}{\frac{\pi (D_2^2 - D_0^2) l}{4}} = \frac{\frac{\pi D_2^2 l}{4}}{\frac{\pi (D_2^2 - D_0^2) l}{4}} = 1.96, \quad (5)$$

that is, approximately two-fold, since the internal part of the rotor and the machine's body might be light enough (e.g. of duralumin). For example, this might be bushing 3 of the rotor and body 5 of the magneto-electric generator the magnets of which are oriented radially by their magnetization (Fig. 2). In the slots of stator core 1 with teeth the armature winding is placed, while on the rotor – permanent magnets fastened to bushing 3 by means of non-magnetic wedges 4 [3–5].

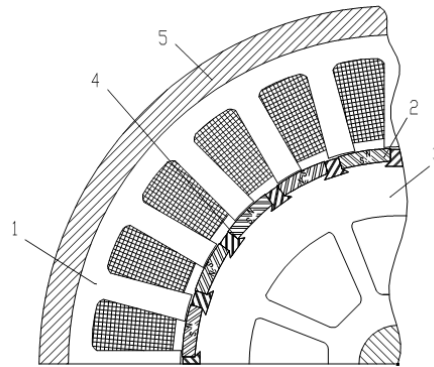


Fig. 2. The magneto-electric generator with radially oriented magnets.

It is important that with increasing diameter  $D_2$  and respective decreasing length  $l$  the total mass of permanent magnets does not increase. Indeed, if, for example, the inner diameter of the stator is increased twice, the number of magnets also rises twice; at the same time, their total length is reduced four-fold. However, due to the necessity to enlarge in this case the air-gap – also approximately twice – we are forced to increase the magnet height, to the same extent. Therefore, here we would not have any gain to the cost.

Another way of how to raise the specific power is to increase the pole overlap coefficient  $\alpha_\delta$  from 0.65 (as it is for usual synchronous machines with distributed armature winding) up to  $\alpha_\delta = 0.80 \div 0.90$ . According to the known investigation [5] the pole overlap coefficient for a multipolar machine can be chosen as

$$\alpha_{\delta} = 1 - \sqrt{\frac{\delta \cdot h_m}{\tau^2}}, \quad (6)$$

where  $\delta$  is the air-gap width;  
 $h_m$  is the magnet height;  
 $\tau$  is the pole pitch.

At this coefficient the pole magnetic flux reaches maximum.

An additional way of how to reduce the generator mass, simplify its technology, and improve the reliability of mounting the magnets is their arrangement between the rotor teeth [6, 8]. The schematic design of a generator in which the permanent magnets are arranged between the rotor teeth is shown in Fig. 3, where 1 – the stator core with slots and windings in them; 2 – tangentially-oriented permanent magnets; 3 – the rotor teeth (cores of the poles) fastened to non-magnetic brass 4. Body 5 and brass 4 are made of light non-magnetic materials.

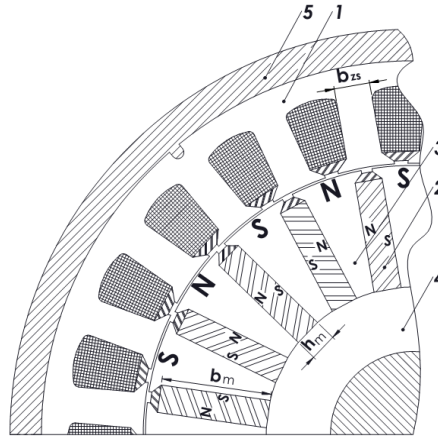


Fig. 3. The magneto-electric generator with tangentially-oriented magnets arranged between the rotor teeth.

Therefore, at the cost of an increased pole overlap coefficient and arrangement of magnets between the rotor teeth it is possible to additionally raise the power of a magneto-electric generator.

### 3. ADVANTAGES OF THE GENERATOR DESIGN WITH MAGNETS ARRANGED BETWEEN THE ROTOR TEETH

Above in Fig. 3 the design is schematically shown for a generator in which the active zone has magnets arranged between the rotor teeth. Electric machines of such a design have acquired the name of generators (or motors) with tangential orientation of magnets [6].

