10.2478/v10144-009-0006-2

SCIENTIFIC PROCEEDINGS OF RIGA TECHNICAL UNIVERSITY
THE 50TH INTERNATIONAL SCIENTIFIC CONFERENCE „POWER AND ELECTRICAL ENGINEERING," OCTOBER 2009

Electrical Machines and Apparatus / Elektriskās Mašīnas un Aparāti

The generated power of multipole induction generator with secondary winding on the stator

Guntis Diļevs, Edgars Jakobsons
Riga Technical University (Riga, Latvia)
Guntis.dilevs@gmail.com, Edgars.jakobsons@inbox.lv

***Abstract* - This paper posses the construction of induction generator, which has the ability to operate at a low rotation speed. This generator can be applied for directly driven turbine without using the gearbox. The generator is multi pole with all of the windings placed on the stator. Rotor is tooth-like and has no windings on it. Primary winding is three phase, secondary winding is two phase.**

I. INTRODUCTION

Due to the development of wind power generators, the applied technologies has drawn out the main directions of developing generator construction – directly driven permanent magnet synchronous generator (PMSG) and double fed induction generator (DFIG). Each of the mentioned construction has its advantages and disadvantages. PMSG can operate directly with the turbine, but it requires semiconductor device when operating to the grid. DFIG can operate directly to the grid, but it requires gearbox, when operating with turbine. This paper posses the solution of how induction generator can be applied as a directly driven double fed generator for wind electric stations. This generator should be designed in a way that all the windings are placed on the stator, rotor is tooth-like without windings [1-4].

II. SPECIAL FEATURES OF THE MULTIPOLE INDUCTION GENERATOR WITH SECONDARY WINDING ON THE STATOR

The electrical circuit diagram of the double fed induction generator is shown in the Fig.1. Primary winding (A-X, B-Y, C-Z) is three phase and secondary winding (a-x, b-y) is two phase to keep the electromagnetic symmetry of the system – rotating electromagnetic field of the secondary winging is similar as to synchronous rotating field of the primary winding. The electromagnetic symmetry of the secondary winding eliminates the appearance of harmonics in the primary winding.

Both of the windings are placed in the slots of the stator. Rotor is tooth-like and has no windings on it. Secondary windings are switched through the capacitors and rectifier to the load. The controllable switch (semiconductor device) is used to provide stable voltage and frequency to the load. Capacitors C_2 compensate the reactive resistance of the secondary winding [5]. The load current i_L is controlled by pulse width modulation device. The capacitors C_1 helps to increase the power factor *cosφ* of the generator.

For creation of the required electromagnetic link between windings it is necessary to have appropriate phase shifts between the processes going in pole extensions. For this purpose the pole extensions are divided into four groups, 12 pole extensions together. Each pole extension from the same phase has a phase shift of 90^0 between two groups. Two opposite groups are embraced with the one coil of one secondary phase winding. This feature gives the phase shift for the currents i_a and i_b of 90^0. The pole extensions in the same group are divided with grooves where the primary windings A-X, B-Y and C-Z are placed. The step between the mixed pole extensions belonging to one group equals $t_1 = 2t_Z/3$, and that between the mixed pole extensions belonging to mixed groups equals $t_2=11t_Z/12$. This provides a phase shift of the pole extensions of 240 degrees within the same group, and of 30 degrees for mixed group. The equations are similar to those for the conventional induction machine having two phase secondary winding on the rotor [9, 10].

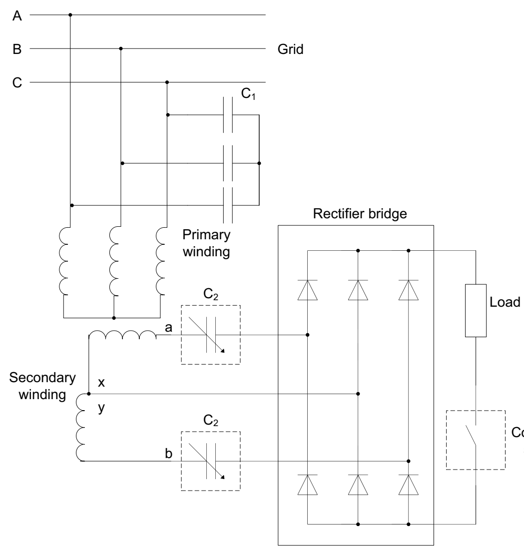

Fig. 1. The electrical circuit diagram of the multipolar induction generator with two phase secondary winding

III. THE EQUIVALENT CIRCUIT DIAGRAM OF THE MULTIPOLE INDUCTION MACHINE

The circuit diagram of such a machine is the same as for conventional induction machine with the number of phases in the rotor $m_2 > 1$. There is negative reactive impedance X_C' and the active load resistance R_L' in the secondary circuit. The circuit diagram was created for the multipole induction machine with two phase secondary winding as shown in Fig. 2.

