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# DIRECT DRIVE RELUCTANCE WIND GENERATOR

## TIEŠĀS PIEDZIŅAS RELAKTANCES VĒJA ĢENERATORIS

L. Ribickis, E.Kamolins, N. Levin, V. Pugachev

*Key words: wind generator, multipolarity, inductance*

### Introduction

The wind power engineering makes rapid strides towards higher reliability and better economical efficiency of the developed wind power plants (WPPs). In this connection it is wind generators that are of primary importance for updating the WPP [1]. These electric machines, which are used for conversion of the wind turbine's mechanical energy into the electric one, should possess a number of important design peculiarities. First, such a machine should be without sliding contacts, which means absence of a collector, brushes, and contact rings. The presence of the latter makes a machine less reliable and more expensive under operation, especially when a WPP is used in winter. Apart from raising the mass and sizes of the generator, sliding contacts increase its mechanical and electric losses. Second, it is advisable to make the wind generator directly-driven, i.e. without using rather unreliable in operation mechanical multipliers. At the same time, the directly-driven design of a wind generator calls for its multipolarity, since only a multipolar generator in its low-turn version can have limited mass and sizes [2]. Third, to achieve the multipolarity, high reliability and low cost of production, it is important that the electric machine does not contain permanent magnets in the excitation system. Fourth, to improve the reliability it is necessary to minimize the number of windings, with the excitation winding also excluded.

In this context, an optimal electric machine meeting the above mentioned requirements is the reluctance one [2-5]. Its design has no excitation windings, whereas the principle of its operation is based on a deep change in the inductance (reluctance) of the armature windings' phases at the rotation of a non-wound rotor. Depending on the specifics of the design arrangement of a reluctance generator and its operating conditions a definite efficiency can be achieved, and, therefore, its possibilities of being used in the WPPs of different capacity.

Now we will consider and estimate these possibilities.

### 1. Operation of reluctance generator to a high-power network

Figure 1 shows the design of a reluctance generator with a three-phase armature winding consisting of six coils and a four-tooth non-wound rotor. The generator is connected to a high-power network. The differential equations of voltages and EMFs for a generator of the presented design are:

$$u_A = i_A R_a + \frac{d\psi_A}{dt}; u_B = i_B R_a + \frac{d\psi_B}{dt}; u_C = i_C R_a + \frac{d\psi_C}{dt}, \quad (1)$$

where  $u_A, u_B, u_C$  are the voltages of network phases;

$i_A, i_B, i_C$  are the phase currents;

$R_a$  is the active resistance of armature windings' phases;

$\psi_A, \psi_B, \psi_C$  are the magnetic-flux linkages of the phases of windings and armature.

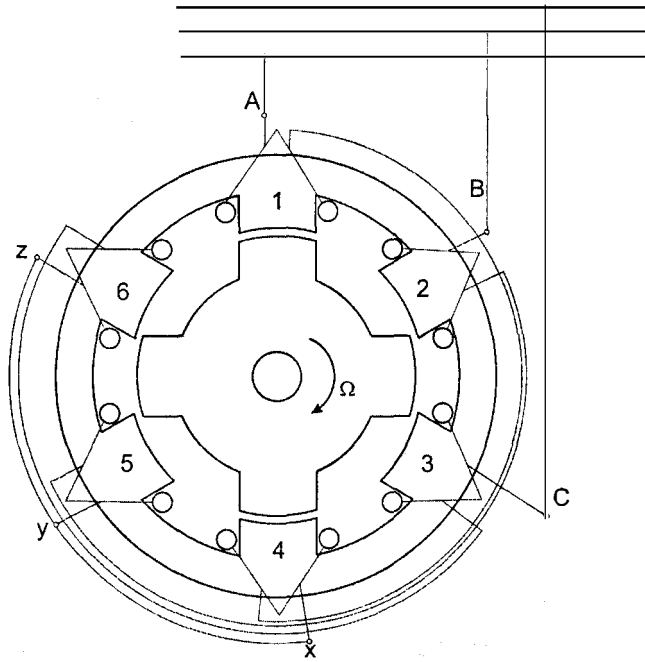


Figure 1. Schematic design of a three-phase reluctance generator connected to the network: A, B, C - windings of stator; 1-6 - stator's teeth

