DEVELOPMENT OF AN EFFICIENT VERTICAL-AXIS ELECTRIC GENERATOR WITH LOW ROTATIONAL SPEED

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Nowadays, in order to effectively use small-capacity wind energy devices in areas with low wind flow, we need to choose the right electric generator within the wind turbine.

Many small-scale wind power plants use generators with low rotational speeds to avoid the disadvantages associated with the use of reducers. For wind power plants intended for use in areas with low average wind speeds, the use of electric generators with low rotational speeds increases the efficiency and reliability of the devices.

The main requirements for a low-speed electric generator to be developed are:

- Since wind speed is variable, the generator is required to produce the electrical energy needed to charge the batteries at low frequencies;
- It is necessary to reduce noise and vibration when the generator is operating;
- The design of the electric generator must be simple and the manufacturing technology must be easy;
- When the electric generator operates at low rotational speed, it is necessary to reduce overall losses;
- It is required to achieve efficiency at low rotation speeds of the electric generator;
- The electric generator needs to be inexpensive and easy to use.

When designing this generator, the type, size, number of magnets, and its magnetic field induction and strength are important parameters, because the voltage and power obtained from the generator depend on these parameters.

The magnetic permeability of a medium containing a current-carrying conductor is determined from the following expression [1]:

$$\mu_{rrec} = \frac{1}{\mu_0} \cdot \frac{\Delta B}{\Delta H} \quad (1)$$

b then : $B_r$and the magnetic $H_c$field induction of permanent magnets and strength.

Magnetic flux density, air gap, and magnetic circuit are explained based on Kirchhoff's law [1]:

$$\begin{cases} \frac{B_r}{\mu_0\mu_{rrec}} \cdot 2h_M = \frac{B_g}{\mu_0\mu_{rrec}} \cdot 2h_M + \frac{B_r}{\mu_0} \cdot 2g + H_{Fe}l_{Fe} \\ \frac{B_r}{\mu_0\mu_{rrec}} \cdot 2h_M = \frac{B_g}{\mu_0\mu_{rrec}} \cdot 2h_M + \frac{B_r}{\mu_0} \cdot 2gk_{sat} \end{cases} \quad (2)$$

The saturation coefficient of the magnetic circuit is determined from the following expression:

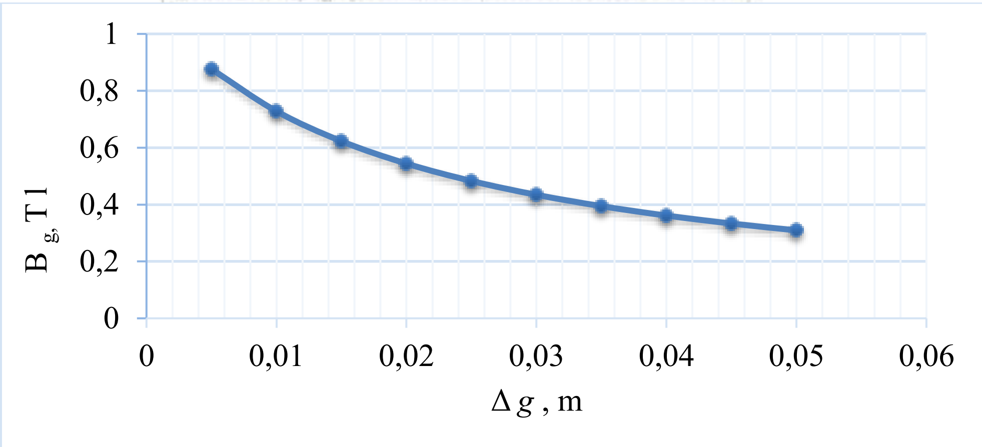
$$k_{sat} = 1 + \frac{l_{Fe}}{2\mu_r(g+0{,}5t_w)} \quad (3)$$

where: B_r −magnetic induction of the permanent magnet, Tl; h_M −height of the permanent magnets, m; ΔH −magnetic field strength of the permanent magnet, A/m; g −distance between the stator and the permanent magnet, m; t_w −thickness of the stator layer, m; l_{Fe} −length of the current path in the multilayer core, m; μ_r −relative magnetic permeability of the multilayer core.

