WIND POWER INDUCTOR GENERATOR WITH ELECTROMAGNETIC REGULATION OF AIR GAP FOR ALTERNATIVE POWER ENGINEERING

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Abstract. The generator consists of the stator, two windings on it – the stator and the windings of the traction electromagnet, a rotating shaft, a rotor moving magnetic conductor with permanent magnets, able to move on the shaft in the axial direction (within a small range – from 0.5 mm to 4-5 mm), a return damping spring, the electronic regulator of current of the traction electromagnet. With the changing of rotor angular frequency the electronic regulator changes current of a traction electromagnet in accordance with a given law, moving a rotor magnetic conductor along the rotor shaft, changing the size of the main magnetic air gap of the electric machine. Thus the magnetic flux linkage and, therefore, the rotating torque (resistance torque) on a rotor shaft are changing depending on the angular speed of the rotor. With a small angular frequency of the rotor the main air gap in the magnetic circuit of the electric machine has the maximum value. With increasing the angular frequency of rotation the traction electromagnet reduces the main air gap in the magnetic circuit of the generator thus increasing the flux linkage. Unlike the design of the suggested generator the kinematic scheme of a moving rotor is simplified, and its moment of inertia is reduced. The values of the output electromotive force (emf) of the generator are calculated and represented in the paper for different operation regimes.

Keywords: air gap, magnetic flux, wind power engineering, super-strong magnets, effect of "magnetic sealing".

Introduction

The paper contains a construction of a synchronous brushless generator with improved regulation features. As it is widely known the disc generators of inductor type with powerful magnets and magnetic circuits made of ferrite have a phenomenon of "magnetic sealing". In particular this phenomenon is significantly increasing the torque of starting the rotor at the initial starting moment. This torque is especially important for wind generators. Nowadays, this problem has some way of solutions. One of these solutions is refusing from the ferrite magnetic circuit. But in this case the power characteristics of the generator are becoming worse. For a partial decreasing of the effect of "magnetic sealing" it is also suggested to decrease or increase a number of permanent magnets n according to the number of coils m for 1-2 units. (Fig. 1). In this case the angular distance α_2 between the magnets 2 is not equal to the angular distance α_1 between the coils 1. $n = m \pm 1$. In [1-4] different constructions of co-axial generators are considered. In this case the generated voltage contains additional harmonic components that are a disadvantage of this method. Another method is a turn of the permanent magnets 2 for the angle β according to a radial axis of the coils 1. The disadvantage of this method is incomplete usage of the area of magnets and cores of the coils (Fig. 2).

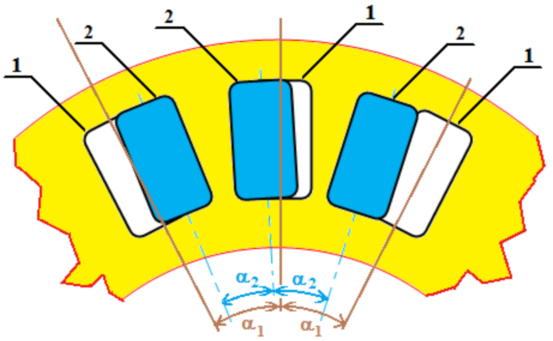

Fig. 1. **Placement of coils 1 and magnets 2 with n =m ± 1**

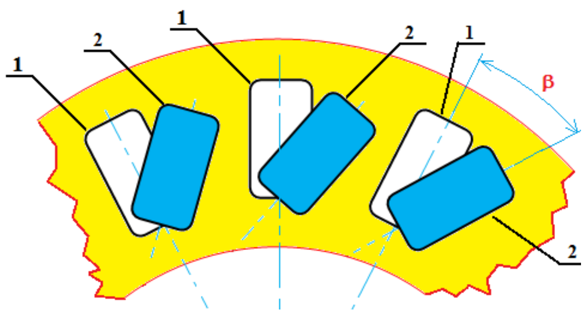

Fig. 2. **Placement of coils 1 and magnets 2 turned for angle β**

Materials and methods

For elimination of the drawbacks mentioned above a construction of inductor contactless generator with a regulated air gap in the basic magnetic circuit of the machine is suggested [5]. The air gap is changed by means of displacement of the rotor magnetic circuit 4 along the rotor axis 5 with the help of traction electro-magnetic regulator that is represented in a simplified scheme in Fig.3.