We will represent the variable magnetic permeances of the air gaps between a stator's tooth and a running rotor's tooth by two first terms of Fourier's series considering that the remaining terms of the series are small and can be neglected, that is, in the form:

$$\begin{aligned} \lambda_1 = \lambda_4 &= a_0 + a_1 \cos(Z_R \Omega t - \varphi_R); \\ \lambda_2 = \lambda_5 &= a_0 + a_1 \cos(Z_R \Omega t - 240^\circ - \varphi_R); \\ \lambda_3 = \lambda_6 &= a_0 + a_1 \cos(Z_R \Omega t - 120^\circ - \varphi_R), \end{aligned} \quad (2)$$

where  $\Omega$  is the rotor's angular rotational velocity;

$Z_R$  is the number of rotor's teeth;

$\varphi_R$  is the phase angle.

For the magnetic-flux linkages of phases the following equalities are valid:

$$\psi_A = 2W_k^2 i \lambda_1; \quad \psi_B = 2W_k^2 i_B \lambda_2; \quad \psi_C = 2W_k^2 i_C \lambda_3. \quad (3)$$

Then, if we consider the phase currents varying by the harmonic law as

$$i_A = I_m \cos(\omega t - \varphi_i); \quad i_B = I_m \cos(\omega t - 120^\circ - \varphi_i); \quad i_C = I_m \cos(\omega t - 240^\circ - \varphi_i), \quad (4)$$

then, taking into account (2), the expressions for magnetic-flux linkages of phases assume the form:

$$\begin{aligned}
\psi_A &= 2W_k^2 I_m [a_o + a_1 \cos(Z_R \Omega t - \varphi_R)] \cos(\omega t - \varphi_i); \\
\psi_B &= 2W_k^2 I_m [a_o + a_1 \cos(Z_R \Omega t - 240^\circ - \varphi_R)] \cos(\omega t - 120^\circ - \varphi_i); \\
\psi_C &= 2W_k^2 I_m [a_o + a_1 \cos(Z_R \Omega t - 120^\circ - \varphi_R)] \cos(\omega t - 240^\circ - \varphi_i),
\end{aligned} \tag{5}$$

where  $\varphi_i$  is the current phase angle.

In equations (3-5),  $W_k$  is the number of turns in a coil embracing a stator's tooth;  $\omega$  is the angular current frequency of the supplying network.

Transformation of expressions (5), if we present the angle cosine products as a half of the sum of the angle sum and difference cosines, gives the resultant expression:

$$\begin{aligned}
\psi_A &= 2W_k^2 a_o I_m \cos(\omega t - \varphi_i) + W_k^2 a_1 I_m \cos(Z_R \Omega t - \omega t + \varphi_i - \varphi_R) + \\
&+ W_k^2 a_1 I_m \cos(Z_R \Omega t + \omega t - \varphi_i - \varphi_R); \\
\psi_B &= 2W_k^2 a_o I_m \cos(\omega t - 120^\circ - \varphi_i) + W_k^2 a_1 I_m \cos(Z_R \Omega t - \omega t - 120^\circ + \varphi_i - \varphi_R) + \\
&+ W_k^2 a_1 I_m \cos(Z_R \Omega t + \omega t - \varphi_i - \varphi_R); \\
\psi_C &= 2W_k^2 a_o I_m \cos(\omega t - 240^\circ - \varphi_i) + W_k^2 a_1 I_m \cos(Z_R \Omega t - \omega t - 240^\circ + \varphi_i - \varphi_R) + \\
&+ W_k^2 a_1 I_m \cos(Z_R \Omega t + \omega t - \varphi_i - \varphi_R).
\end{aligned} \tag{6}$$

Differentiation of the expressions obtained makes it possible to define the electromotive forces, i.e.