The change in the magnetic field induction between two opposing permanent magnets placed on the vertical axis of the generator rotor depends on the induction of these permanent magnets, the magnetic field strength, and the distance between them. The expression for this relationship is is defined as follows [2]:

$$B_g = \frac{2B_r h_M}{2h_M+(2g+t_w)\cdot k_{sat}\mu_{rrec}} \qquad (4)$$

Figure 1 shows a graph of the dependence of the distance between the permanent magnets installed in the generator on the magnetic field induction. The smaller the distance between the permanent magnets, the greater the magnetic field induction value. However, the number and length of the generator stator windings are reduced. In this case, when designing the generator, its optimal parameters are determined and then manufactured.



2. Graph of the dependence of the distance between permanent magnets on the magnetic field induction

2 - in the picture two two rotor the generator stator and rotor between dependency of parameters The generator we are designing is arranged on a vertical axis and consists of a rotor and a stator made of permanent magnets.

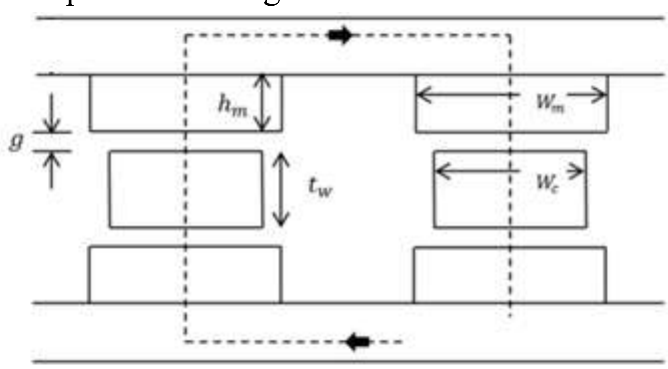


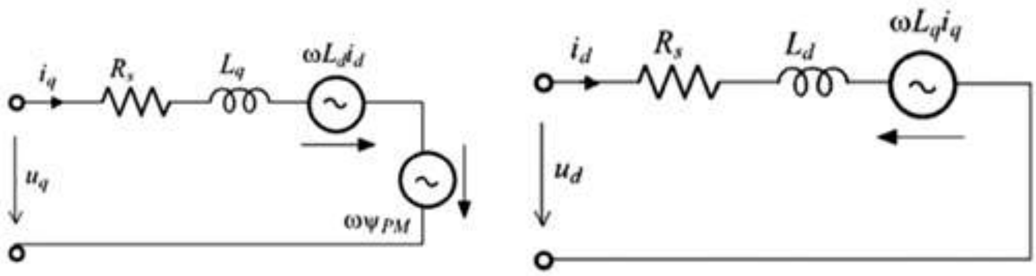
Figure 2. Two- rotor the generator stator and rotor between dependency of parameters to be determined

Energy in the sector mathematician Modeling, even of the simplest and most common devices, leads to significant cost savings and improved product quality. The more complex the designed object, the more important the role of modeling in its study and creation, as a rule.

The representation of any electrical machine, in any software package, begins with the formulation of equations describing that machine and the introduction of some assumptions to simplify the calculations.

Thus, characterizing processes and relating them to any coordinate system connected new coefficients through of the car The periodic coefficients of the differential equations of a synchronous machine, expressing the variables that describe its characteristics (current, current and voltage in each phase of a three-phase system) It is hard.

Vertical son permanent from magnets organization found generator dynamic model in modeling d and q son equivalent replacement pallet We use the generator. dynamic The model is shown in Figure 3. equations application with can be simplified.



a) b)

Figure 3. Generator equivalent scheme (a) q o' qi and (b) in d o ' qi

The equation for the voltage generated over time in the stator winding of synchronous generators consisting of permanent magnets [3]:

$$\begin{cases} U_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \\ U_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega\psi_{PM} \end{cases} \quad (5)$$

The calculation of the electromagnetic power obtained from a generator consisting of three-phase permanent magnets is determined from the expression below [4]:

$$P_e = \frac{3}{2}\omega[\psi_{PM} + (L_d - L_q)i_d]i_q (6)$$

Couple poles number r was generator electromechanical moment following expression through is defined as :

$$M_e = \frac{3}{2}p[\psi_{PM} + (L_d - L_q)i_d]i_q (7)$$

where : ψ_{PM}– magnetic flux, etc.

$$\psi_{PM} = \frac{\sqrt{2}E_f}{\omega} (8)$$

The electromagnetic speed of an electric generator when the stator and rotor rotate in opposite directions is determined by the following expression:

$$\omega = p(\omega_{m1} + \omega_{m2}) \quad (9)$$

where: p –the number of pairs of poles.