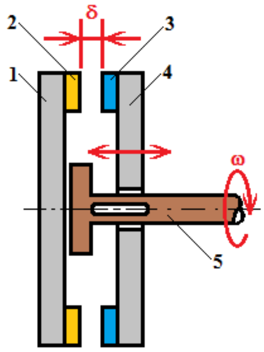

Fig. 3. **Simplified kinematic scheme of generator with regulated air gap:** 1 – stator; 2 – cores with windings; 3 – permanent magnets; 4 – rotating (on the axis with angular frequency ω) and movable (along shaft 5 for the value of air gap δ) rotor; 5 – shaft

The suggested construction gives an opportunity to decrease the resistive torque of the inductor electric machine at start and low angular rotation frequency, to provide a distance regulation of the air gap in accordance with the angular rotation frequency and load, to simplify the kinematic scheme. In the before suggested construction the rotor magnetic circuit was moved with the help of the centrifugal regulator [6-8].

The value of the rotor magnetic circuit replacement depends on the angular rotation frequency of the rotor shaft and determines the value of the air gap δ of the electric machine. In the case of an unmovable rotor (at start) or with a low angular rotation frequency the air gap has a maximum value, minimum flux linkage and, therefore, minimum resistive torque. The mentioned feature allows to eliminate the effect of “magnetic sealing” at start. Fig. 4 illustrates the construction of the inductor machine with a decreased resistive torque at start and opportunity of electro-magnetic regulation of the air gap. The changing magnetic flux of the stator winding Φ_1 and magnetic flux Φ_2 of the electric magnet of the regulator are separated with a non-magnetic insertion.

Inductor generator with a variable air gap δ and reduced resistive starting torque consists of the stator 1 with core 4 and stator windings 11 radial placed on the inside radial surface of the stator, non-magnetic insertions 2 and 5 dividing the magnetic fluxes of the stator winding and that of traction electro-magnet 9, consisting of movable and static elements, rotating shaft 7 with movable magnetic circuit 6 with permanent magnets 10 radial placed on the inside radial surface of the movable magnetic circuit, return spring 12 and electro-magnetic regulator of the air gap with the winding 9 on core 3, magnetic circuit 8 that can move along the rotor shaft 7 axis and rotate with it.

The winding of traction electro-magnet 9 is supplied from the bridge-type rectifier 13 (Fig. 5) connected to the stator three-phase winding 11 of the inductor machine through semiconductor regulator 14 realising the necessary law of control of the air gap value in accordance with rotor 7 angular rotation frequency.

After the full starting of the inductor electric machine at the rated rotating frequency and rated voltage regulator 14 gives the command for turning of contact 15 that with its contacts 15.1 and 15.2 connects the outside load – accumulator, inverter, etc.

With low angular frequency of rotation or that close to zero (starting) the moving magnetic circuit 5, 6, 8 driven by the return spring 12 is at its rightmost location on the shaft of the rotor 7 and rotates with it. At the same time the air gap δ has its maximum value. Due to insignificant flux linkage the resistive torque on the shaft 7 is minimum. With increasing of the angular rotation frequency of the shaft the current in the stator windings of the machine flows to the rectifier and then through the regulator to the winding of the driven electro-magnet. Under the influence of the magnetic flux the rotor is replacing to the left overcoming the force of the return spring. It decreases the air gap δ in the magnetic system increasing flux linkage and the value of the produced EMF in the coils 11 of the stator. It results in increasing of the generator resistive torque. Selecting the law of current regulation of the driven electro-magnet by means of the semiconductor regulator an optimal dependence of the air gap δ value on the shaft angular rotation frequency can be obtained. Therefore, at starting the shaft of the generator has low starting resistive torque. The maximum value of the air gap δ is selected to be equal to the width of the permanent magnets 10. The distance between the magnets on the end surface of the rotor is selected to be equal to the width of the magnet for decreasing the mutual dissipation fluxes.