Advantage of this design is the possibility to better utilize the energy of magnets and to obtain the magnetic induction in the air-gap which would exceed the residual induction of the magnets. In this case, the magnetic induction in the air-gap can be determined from the formula:

$$B_{\delta} = 2B_m \frac{b_m}{b_{zs}}, \quad (7)$$

where  $B_m$  is the induction on the surface of a magnet;  
 $b_m$  is its width;  
 $b_{zs}$  is the width of a stator tooth.

Figure 4 shows the curve of de-magnetization with point A characterizing the operating state – here at the maximum energy of a strontium-ferrite magnet, type 28CA250 [7, 8].

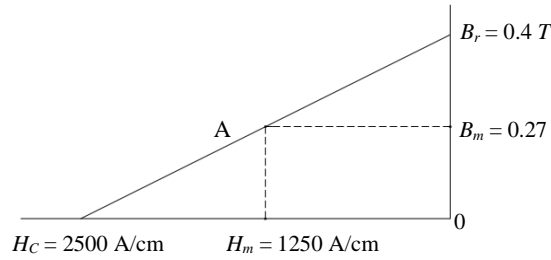


Fig. 4. The curve of de-magnetization with point A characterizing the operating state of a magnet at the maximum field energy.

From Fig. 4 and formula (7) it follows that in the electric machines under consideration quite possible is to use inexpensive (e.g. strontium-ferrite) magnets and provide in so doing high values of the magnetic induction in the air-gap (up to 1.2÷1.5 T). If the operating point is chosen correctly, the required magnetization force could be provided.

Indeed, at the air-gap  $\delta = 0.6$  mm the inner diameter of stator  $D = 190$  mm, the length of stator (rotor) core  $l = 50$  mm, and the rotational speed  $n_N = 250 \text{ min}^{-1}$  a generator with expensive (Nd–Fe–B) radially-oriented magnets (shown in Fig. 2) is capable of developing a power of 2000 W. At the same time, a generator of the same size and with the same number of poles but having tangentially-oriented magnets (Fig. 3) can develop at the same rotational speed (of  $250 \text{ min}^{-1}$ ) almost equal power. As distinguished from the generator depicted in Fig. 2, here the magnets are twice as high ( $h_m \approx 12.7$  mm) and 1.75 times wider as compared with these parameters for an expensive magnet from magneto-hard material (Nd–Fe–B).

According to formula (7) and location of point A in Fig. 4, the induction in air-gap will be:

$$B_{\delta} = 2 \cdot B_m \frac{b_m}{b_{zs}} = 2 \cdot 0.27 \frac{44.6}{12.7} = 1.4 \text{ T}, \quad (8)$$

where  $B_m = 0.27 \text{ T}$  is the induction on the surface of a magnet (point A in Fig. 4);  
 $b_m = 44.5 \text{ mm}$  is the magnet width;  
 $b_{zs} = 12.7 \text{ mm}$  is the width of a stator tooth.

This value for magnetic induction cannot be achieved in the generator shown in Fig. 2.

As concerns the magnetizing force (MMF), at point A in Fig. 4 it is:

$$F_A = \frac{H_C}{2} h_m = \frac{2500}{2} \cdot 1.27 = 1586 \text{ A}, \quad (9)$$

while the MMF for carrying a magnetic flux with induction  $B_\delta = 1.4 \text{ T}$  through the air-gap reaches the value:

$$F_\delta = \frac{2B_\delta\delta}{\mu_0} = \frac{2 \cdot 1.4 \cdot 0.6 \cdot 10^{-3}}{4\pi \cdot 10^{-7}} = 1338 \text{ A}. \quad (10)$$

This is considerably less than the magnetizing force that is at our disposal in compliance with (9) and suffices under these conditions for carrying magnetic flux also through steel and for compensation of the de-magnetizing action of the armature reaction.

It should be noted that the volume of ferrite-strontium magnets at their optimal utilization turns out to be only 3.5 times that of expensive magnets made of magneto-hard materials – that is, these former are more than half as cheap as the high-energy magnets.

Thus, the second significant advantage of the generator design with tangential orientation of magnets is the possibility to efficiently employ cheap strontium-ferrite magnets, which, in addition, possess higher thermal stability as well as higher resistance to impacts and vibrations, being at the same time more reliable. Furthermore, with temperature increasing the energy of strontium-ferrite magnets (e.g. of the 28CA250 type) can even be also increasing.