Generator dynamic in modeling inertia moment following from the expression is defined as :

$$J\frac{d\omega_m}{dt} = M_m - M_e - k\omega_m (10)$$

where : J −moment of inertia of the rotor mass kg ·m [2,] M_m and M_e generator mechanic and electromagnetic moments, Nm ·; k − coefficient of friction, ω_m − generator angle fast gi, rad/s.

Phase vines i_A, i_B, The relationships between the d and q in the i_q, i_d and are determined i_C by the following expressions:

$$\begin{cases} i_d = \frac{2}{3}[i_A\cos\omega t + i_B\cos(\omega t - \frac{2\pi}{3}) + i_C\cos(\omega t + \frac{2\pi}{3})] \\ i_q = -\frac{2}{3}[i_A\sin\omega t + i_B\sin(\omega t - \frac{2\pi}{3}) + i_C\sin(\omega t + \frac{2\pi}{3})] \end{cases} \quad (11)$$

Simplifying expression 11, we evaluate the relationship between the currents in each phase and i_q, i_d the currents in the axes, where $i_A + i_B + +i_C = \delta$ is equal to 0.

$$\begin{cases} i_A = i_d\cos\omega t - i_q\sin\omega t \\ i_B = i_d\cos\left(\omega t - \frac{2\pi}{3}\right) - i_q\sin\left(\omega t - \frac{2\pi}{3}\right) \\ i_C = i_d\cos\left(\omega t + \frac{2\pi}{3}\right) - i_q\sin\left(\omega t + \frac{2\pi}{3}\right) \end{cases} \quad (12)$$

The equations relating the voltages U d, U q on the shaft and the voltages U A, U B, U C in the stator winding are as follows:

$$\begin{cases} U_d = \frac{2}{3}[U_A\cos\omega t + U_B\cos(\omega t - \frac{2\pi}{3}) + U_C\cos(\omega t + \frac{2\pi}{3})] \\ U_q = -\frac{2}{3}[U_A\sin\omega t + U_B\sin(\omega t - \frac{2\pi}{3}) + U_C\sin(\omega t + \frac{2\pi}{3})] \end{cases} \quad (13)$$

The relationship between the voltages d in each phase of the generator and the voltages U d, U q on the axis is given in the following expressions.

$$\begin{cases} U_A = U_d\cos\omega t - U_q\sin\omega t \\ U_B = U_d\cos\left(\omega t - \frac{2\pi}{3}\right) - U_q\sin\left(\omega t - \frac{2\pi}{3}\right) \\ U_C = U_d\cos\left(\omega t + \frac{2\pi}{3}\right) - U_q\sin\left(\omega t + \frac{2\pi}{3}\right) \end{cases} \quad (14)$$

Stator Calculation of the inductance of the coil [92]:

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$$\begin{cases} L_d = m\mu_0\frac{1}{\pi}\cdot(\frac{Nk_w}{p})^2\cdot\frac{(R_1^2-R_2^2)}{g'}\cdot k_{fd} \\ L_q = m\mu_0\frac{1}{\pi}\cdot(\frac{Nk_w}{p})^2\cdot\frac{(R_1^2-R_2^2)}{g'_q}\cdot k_{fq} \end{cases} \quad (15)$$

in this :N − the number of rolls in one bundle ;R_1 − stator n ing outer diameter, m;R_2 − stator n ing internal diameter, m;p − number of pairs of poles; k_w −stator winding filling factor;m − phases number.

