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Contactless Multipolar Doubly-Fed Asynchronous Generator For Windmills

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Summary: **A multipolar contactless doubly-fed asynchronous generator is considered where the primary and secondary generation windings are arranged on the teeth of the stator, while the rotor is tooth-like and without windings. Analytical treatment of such a generator has been performed and the basic equations that allow the parameters and performance of the machine to be calculated in generation mode of operation have been obtained. The results of experimental investigations are presented for the physical model of the generator and comparison with the calculation data is given.**

Key words:
doubly-fed,
multipole,
asynchronous generator,
contactless,
teeth-zone,
module

1. INTRODUCTION

In the modern electrical engineering asynchronous generators are widely employed as energy sources for windmills. They are simple in design, posses a high specific power, reliable and require little expenses on their making and maintenance. At the same time, asynchronous machines with a high rotational speed are used in combination with mechanical multipliers. However, the use of multipliers makes the running of these machines much more complicate and expensive, especially in certain climatic zones, where abrupt temperature changes, together with dust, sand and active chemical substances presence in the air, may frequently occur.

During the last years doubly-fed induction generators got wide application for increasing of the factor of wind power using. Such generator is an asynchronous machine with brush gear. The primary winding as usual is connected directly to the three-phase network, but the secondary one which is placed on the rotor is connected through the brush gear and semiconductor converter of frequency [1]. The use of doubly-fed induction generators allows widening the range of operation rotation frequencies and significant increasing of the factor of wind power using at the changes of its speed. But the presence of brushes and contact rings complicates the construction of the generator and the windmill, decrease its reliability and increase the expenses for maintaining.

In the work design circuits of multipole asynchronous machines are considered in which the number of pole pair can reach 100 and more. Both the multiphase in such machines — the primary and the secondary — are mutually immovable and are arranged on the stator. The rotor is tooth-like, winding free and consequently contactless. Each tooth determines the pole pair of the machine and they are directly driven from the wind turbine [2–6].

2. DESIGN FEATURES OF THE MULTIPOLE AYNCHRONOUS GENERATOR

The basis for the multipole asynchronous generator is the design circuit of an inductor-type synchronous electric machine. In such machines the excitation winding fed with direct current is arranged, like the armature winding, on the stator. In multipole asynchronous generators the excitation winding arranged on the stator is multi-phase and is fed with alternative current.

A multipole asynchronous generator can be presented consisting of several modules (elementary homophase machines) arranged uniformly in its recess. Every module presents a tooth—like stator's segment embraced by the coil of one phase connected to the circuit of the primary winding and a corresponding segment of the winding-free tooth-like rotor bordering with the former through an air gap, with each tooth of the rotor determining as usual one pole pair of the machine. On the stator's teeth of each module there are coils of all phases of the multiphase secondary windings, which in analogy with a conventional asynchronous machine, can be either short-circuit or connected to capacitors and loads. Since the coil pitch of one phase of the primary winding does not depend on the number of pole pair (of the rotor's teeth) in such a machine there are absent prerequisites to any rise in