At the same time, a significant drawback of the generators with tangential orientation of magnets should be pointed out: since their rotors are usually made of magneto-soft material they are highly sensitive to the de-magnetizing action of the armature reaction, i.e., all other factors being equal, there is a stronger tendency towards a rise in the synchronous resistance. In the generators with radial orientation of magnets the synchronous resistance is low enough owing to high reluctance of the magnets placed on the way of propagation of de-magnetization flows.

#### 4. THE DE-MAGNETIZING ACTION OF ARMATURE REACTION IN GENERATORS WITH TOOTHED ROTORS AND THE METHODS TO REDUCE IT

Magnetic flows of the armature reaction and dissipation can exert a negative influence not only on the generators with tangential orientation of magnets but also on those in which prismatic magnets with a radial orientation possess equal polarity when placed between the rotor teeth (Fig. 5) but together with them form the poles of alternate polarity [5].

Figure 5 shows the cross-section of a generator's core with alternating rotor teeth and magnets for the case when the number of teeth on stator ( $S$ ) is  $Z_S = 18$  (1–18), the number of teeth on rotor ( $R$ ) is  $Z_R = 10$ , and the number of poles is  $2p = 20$ .

The explanation of this phenomenon is as follows. When a stator slot opposes a pole made of magneto-soft material (Fig. 6a), the MMF of the slot excites the maximum flow passing through two air-gaps  $\delta$ , pole 1 of the rotor and

teeth 2 of the stator (shown by dotted lines). In this case, as seen in Figs. 5 and 6a, the smaller slot openings  $\Delta R$ , the greater the reaction (dissipation) fluxes arise. From this it follows that, in order to reduce the action of these fluxes it is necessary to increase the opening of stator slot. However, as this takes place, the useful magnetic flux decreases owing to the decreasing tooth-core area facing a pole through air-gap. Obviously, the air-gap also could be extended, but this would lead to decrease in the useful magnetic flux, and besides – to an increase in the no-load tooth torque.

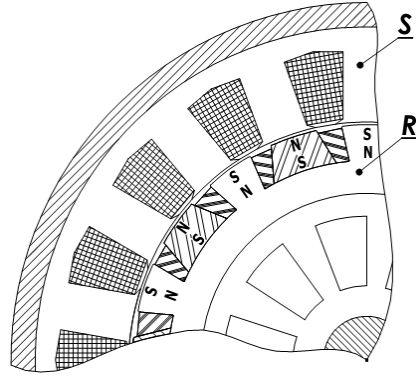


Fig. 5. The cross-section of generator core with alternating rotor teeth and magnets ( $Z_S=18$ ;  $Z_R=10$ ;  $2p=20$ ).

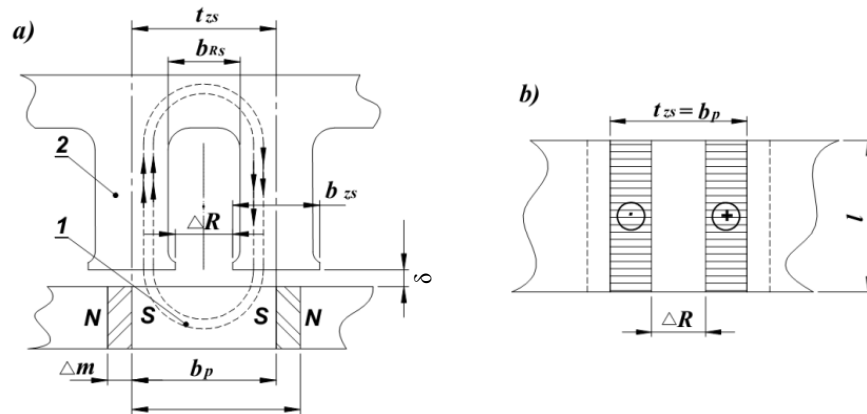


Fig. 6. Illustration of the role played by the magneto-soft poles in forming additional armature reaction and dissipation fluxes:  $t_{zs}$  – pitch of stator teeth;  $b_{zs}$ ,  $b_{rs}$  – the width of a tooth and a slot, respectively;  $b_p$  – the pole width;  $\Delta R$  – the slot opening;  $\Delta m$  – the pole spacing (the picture is made for a half-closed slot when  $\Delta R < b_{rs}$ )

The passage of the magnetic flux from tooth to tooth of stator through the air-gap and rotor pole shown in Fig. 6 (in plan) has a peculiarity that due to execution of the stator and rotor teeth laminated (designated in this figure by a horizontal hatching) the magnetic flux can close only in the boundaries of each electro-technical steel sheet. In practice, such a flux cannot pass through lamination sheets cross-wise due to the presence of a non-magnetic oxide or lacquer layer between the sheets.