The equivalent air gap in the d and q axes for the surface configuration of permanent magnets is determined by the following expressions:

For stator coreless condition

$$\begin{cases} g' = 2[(g + 0{,}5t_w) \cdot k_{sat} + \frac{h_m}{\mu_{rrec}}] \\ g'_q = 2(g + 0{,}5t_w + h_m) \end{cases} \quad (16)$$

We assume the surface configuration of permanent magnets when d and q $\mu_{rrec} \approx 1$are equal. Then $k_{fq} = k_{fd} = 1$d and q in the arrows anchor reaction inductance following comes to a simplified expression:

$$L_d = L_q = m\mu_0 \frac{1}{\pi} \cdot (\frac{Nk_w}{p})^2 \cdot \frac{(R_1^2 - R_2^2)}{g'} (17)$$

Generator in the fields harvest to be E Y K following dependency with is defined [5]:

$$E_f = \sqrt{2}\pi f p N k_w F_f = \sqrt{2}\pi n N k_w B_g (R_1^2 - R_2^2) (18)$$

where: F_f −magnetic flux, Vb; B_g −magnetic induction, Tl; f −frequency, 1/s.

The active resistance generated in the stator winding is determined by the following relationship:

$$R = \rho \frac{L}{S} (19)$$

in this : ρ −relative resistance (for copper $1{,}75 \cdot 10^{-8}$ $om \cdot m$, L − length of the pipe, m ;S − Cross - sectional area of the wire, mm 2.

The operating current of an electric generator is determined by the following expression:

$$I = \frac{E}{\sqrt{R + (X_L - X_C)^2}} (20)$$

in this case : R −stator chul g' amining asset resistance, ohms; X_L va X_C −inductive and capacitive resistances of the stator winding, ohms.

On the generator harvest to be magnet field current permanent magnets to the dimensions and magnet field change in induction depends on the value It will be. expression following from the formula is defined as :

$$F_f = \frac{B_g}{p} (R_1^2 - R_2^2) (21)$$

The electromagnetic torque is as follows simplified expression through is defined as :

$$M_e = \frac{m}{\sqrt{2}} p N k_w F_f I (22)$$

Designed to the car relevant exit of power approximate value following equality using to be counted possible [6] :

$$P_e = \sqrt{3} E I \cos\varphi = M_m \omega_m \eta_g \quad (23)$$

above mathematical expressions, a mathematical model of a vertical axis wind turbine that operates effectively in variable and weak wind flows is created, based on the assessment of the potential of wind energy resources and the characteristics of the wind flow, and a wind turbine is manufactured based on this model. In Figure 4, the electric generator general appearance cited.

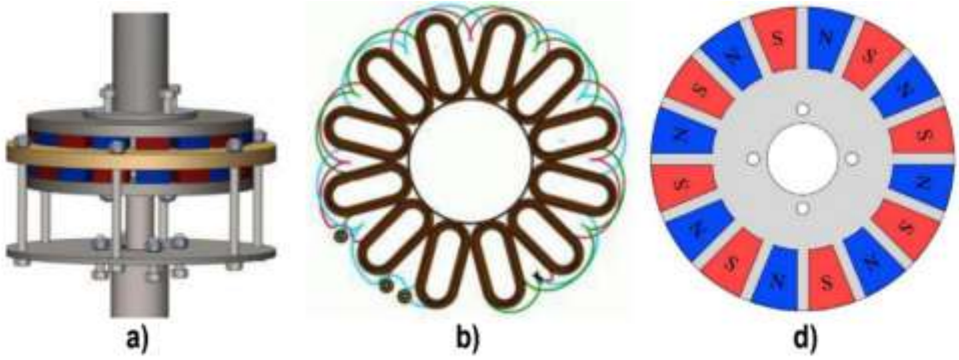

Figure 4. Magnetoelectric generator structure (a – electric generator general appearance ; b – anchor your uncle connection circuit ; d – electric generator inductor external appearance)

During the experimental testing of the electric generator, the expected results were achieved and no problems arose. After several measurements, the dependence of the rotation speed of the armature and inductor of the electric generator on the output voltage of the generator is shown in Figure 5. Figure 6 shows the volt-ampere characteristic of the electric generator.