$$\begin{aligned}
e_A &= -\frac{d\psi_A}{dt} = 2W_k^2 \omega a_o I_m \sin(\omega t - \varphi_i) + \\
&+ W_k^2 (Z_R \Omega - \omega) a_1 I_m \sin(Z_R \Omega t - \omega t + \varphi_i - \varphi_R) + \\
&+ W_k^2 (Z_R \Omega + \omega) a_1 I_m \sin(Z_R \Omega t + \omega t - \varphi_i - \varphi_R); \\
e_B &= -\frac{d\psi_B}{dt} = 2W_k^2 \omega a_o I_m \sin(\omega t - 120^\circ - \varphi_i) + \\
&+ W_k^2 (Z_R \Omega - \omega) a_1 I_m \sin(Z_R \Omega t - \omega t - 120^\circ + \varphi_i - \varphi_R) + \\
&+ W_k^2 (Z_R \Omega + \omega) a_1 I_m \sin(Z_R \Omega t + \omega t - \varphi_i - \varphi_R); \\
e_C &= -\frac{d\psi_C}{dt} = 2W_k^2 \omega a_o I_m \sin(\omega t - 240^\circ - \varphi_i) + \\
&+ W_k^2 (Z_R \Omega - \omega) a_1 I_m \sin(Z_R \Omega t - \omega t - 240^\circ + \varphi_i - \varphi_R) + \\
&+ W_k^2 (Z_R \Omega + \omega) a_1 I_m \sin(Z_R \Omega t + \omega t - \varphi_i - \varphi_R).
\end{aligned} \tag{7}$$

The first terms in equation (7) express the self-induction EMFs due to a constant component of the permeances of stator teeth relative to those of rotor teeth. The third terms present the EMFs induced at rotor running. However, their influence can be ignored since they have no phase shift and, consequently, do not manifest themselves in the three-phase system "network-generator".

The main generating factor is the EMFs represented by the second terms of equations (7). However they play a positive role in the achievement of normal operation of the generator-network system only in the case when the generated frequency is equal to the frequency of "network", i.e.

$$Z_R \Omega - \omega = \omega. \tag{8}$$

This occurs at the rotor's angular rotational velocity expressed as

$$\Omega = \frac{2\omega}{Z_R}, \quad (9)$$

that is, if it is twice as large as compared with the synchronous one, i.e.

$$n = \frac{120f_1}{Z_R}, \quad (10)$$

where  $f_1 = \frac{\omega_1}{2\pi}$  is the synchronous rotational speed.

If condition (10) is satisfied, equations (1) of the generator, as, for example, for the linear voltage  $U_{AB}$ , are slightly modified:

$$u_{AB} = u_A - u_B = R_a(i_A - i_B) + 2W_k^2 \omega \alpha_o I_m [\sin(\omega t - \varphi_1) - \sin(\omega t - 120^\circ - \varphi_1)] + W_k^2 \omega \alpha_1 I_m [\sin(\omega t + \varphi_i - \varphi_R) - \sin(\omega t - 120^\circ + \varphi_i - \varphi_R)] \quad (11)$$

which in a complex form is written as

$$\dot{U}_1 = \dot{I}_1 \dot{R}_a + j \dot{X}_a \dot{I}_1 + j \dot{X}_m \dot{I}_1 e^{j(\varphi_i - \varphi_R)}, \quad (12)$$

where  $\dot{U}_1, \dot{I}_1$  are the linear voltage and current;  $X_a$  is the armature reactance;  $X_m$  is the resistance determining the generation of energy into the network.

The remaining equations (for other linear voltages) are written in a similar manner.

From the analysis of the results obtained one can draw two important inferences. First, in the absence of biasing from the invariable component of armature current the generator can normally function only at the frequency that is twice as large as the synchronous one. Second, the value of induced EMF corresponding to the current frequency in the network is half that for the generator of similar design but with MMF excitation of stator teeth due to direct current.

In view of the mentioned above it can be concluded that, owing to a low EMF induced, it is not recommended to use the reluctance generator in the mode of MMF excitation of stator teeth with alternating current. For the efficiency improvement it is necessary to introduce a biasing factor [3, 5].

### 3. Reluctance generator with biasing

As was shown above, the reluctance generator is inefficient when excited by the alternating current of the armature winding. We will therefore turn our attention to the design in which through the armature winding, along with a.c. current, also the d.c. biasing current flows. Figure 2 shows this design for a generator having four pole horns (1-4) with small teeth on which of them. Rotor (5) is also made with similar small teeth. Further in the text the term "pole horn" stands for the stator' part confined on both sides by slots with the armature winding.