Therefore, it is expedient to employ this peculiarity by blocking additionally the way to the reaction fluxes – for example, if the stator teeth are executed bevelled.

This way of reducing the magnetic fluxes that close around a slot through the rotor air-gap and tooth is illustrated in Fig. 7. In this figure,  $t_{zs}$  is the stator tooth pitch;  $b_p$  – the pole width;  $\Delta m$  – the pole spacing;  $l$  – the axial length of stator core;  $\Delta R$  – the slot opening.

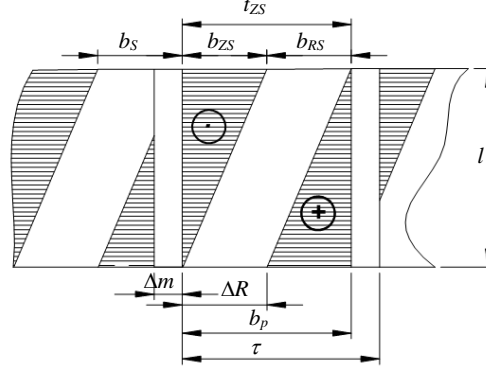


Fig. 7. Illustration of the influence exerted by bevels of stator teeth (slots) on reducing the magnetic fluxes closing around a slot (the picture is made for an open slot when  $\Delta R = b_{rs}$  and bevel  $b_s = b_{rs}$ ; the designations are identical to those in Fig. 6).

From Fig. 7 it follows that the slot opening is directed diagonally, so the magnetic flux passing to the right tooth is to be split into the fluxes of separate sheets of steel. Then for each of the sheets, as distinguished from Fig. 6b, the reluctances right and left of the slot opening  $\Delta R$  will not be the same, since for the “upper” and “lower” (in the figure) sheets one of the reluctance addends will be facing infinity; therefore, the total (summary) reluctances of these sheets to the magnetic flow will be infinite. The least reluctance will be for the flow passing through the middle sheet, whereas for the sheets closer to the farthest ones it will be tending to infinity.

Thus, it can be proved that a measure such as linear slot bevelling  $b_s$  by stator tooth width  $b_{zs}$  (i.e.  $b_s = b_{zs}$ ) will increase reluctance  $R_m$  to the reaction flux 1.5 times in compliance with the expression:

$$R_m = \frac{6\delta}{b_s l \mu_0}, \quad (11)$$

where  $\delta$  is the air-gap, m;

$l$  is the axial length of stator core, m;

$b_s$  is the slot bevel, m;

$\mu_0 = 4\pi \cdot 10^{-7}$ ,  $\Omega \cdot s/m$  is the magnetic permeability of the air.

Meanwhile, the reluctance rise according to (11) will be somewhat overvalued, since at deriving this formula the factor of presence of an axial component in the magnetic flux – from sheet to sheet, arising due to the axial component of the difference in magnetic potentials of the stator and rotor teeth – was not taken into account.



From this it follows that the most effective way to control the arising flows through an air-gap and a rotor tooth is non-linear slot bevelling [9] as shown in Fig. 8, where also the layout is depicted for the areas of the stator and rotor teeth overlap at arc-wise bevelling of stator slots (teeth). The corresponding designations are:  $S_1$ ,  $S_2$  – areas of pole overlapping with adjacent teeth on the stator;  $\tau$  – the pole pitch;  $t_{zs}$  – stator tooth pitch;  $h_m$  – magnet's height;  $b_{RS} = b_s$  is the stator slot's width and the slot (tooth) bevel equal to it.

Fig. 8. The areas of the stator and rotor teeth overlap at arc-wise bevelling of stator slots (teeth); (the parameters are identical to those in Fig. 7)

Obviously, the non-linear bevelling could be executed sinusoidal; however, this shape makes it difficult to drop the armature windings into the stator slots.

the rotor pole width, with overlapping not less than 90%. The bevel is to equal the slot opening width and to have an arc shape with the curvature radius considerably exceeding the axial length of the stator core. The mentioned above parameters can be achieved only at even number of pole pairs which is less by half than the number of stator teeth, i.e. at

$$p < Z_R / 2 . \quad (13)$$

The parameters listed above provide also a reduced no-load torque of the generator:

$$M_0 \leq 0.01 M_N , \quad (14)$$

where  $M_N$  is its nominal electromagnetic torque.