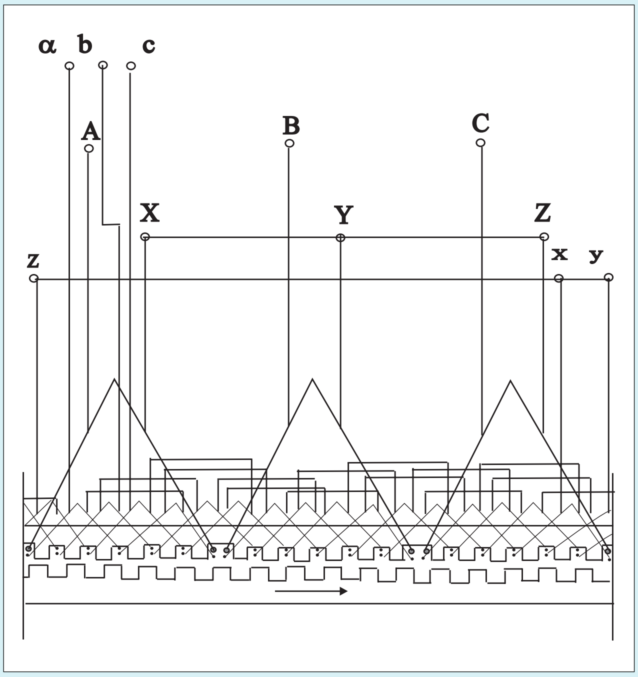

Fig.1. The teeth-zone and connection of the circuits of asynchronous generator

the magnetization power and losses in the primary winding with increasing the number of poles. Figure 1 demonstrates one of the ways of scanning the teeth zone and the connection circuit for a three-phase asynchronous generator's windings.

The stator consists of three modules, each of them embraced with the coil of one phase of a three-phase ($m_1 = 3$) primary winding, A-X, B-Y and C-Z. In the limits of every module there are six stator's teeth on which a three-phase ($m_2 = 3$) secondary winding — a-x, b-y and c-z — is arranged, with the coils of the secondary winding each embracing three teeth. To provide the electromagnetic links required for an asynchronous machine, the tooth pitch of the stator, in one module's limit, is chosen $t_1 = \frac{2m_2 - 1}{2m_2} t_z$, where t_z is the teeth division of the rotor.

The necessary phase shift between the adjacent modules (120 or 240 electrical degrees) is created raising the pitch t_2 of adjacent modules by $t_z/3$ or $2t_z/3$. In the machine under consideration $t_2 = \frac{7t_z}{6}$. Taking into account all mentioned above the total number of the stator teeth is $Z_S = 2m_1m_2 = 2 \times 3 \times 3 = 18$. On the winding-free rotor there are $Z_R = 16$ teeth (pole pair of the machine). In the general case, to increase the number of the pole pair one can multiply the number of above considered elementary three-phase machines in a stator's recess or, alternatively, a comb-like structure of the tooth-zone is employed [5].

3. THE MAIN EQUATIONS OF A MULTIPOLE ASYNCHRONOUS GENERATOR

Under assumptions usually made when analyzing electric machines the equations written for the considered electric generator are as follow [5]:

$$u_A = R_1 i_A + \frac{d\Psi_A}{dt}; u_B = R_1 i_B + \frac{d\Psi_B}{dt}; u_C = R_1 i_C + \frac{d\Psi_C}{dt};$$

$$-u_a = R_2 i_a + \frac{d\Psi_a}{dt}; -u_b = R_2 i_b + \frac{d\Psi_b}{dt}; -u_c = R_2 i_c + \frac{d\Psi_c}{dt} \tag{1}$$

Here we have:

R_1, R_2 — active resistances of the winding,

$u_A, u_B, u_C, i_a, i_b, i_c, \Psi_A, \Psi_B, \Psi_C, \Psi_a, \Psi_b, \Psi_c$ — the applied voltages, currents and magnetic flux linkages of the windings;

u_a, u_b, u_c — the voltage drops across the capacitors connected to the circuit of the secondary winding and the load connected to the secondary.

The flux linkages of the coil's turns could be as follows:

$$\Psi_{A(B,C)} = w_1 \sum_{k=1}^{Z_s} \pm\Phi_k; \Psi_{a(b,c)} = w_2 \sum_{k=1}^{Z_s} \pm\Phi_k \tag{2}$$

where:

w_1, w_2 — number of coil's turns in the primary and secondary windings;

Φ_k — magnetic flux of the stator's *k*–tooth.

The signs + or – before the flux sign correspond to direct or reverse connection of a coil in the winding phase.

The magnetic flux of the stator's *k*–tooth could be defined as follows:

$$\Phi_k = \lambda_k F_k \tag{3}$$

where:

λ_k — magnetic conductivities of the stator's *k*–tooth;

F_k — *mmf*s acting upon stator's *k*–tooth.