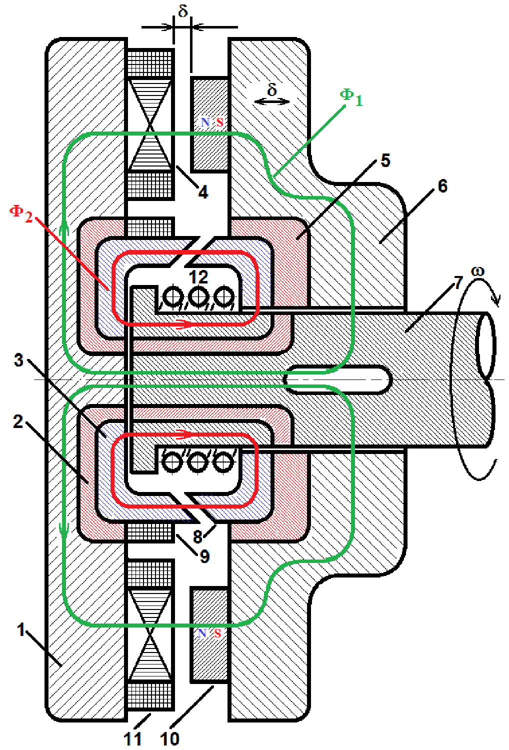

Fig. 4. **Inductor electric machine (disc inductor generator) with permanent magnets with decreased resistive torque at start and electro-magnetic regulator of the air gap δ:** 1 – stator; 2 – non-magnetic splitting insertion – non-movable part; 3 – magnetic circuit of the traction electro-magnet through which magnetic flux is running Φ_2; 4 – core of the stator, through which changing magnetic flux is running Φ_1; 5 – non-magnetic insertion of the rotor – movable part; 6 – movable rotor, rotating with shaft 7; 7 – generator shaft; 8 – rotating element of the magnetic circuit of the traction electro-magnet; 9 – winding of the traction electro-magnet on the stator 1; 10 – permanent magnet of the main magnetic circuit of the generator; 11 – stator winding of the main magnetic circuit of the generator; 12 – return damper spring operating for compressing; δ – variable air gap of the magnetic circuit of the generator

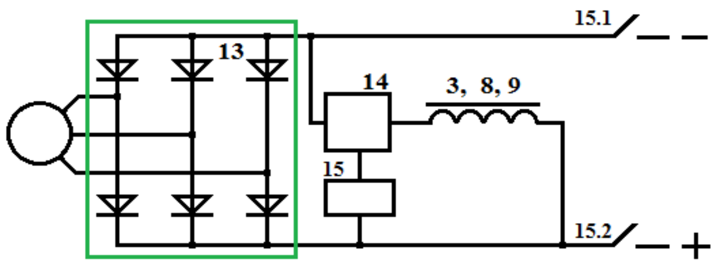

Fig. 5. **Scheme of electro-magnetic regulator of air gap**

It is known that with the same number of permanent magnets on the rotor and coils on the stator the inductor machines of disc construction have the maximum effect of “magnetic sealing”. The suggested construction of the inductor machine – generator with regulated air gap, and therefore, regulated flux linkage significantly reduces its effect.

Unlike the variant of the inductor machine with regulation of the air gap by means of a centrifugal regulator [7] the suggested construction has a wider range of the air gap value regulation in the magnetic circuit of the machine. In addition, in the previous variant the air gap regulation demands changing of the rigidity of the return spring, mass of the weights and the arms ratio of the centrifugal regulator that requires stopping the inductor machine and opening of its case. The suggested new construction has much simpler kinematic scheme, the number and mass of the rotating parts is reduced improving thus the dynamic properties, the rotor moment of inertia is decreased, the law of the traction electric magnet can be distantly changed.