Based on the QuickField software and the method (developed for passing from 2D problems to 3D ones), the calculation was performed for the torque non-uniformity at no load and the torque itself at the presence of current in the armature winding.

The torque non-uniformity and its maximum at the nominal armature current were obtained for the case when strontium-ferrite of 28CA250 type was used as magneto-hard material; this non-uniformity was 1%.

From the results obtained it could be inferred that the optimal bevelling and the installation of tangentially-oriented magnets significantly improves the efficiency of electric machine, making it highly promising for the use as a direct-drive wind generator.

## 6. CONCLUSIONS

Synchronous generators with excitation from strontium-ferrite permanent magnets can possess high specific power and torque. If made annular and with tooth-wise armature winding, they can have a large number of pole pairs. However, if no special designing measures are taken, these generators are difficult to load due to excessive synchronous torque; they have high vibration and noise levels, and, consequently, a quickened wear of bearings.

To improve the efficiency of magneto-electric generators it is proposed to execute them with a high coefficient of pole overlapping (0.8–0.9), as well as with arc-wise and sine-wise stator tooth bevels equal to the angular openings of stator slots; it is shown to be expedient to make such generators with the even number of pole pairs but less by half than the number of stator teeth.

For excitation, inexpensive strontium–ferrite magnets can successfully be used. They should be placed between the teeth of tangentially-oriented rotors in such a manner that these teeth have alternate polarity. The proposed measures make it possible to reduce the cost of generators and simplify the mounting of magnets.

## ACKNOWLEDGEMENT

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## REFERENCES

1. Levin, N., Kamolins, E., & Vitolina, S. (2011). *Brushless Electrical Machines*. Riga: RTU, p. 276 (in Latvian).
2. Dirba, J., Ketner, K., Levin, N., & Pugachev V. (2002). *Transport Electrical Machines*. Riga: Jumava, p. 345 (in Latvian).
3. Dirba, J., Levin, N., & Pugachev, V. (2006). *Electromechanical Converters of Wind Energy*. Riga: RTU, p. 312 (in Latvian).
4. Special Report. *Wind Turbine Market 2010*, p 104.
5. Dirba, J., Daskova-Golovkina, J., Ketner, K., Levin, N., & Pugachev, V. (20.08.2009). *Synchronous machine with permanent magnet rotor*. LV Patent No. 13924B.
6. Boot, D.A. (1990). *Brushless Electrical Machines*. Moscow: High School, p. 416 (in Russian).
7. Guide (1980). *Permanent magnets* (edited by Pjatin). Moscow: Energy, p. 388.
8. Bezruchenko, V., & Galteev, F. (1983). *Electrical machines with permanent magnets*. The results of a science and technics. Ser. Electrical machines and transformers. Moscow.: VINITI, p. 148 (in Russian).
9. Serebryakov, A, Levin, N., & Sokolov, A. (18.04.2012). *A contactless direct-driven wind generator*. LV Patent notification No. P-12-62.
10. Ketner, K., Dirba, J., Levin, N., Orlova, S., & Pugachev, V. (20.11.2009). *Axial Inductor Machine*. LV Patent No. 13971B.

## TIEŠĀS PIEDZIŅAS SINHRONO ĢENERATORU AR IEROSMI NO STRONCIJA-FERĪTA PASTĀVĪGAJIEM MAGNĒTIEM EFEKTIVITĀTE

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### Kopsavilkums

Darbā apskatīta iespēja paaugstināt sinhrono ģeneratoru ar ierosmi no pastāvīgajiem magnētiem īpatnējo jaudu. Tiek piedāvāts izmantot vienzobspoles enkura tinumus un pastāvīgos magnētus, kuri izgatavoti no lētiem magnētiskajiem materiāliem, piemēram, stroncija-ferīta. Turklāt, izveidojot statora zobus ar noslīpinājumu, iespējams paaugstināt ģeneratora īpatnējo jaudu, samazināt troksni un vibrācijas, paaugstināt magnētu un gultņu kalpošanas laiku, kā arī samazināt palaišanas momentu, kas ir būtiski, ja ģenerators tiek izmantots vēja enerģētiskajās iekārtās.

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