The *mmf*s acting upon each of Z_s=18 teeth of the stator could be defined as follow (Eq. 4):

$$F_1 = w_1 i_A + w_2(i_a + i_b - i_c); F_{10} = w_1 i_B + w_2(-i_a - i_b + i_c);$$

$$F_2 = w_1 i_A + w_2(i_a - i_b - i_c); F_{11} = w_1 i_B + w_2(-i_a + i_b + i_c);$$

$$F_3 = w_1 i_A + w_2(i_a - i_b + i_c); F_{12} = w_1 i_B + w_2(-i_a + i_b - i_c);$$

$$F_4 = w_1 i_A + w_2(-i_a - i_b + i_c); F_{13} = w_1 i_C + w_2(i_a + i_b - i_c);$$

$$F_5 = w_1 i_A + w_2(-i_a + i_b + i_c); F_{14} = w_1 i_C + w_2(i_a - i_b - i_c);$$

$$F_6 = w_1 i_A + w_2(-i_a + i_b - i_c); F_{15} = w_1 i_C + w_2(i_a - i_b + i_c);$$

$$F_7 = w_1 i_B + w_2(i_a + i_b - i_c); F_{16} = w_1 i_C + w_2(-i_a - i_b + i_c);$$

$$F_8 = w_1 i_B + w_2(i_a - i_b - i_c); F_{17} = w_1 i_C + w_2(-i_a + i_b + i_c);$$

$$F_9 = w_1 i_B + w_2(i_a - i_b + i_c); F_{18} = w_1 i_C + w_2(-i_a + i_b - i_c)$$

At the stator's tooth width equal to $\frac{t_Z}{3}$ and that of rotor's tooth — $\frac{2t_Z}{5}$ the magnetic conductivity of the stator's tooth, which varies according to the periodic law with due consideration for the slot and front leakages of the coils, can be presented by the following two terms of the Fourier series:

$$\lambda_k = a_0 + a_1 \cos(z_R a - \gamma_k) \tag{5}$$

where a_0 and a_1 are the constant components and the first harmonic of the expansion of the conductivity curve, respectively, α is the turn angle of the rotor and γ is the initial phase angle. For the considered design circuit of the machine the conductivity λ_k consists of the elements:

$$\begin{aligned} \lambda_k &= a_0 + a_1 \cos\left[z_R\alpha - 300(k-1)\right] && at 1 \le k \le 6 \\ \lambda_k &= a_0 + a_1 \cos\left[z_R\alpha - 300(k-1) - 120^\circ\right] && at 7 \le k \le 12 \\ \lambda_k &= a_0 + a_1 \cos\left[z_R\alpha - 300(k-1) - 240^\circ\right] && at 13 \le k \le 18 \end{aligned} \tag{6}$$

Solving jointly the set of expressions (1-6) and reducing the results to the A,B,C coordinate system, one can obtain the final form of the equations for the primary and secondary windings as a complex description of an asynchronous machine operating in the symmetrical mode:

$$\begin{gathered} \dot{U}_1 = -\dot{E}_1 + (R_1 + jX_1)\dot{I}_1 \\ \dot{E}_2' = \left(\frac{R_2}{s} + jX_2' - j\frac{X_{ck}''}{s^2}\right)\dot{I}_2' + \frac{R_L'}{s}\dot{I}_2' \\ \dot{I}_{0\mu} = \dot{I}_1 + \dot{I}_2' \end{gathered} \tag{7}$$

Here $\dot{E}'_2 = \dot{E}_1 = -j12\pi f_1 w_1^2 a_1 \dot{I}_{0\mu}$ are the *emf*s of the winding arising due to the flux of mutual induction (with the secondary *emf* $\dot{E}'_2$ reduced to the primary circuit);

$\dot{I}_{0\mu}, \dot{I}_1, \dot{I}'_2$ are the currents: magnetizing, primary and secondary reduced to the primary circuit, respectively;