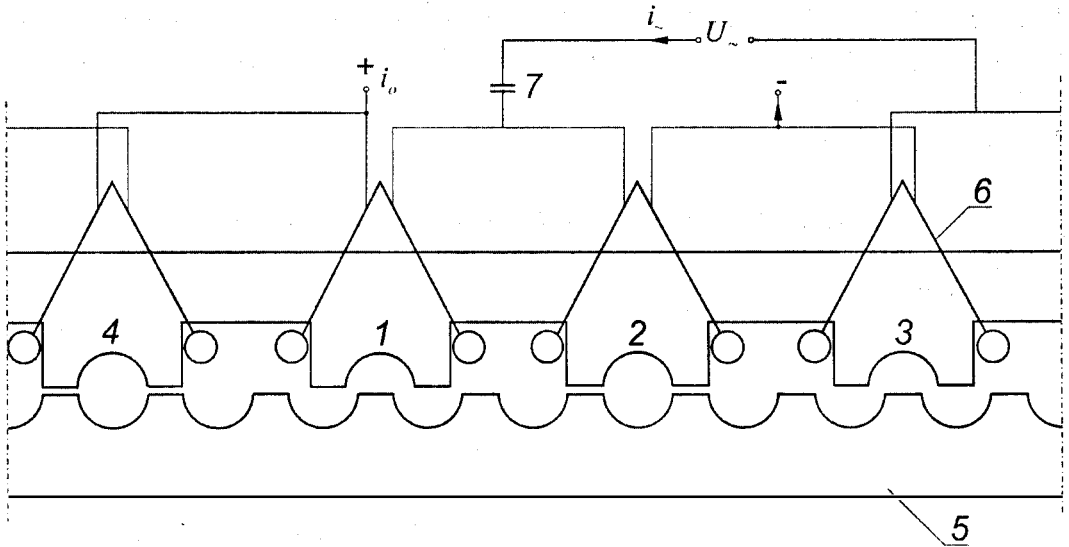


Figure 2. Schematic design of a reluctance generator with biasing: 1-4 - pole horns; 5 - tooth rotor; 6 - coils; 7 - capacitor

The peculiarity of the proposed design is the identical arrangement of opposite pole horns with respect to the rotor's teeth. Here the neighbouring pole horns are mutually shifted in phase by a half of the rotor's tooth division (180 electrical degrees). Coils 6 arranged on the pole horns are connected into a bridge, to one of the diagonals of which a d.c. biasing source is connected, while to the other - through capacitor 7 - the load resistance.

The presented design is described by the equation:

$$-u = i_- R_a + u_c + 2 \frac{d\psi_k}{dt}, \quad (13)$$

where  $u$  is the voltage across the load;

$i_-$  is the alternating current of the load;

$u_c$  is the voltage across the compensating capacitor;

$2\psi_k$  is the magnetic-flux linkage of two series-connected coils.

The value of the magnetic-flux linkage of two series-connected coils in the a.c. branch is:

$$\begin{aligned} 2\psi_k &= W_k (\Phi_1 + \Phi_2) = W_k (F_1 \lambda_1 + F_2 \lambda_2) = W_k^2 [0,5(i_- - i_o) \lambda_1 + 0,5(i_- + i_o) \lambda_2] = \\ &= 0,5W_k^2 (2a_o i_- + 2i_o a_1 \cos(Z_R \Omega)) = W_k^2 a_o i_- + W_k^2 i_o a_1 \cos(Z_R \Omega). \end{aligned} \quad (14)$$

The first term of expression (14) further determines the voltage fall across the inductive resistance of armature reaction due to the invariable component of the permeance of the stator's pole horn. The second term determines the EMF caused by the variable component of the permeance of the stator's pole horn.

In this case the capacitor capacity is chosen in a manner allowing the mentioned voltage fall across the armature reactance to be compensated. Then, in a complex form of notation, equation (13) is presented as

$$\dot{U} = 2\dot{E}_o - \dot{I}_- R_a, \quad (15)$$

where  $2E_o = W_k^2 a_1 I_o$  are the EMFs of two series-connected coils due to the variable permeance component ( $a_1$ ) of the pole horn excited by direct current equal to  $0.5I_o$ .