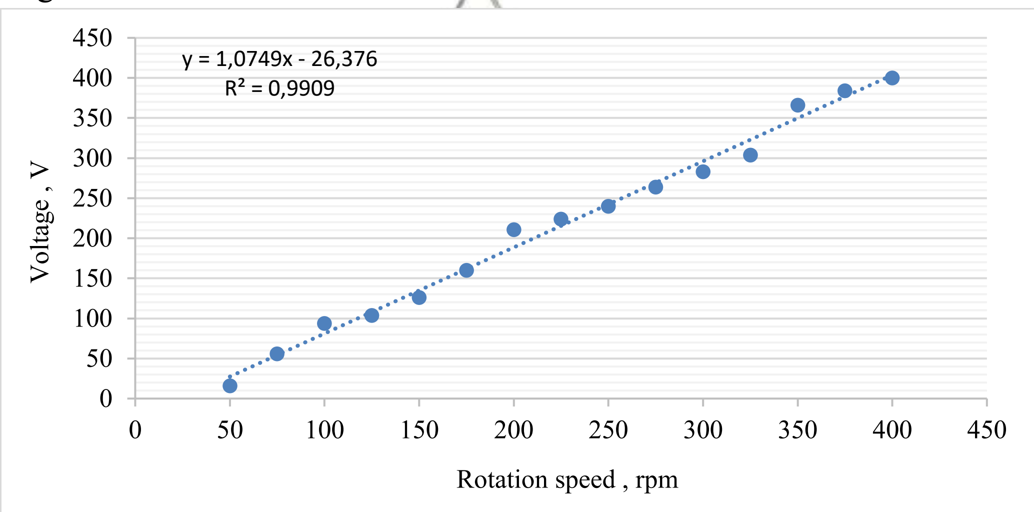

Fig. 5. The graph of the dependence of the rotation speed of the electric generator on the output voltage of the generator

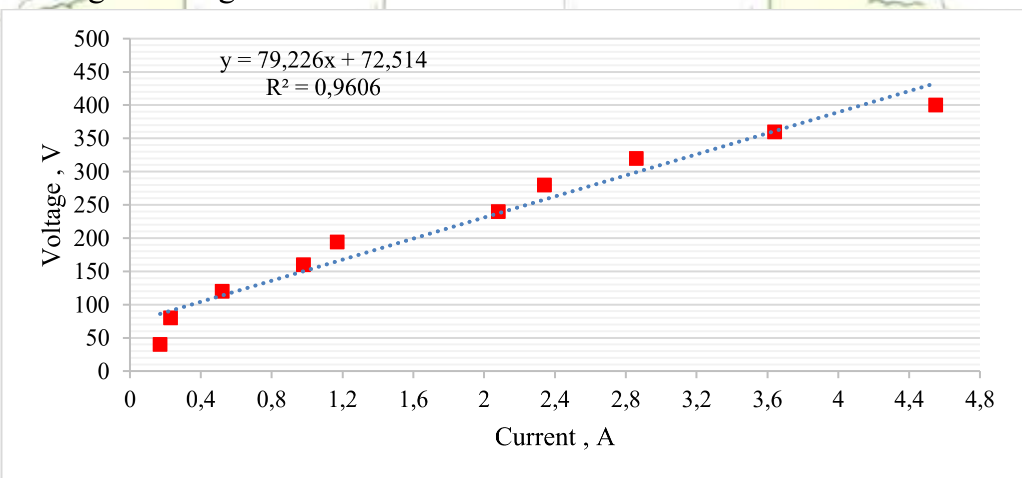

Fig. 6. Volt-ampere characteristic of the electric generator

The results presented in Figure 6 confirm the agreement between the measurement and calculation results. These results also lead to the conclusion that the results of applying the mathematical model are accurate and correct.

This article presents analytical expressions of the magnetoelectric axial generator. A mathematical model of a three-phase magnetoelectric axial generator was developed. Experiments were conducted based on the developed mathematical models for a generator operating under a symmetrical load. The mutual agreement of the measurement and calculation results proved the correctness of the models. It was found that the active power of the developed magnetoelectric generator can be increased to 1 kW. To increase this value, design improvements such as placing more permanent magnets and increasing the size of the inductor disks are required. However, at a rotation speed of 200 rpm, it can reach a maximum power of up to 4 kW in small-power wind power plants.

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