$R'_2 = R_2 \dfrac{w_1^2}{w_2^2}$ is the active resistance of the secondary winding reduced to the primary circuit;

R'_L is the active resistance of the effective load on the secondary winding reduced to the primary circuit;

$X_1 = 12\pi f_1 w_1^2 (a_0 - a_1)$; $X'_2 = 12\pi f_1 w_1^2 (4a_0 - a_1)$ are the resistances of flux dissipation of the primary and reduced secondary circuits at the main frequency f_1;

$X'_{ck} = \dfrac{w_1^2}{2\pi f_1 C_2 w_2^2}$ is the resistance of the compensating capacitor reduced to the primary circuit;

$s = \dfrac{\omega_1 - Z_R \omega_2}{\omega_1}$ is the slip;

$\omega_1 = 2\pi f_1$ is the angular frequency of the primary circuit;

ω_2 is the angular rotation speed of the rotor. In the optimum generation mode of operation $\omega_2 \approx \dfrac{2\omega_1}{Z_R}$ and, consequently, $s_N \approx -1$.

It should be noted that the equations obtained coincide in the form with the similar equations for a conventional asynchronous machine with the secondary windings on the rotating rotor, therefore the generator under consideration can be represented by the known electric equivalent circuits [4]. Based on these circuits, the steel losses can be taken into account introducing the complex resistance of the magnetizing loop.

4. THE SCHEME OF THE GENERATOR CONNECTION TO THE NETWORK

Figure 2 demonstrates the scheme of the connection of doubly-fed generator 1 to network 2. Primary winding 3 here is directly connected to the supplying source, but secondary winding 4 in connected through semiconductor converter 5. The latter consists of rectifier 6 and grid-controlled inverter 7. Rotor of the multipole generator, which has a low rotation frequency, is directly connected to the wind turbine 8. Sometimes semiconductor converter could be absent. Then secondary winding 4 is turned to the receivers of the electric energy through the compensating capacitors 9 only. Such receivers could be the heating devices which do not require energy of high quality. Capacitors 9 are necessary for power factor increasing. Their values are defined from the resonance conditions in the secondary circuit for Γ–type substitution scheme:

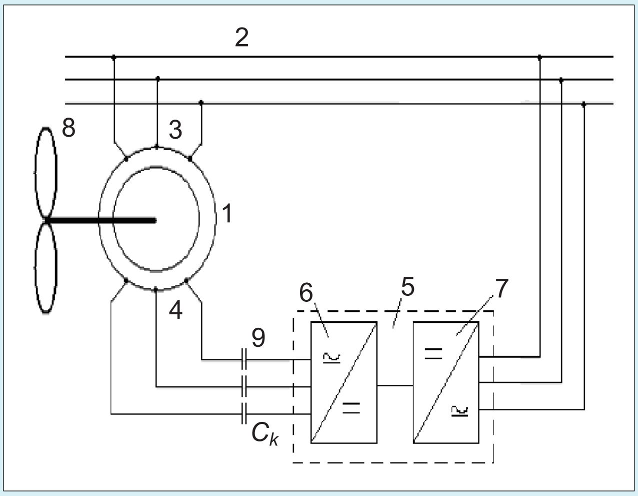

Fig. 2. Scheme of the generator's connection to the network

$$C_2 = \frac{w_1^2}{2\pi f_1 w_2^2 \left(\dfrac{x_1}{a_0} a_1 + x'_2 \right) s_N^2} \tag{8}$$

The primary winding thus receives the energy the power of which is:

$$P_1 = 3U_1 I_1 \cos\varphi_1 \tag{9}$$

here U_1, I_1 and $\cos\varphi_1$ are respectively the voltage, current and power factor. The currents of slipping frequency $f_2 = f_1 s$ in the secondary circuit I_2 determine the power of the second channel:

$$P_2 = 3I_2^2 R_L \tag{10}$$

5. RESULTS OF THE EXPERIMENTS

The design of a test specimen (a 32-pole machine is shown in Figure 1). In Figure 3 the main elements of the test specimen are presented. The normal values, main sizes and other parameters are the following:

Phase voltage U_1	127V
Current frequency in the primary circuit f_1	50Hz
Phase number of the primary winding m_1	3
Phase number of the secondary winding m_2	3
Number of pole pairs (rotor's teeth) $p = Z_R$	16
Diameter of the stator's recess	0.153 m
Length of the stator's core	0.100 m
Air gap	0.0004 m
Rated rotational speed n_N	366RPM
Rated slip s_N	0.95
Generator's weight G	18.6 kg

The experimentally obtained curves of powers $P_2 = P_{21} + P_{22}$ versus the rotational speed n are presented in Figure 4 for the generation mode of a machine. The compensating capacity is $C_2 = 12\ \mu F$ and load resistance $R_L = 27\Omega$. P_{21} is the power referred to the first channel of power generation (from the primary winding side to the

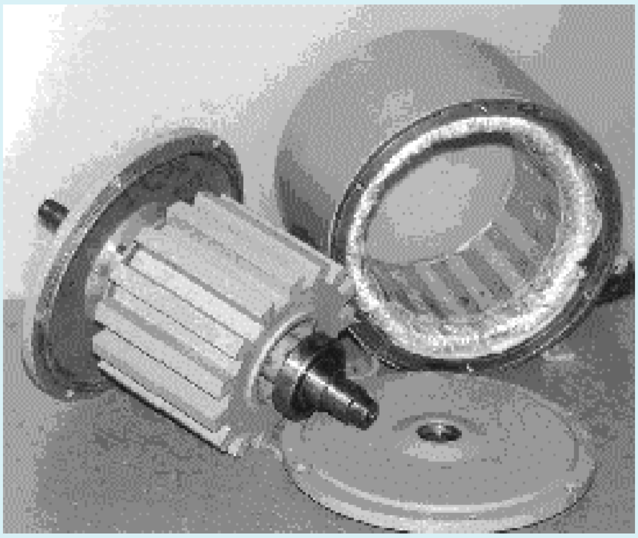

Fig. 3. The main elements of the test specimen of an asynchronous machine

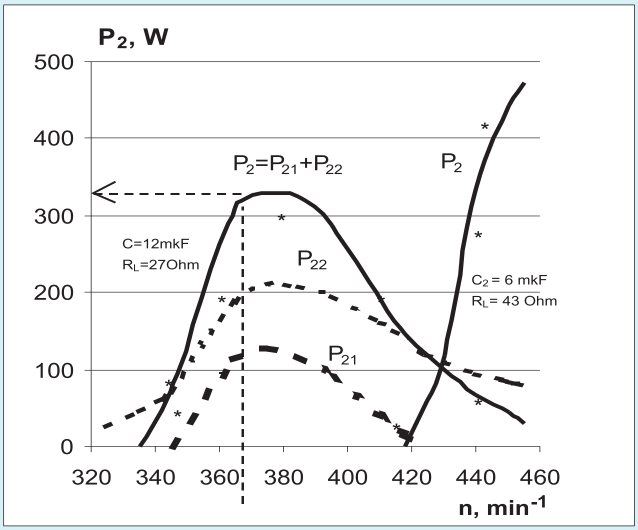

Fig. 4. Curves: $P_2 = P_{21} + P_{22}$ vs the rotational speed for compensating capacity $C_2 = 12$ μF and load resistance $R_L = 27\Omega$; $P_2 = f(n)$ for compensating capacity $C_2 = 6$ μF and load resistance $R_L = 42$ Ω. *** — experimental results