Selecting the law of current regulation of the driven electro-magnet by means of a semiconductor regulator an optimal dependence of the air gap δ value on the shaft angular rotation frequency can be obtained. Therefore, at start of the shaft the generator has low starting resistive torque.

At the present moment a prototype of the inductor generator is being constructed on the basis of NdFeB permanent magnets. The magnets are of rectangular shape with sizes 25x15x5 mm. The number of magnets is 18 units, 6 magnets and coils per phase.

Calculation of output voltage of multi-pole low speed electric generator with permanent magnets

A simplified (in accordance with the Faraday Law) and accurate (on the basis of magnetic field calculation with finite elements methods) calculation is required for the output voltage of the generator with application of the parameters depending on the construction and magnetic properties of the generator elements (Fig. 6).

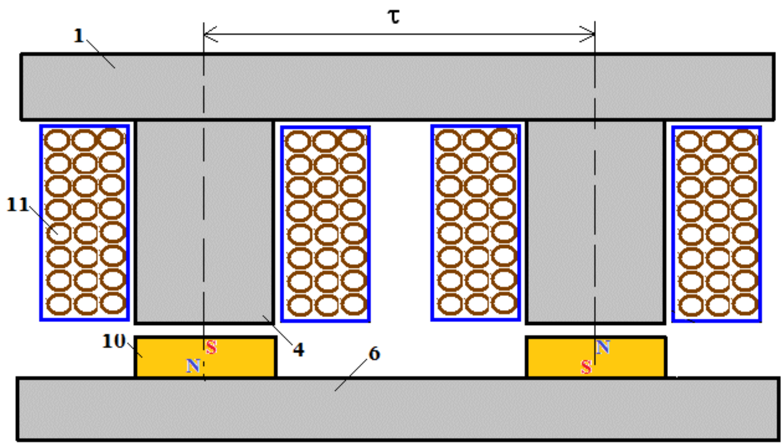

Fig. 6. **Elementary cell of generator magnetic circuit:** the numbering of the elements corresponds to the numbering of the elements in Fig. 4

Simplified calculation of generator using Faraday Law

Let us assume that the number of the magnet poles is ($m = p$), but at rotating of the magnet according to the coils the magnetic flux across the core of the coil is changed in accordance to the law:

$$\Phi = \Phi_0 \cos\left(\frac{p\omega t}{2}\right) \tag{1}$$

where $\Phi_0 = B_{eff}S$, Wb;
Φ – magnetic flux across the core of the coil, Wb;
S – area of the pole, m^2;
B_{eff} – root mean square (RMS) value of the magnetic induction in the air gap, T.

RMS value of the magnetic induction in the air gap is obtained averaging it per pole area. In accordance with the Faraday Law [9]:

$$E = -\frac{d(N\Phi)}{dt}, \tag{2}$$

where E – electromotive force (EMF) of the coil, V;
N – number of the turns of the coil.

EMF of the coil:

$$E = \frac{pN\omega\Phi_0 \sin\left(\frac{p\omega t}{2}\right)}{2} = \frac{1}{2} pN\omega B_{eff} S \sin\left(\frac{p\omega t}{2}\right), \quad (3)$$

where p – number of poles of the magnet;
ω – rotation frequency of the generator, rad·s^{-1}.