#### 4. Results of the experimental studies

Figure 3 shows an experimental model of the generator for which a third of one core (two in total) of a three-phase axial inductor machine is used. Each core contained 12 pole horns, and on the rotor 46 teeth were arranged.

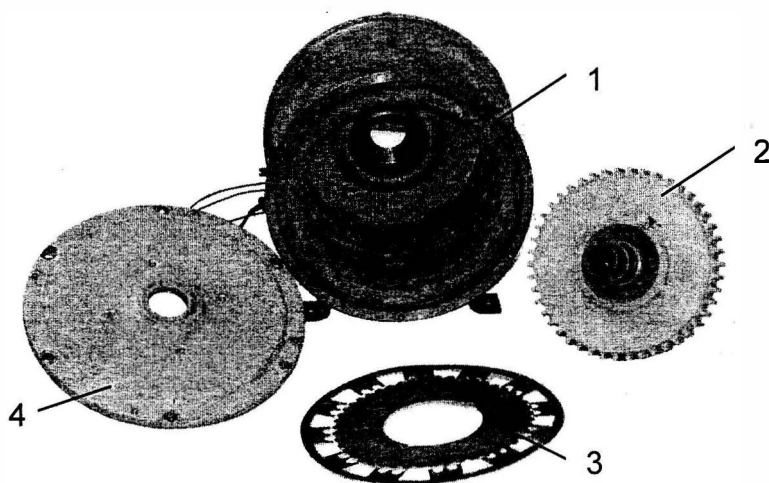


Figure 3. An experimental model of the generator: 1 – stator; 2 – rotor; 3 – plates of stator and rotor; 4 – shield

The tests were carried out at the rotational speed  $n = 700 \text{ min}^{-1}$ . In the inductor machine's mode each core consisting of 12 coils gave a power of  $360 \text{ W}$ . In the operating condition of the reluctance generator – a power  $399 \text{ W}$ . At the mentioned rotational speed the positive balance (minus the losses for excitation): inductor generator –  $330 \text{ W}$ ; reluctance generator –  $309 \text{ W}$ . Therefore, taking into account a considerable mass reduction at the one-core version and with exclusion of the heavy body and bush, the reluctance generator compares well in mass and sizes with the inductor machine, whereas in the reliability and design simplicity it by far outperforms the latter.

#### Conclusions

The results of tests carried out in order to check the serviceability and performance of the wind generator for low-power WPPs based on the reluctance electric machine have shown that the proposed version possesses simpler design, higher reliability and lower cost of production; operational expenses are also reduced. This is achieved owing to the absence of windings and magnets on the running rotor, exclusion of a heavy ferromagnetic body and of a bush, a smaller number of windings and the possibility to make rotors with a large number of teeth, each tooth determining a pair of poles. All this has resulted in its multipolarity, low

rotational speed, and, therefore, the possibility of its tie-in with the wind turbine without using a multiplier.

A reluctance generator, along with much simpler design, its higher reliability and being easier repairable at the same time, possesses mass-size indices that are by far better than those of the inductor machine.

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**Leonid Ribickis**, Prof. Dr. hab. Sc. Ing.  
Riga Technical University, Industrial Electronics and Electrical Engineering  
Address: Kalku street 1. LV-1050, Riga, Latvia  
Phone: +371-7089415  
e-mail: [Leonids.Ribickis@rtu.lv](mailto:Leonids.Ribickis@rtu.lv)

**Edmunds Kamolins**, Doctoral student, M. Sc. Ing.  
Riga Technical University, Faculty of Power and Electrical Engineering  
Address: Kronvalda boulevard 1. LV-1030, Riga, Latvia  
Phone: +371-7568607, Fax: +371+7568605  
e-mail: [edmunds@tuv-lrtdea.lv](mailto:edmunds@tuv-lrtdea.lv)

**Nikolaj Levin**, Prof. Dr. hab. Sc. Ing.  
Latvian Academy of Sciences, Institute of Physical Energetics  
Address: Aizkraukles street 21, LV-1006, Riga, Latvia  
Phone: +371-7558634, Fax: +371-7550839  
e-mail: [magneton@edi.lv](mailto:magneton@edi.lv)