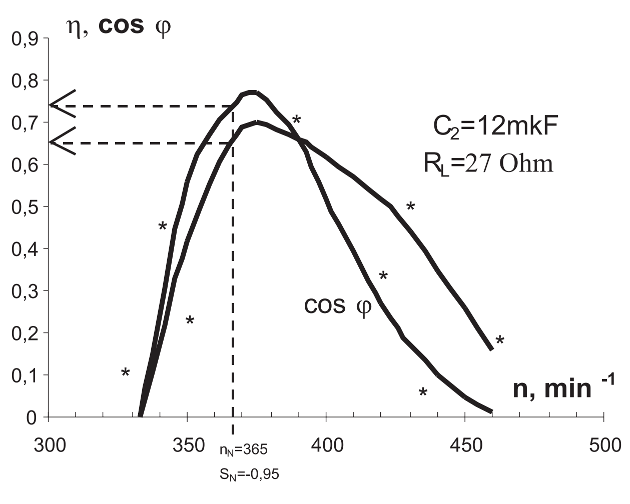

Fig. 5. Efficiency and cosφ vs rotational speed for compensating capacity $C_2 = 12$ μF and load resistance $R_L = 27\Omega$

network), P_{22} is the power referred to the second channel of power generation (from the secondary winding side to the load R_L). With *** the experimental point are marked. In the same figure the dependence $P_2 = f(n)$ is presented for the compensating capacity $C_2 = 6$ μF and load resistance $R_L = 42$ Ω. For this operation mode Figure 5 shows the efficiency and cosφ_1 dependences on the rotational speed for the previously mentioned C_2 and R_L values (12 μF and 27Ω, respectively).

The analytical treatment of the performance data presented with due regard for heat loads in the secondary winding of a machine allows the following data to be accepted as nominal: power $P_N = 300$W, with the power of the first channel connected to a three-phase network being $P_{21} = 115$W and the power of the second channel feeding the load R_L is $P_{22} = 185$W. The efficiency of the generator in this mode is 0.65 and the power factor cos$\varphi = 0.73$. The elevated value of flux dissipation of the secondary winding is compensated by capacity C_2. The application of an additional capacitive compensation in the primary winding ($C_1 = 10\,\mu$F) increases the power factor of the generator up to 0.95 – 0.98. Apart from that, Figures 4 and 5 show a sufficiently good agreement of experimental and calculation data, which evidences the validity of the above described theoretical approach and the relations obtained from the calculations.

In order to prove the effectiveness of the suggested construction of the asynchronous contactless multipole doubly-fed wind generator an experimental sample of it has been designed with rated power $P = 4000$W for the rotational frequency $n_N \approx 176$ min^{-1} ($2p = 68$), weight of this generator is $G = 195$kg, power factor $\eta = 0.75$, size 400 x 300 mm^2, stator's recess $D = 300$ mm, length of the stator set is $l = 200$ mm, air gap $\delta = 0.0008$ mm.

REFERENCES

1. Niiranen J.K.: *Simulation of Doubly Fed Induction Generator Wind Turbine*. EPE-PEMC 2004, Riga. Proceeding Vol. 5, pp. 5-99 – 5-104.
2. Levin N., Pugachov V., Shipkov L.: *Asynchronous generator*. Patent LV Nr.12598B 20.04.2001. (Latvia).
3. Levin N., Pugachov V., Ribickis L.: *Wind electric device*. Patent LV Nr.P-05-51 25.04.2005. (Latvia).
4. Levin N., Pugachov V., Ribickis L., Manonov M.: *Multipole asynchronous machines with mutually immovable windings*. 10th International Power Electronic and Motion Control Conference EPE-PEMC 2002, Dubrovnic, CROATIA, 9–11 September 2002.
5. Pugachov V., Levin N., Ribickis L., Manonov M.: *A Multipolar Asynchronous Generator with Two Channels of Electric Energy Generation*. 11th International Conference EPE-PEMC 2004, Riga. Proceeding Vol.3, pp.3-341 – 3-349.
6. Levin N.N.: *Method of Investigation of Multiphase Unlike Poles Inductor Machines*. Contactless electrical machines. II, Latvian Academy of Science, Riga, 1962, pp.85–105 (in Russian).

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