As $f = \omega/(2\pi)$, the amplitude of EMF for one coil is

$$E_0 = \pi f p\omega N B_{eff} S = \frac{1}{2} p\omega N B_{eff} S \quad (4)$$

With the series connection of the coils group the output RMS voltage of the generator for one phase (EMF is of sine-form):

$$E_{gen} = \frac{\omega}{\pi\sqrt{2}} p^2 N B_{eff} S \quad (5)$$

If the distribution of the magnetic induction is described with a sine-form the output rms value of the voltage per single phase is determined:

$$E_{gen} = \frac{\omega}{\pi\sqrt{2}} p^2 N B_0 S \quad (6)$$

Accurate calculation of generator voltage (on the basis of magnetic field calculation with the method of finite elements)

The analysis of the output voltage of the three-phase generator is made on the basis of the magnetic field calculation of the suggested construction (Fig. 6). The calculations are for the pole division by means of finite elements with software Quick Field [10; 11]. It takes into account the peculiarities of the construction and parameters of magnetic materials of the generator element (for example, the core of the magnetic circuit of the stator 1 (Fig. 6) is electric steel, permanent magnet of the generator 10 is of NdFeB).

The results of the calculations with both methods (RMS value) and the experiment are presented in Table 1.

Table 1

Comparative table of EMF values

E_{gen} (Faraday Law),V	E_{gen} (Finite elements method), V	E_{gen} (experiment), V
8.94	11.17	11.95

Table 1 illustrates the comparison only of the final values of the calculated and experimentally obtained characteristics.

The results demonstrate 19 % deviation of the EMF value calculating it with the Faraday formula, and 6.5 % – with the finite elements method.

A number of optimization calculations have been completed with different numbers of poles (Fig. 7), cores, with different angular frequencies of rotation (Fig. 8) and number of turns of the winding. On the basis of these calculations an optimal construction has been selected with maximum output voltage of the generator.

Conclusions of the optimization task

With constant angular rotation frequency the output voltage of the generator with permanent magnets is increasing in direct proportion to the square of the pole number in case if the pole area is constant. Designing low speed generators a ring magnet with maximum residual induction should be applied with as large as possible outside diameter and maximum number of poles.

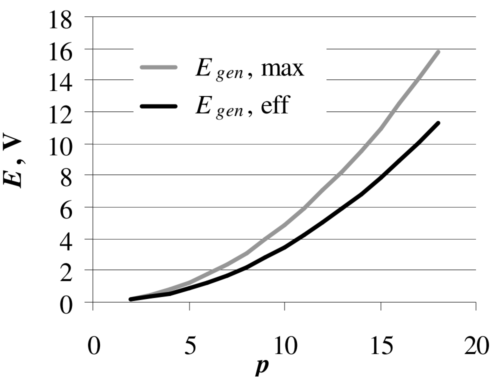

Fig. 7. **Dependence of output voltage of generator on number of poles ($p = m$, N = const)**

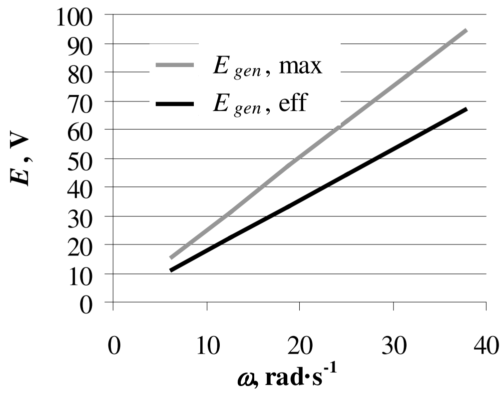

Fig. 8. **Dependence of output voltage of generator on rotation frequency ($p = m$, N = const)**

The refined characteristics of the generator – those of idle- run, external, $E = f(\delta)$, current-speed will be taken with the full ready prototype.

Conclusions

1. An innovative solution is suggested for wind and hydro generators with an opportunity to improve sufficiently the energy parameters of the existing constructions of the axial generators.
2. The suggested construction of the synchronous brushless generator gives an opportunity to weaken the effect of "magnetic sealing" and improve the dynamic parameters.
3. For calculation of the output voltage of the generator a simplified method with the Faraday Law gives an error of 19 %, but the finite elements method – 6.5 %.

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