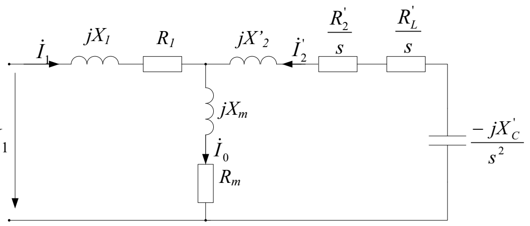

Fig. 2. The circuit diagram of the multipole induction machine with secondary winging on the stator

According to the construction diagram in Fig. 1 and the equivalent circuit diagram in Fig. 2 it is possible to write the complex equations [7].

$$\begin{aligned} \dot{U}_1 &= -\dot{E}_1 + \dot{I}_1\hat{Z}_1; \\ \dot{U}_2' &= -\dot{E}_2' - \dot{I}_{21}'\hat{Z}_{2S}'; \\ \dot{I}_0 &= \dot{I}_1 + \dot{I}_2', \\ \dot{E}_1 &= \dot{E}_2' = -j\sqrt{2}\pi w_1 \Phi f_1 k_w . \end{aligned} \tag{1}$$

where
E_1 = *emf* generated in the windings,
w_1 – number of windings in the phase coil;
Φ – magnetic flux;
f_1 – frequency;
k_w – winding factor.
$\dot{I}_1$ – primary current;
$\dot{I}'_2$ – secondary current;
$\dot{I}_0$ – magnetizing current.

$$\begin{aligned} \hat{Z}_1 &= R_1 + jX_1; \\ \hat{Z}_{2S}' &= \frac{R_2'}{s} + jX_2' - j\frac{X_{C2}'}{s^2} \end{aligned} \tag{2}$$

where
R_1- active resistance of the primary winding,
R_2' – active resistance of the secondary winding, which is reduced to the stator,
X_1 – reactive impedance of the primary winding,
X_2' – reactive resistance of the secondary winding,
s – slip,
X_{C2}' – impedance of the capacitors in the secondary winding;

Voltage of the secondary load equals

$$\dot{U}'_L = \frac{R_L}{s}\dot{I}_2' . \tag{3}$$

Where R_L – secondary load resistance.

To calculate the parameters of the equivalent circuit diagram it is necessary to obtain the values of magnetic flux linkage Ψ between the primary and secondary windings. This can be done with matrix equation

$$[\Psi_{ik}] = [w_{ik}] \times [\lambda_{ik}] \times [w_{ik}]^T \times [i_{ik}], \tag{4}$$

where

$$[\Psi_{ik}] = \begin{bmatrix} \Psi_A \\ \Psi_B \\ \Psi_C \\ \Psi_a \\ \Psi_b \end{bmatrix}$$

is the column matrix of magnetic flux linkages of the windings;

$$[i_{ik}] = \begin{bmatrix} i_A \\ i_B \\ i_C \\ i_a \\ i_b \end{bmatrix}$$

is the column matrix of currents in the windings.

$$[w_{ik}] = \begin{bmatrix} w_k & 0 & 0 & w_k & 0 & 0 & w_k & 0 & 0 & w_k & 0 & 0 \\ 0 & w_k & 0 & 0 & w_k & 0 & 0 & w_k & 0 & 0 & w_k & 0 \\ 0 & 0 & w_k & 0 & 0 & w_k & 0 & 0 & w_k & 0 & 0 & w_k \\ w_k & w_k & w_k & 0 & 0 & 0 & -w_k & -w_k & -w_k & 0 & 0 & 0 \\ 0 & 0 & 0 & w_k & w_k & w_k & 0 & 0 & 0 & -w_k & -w_k & -w_k \end{bmatrix}$$

W_{ik} is the rectangular matrix of the winding turns per each coil, where the rows represent the phases and the columns represent the pole extensions. The sign "–" shows the secondary winding direction according to the primary winding direction.

$$[\lambda_{ik}] = \begin{bmatrix} \lambda_1 & 0 & \dots & 0 \\ 0 & \lambda_2 & \dots & 0 \\ \dots & \dots & \dots & 0 \\ 0 & 0 & \dots & \lambda_{12} \end{bmatrix}$$

is the diagonal matrix of magnetic conductivities. Magnetic conductivity λ_k represented by the Fourier series as a function of the turning angle α of the rotor equals

$$\lambda_k = a_0 + a_1\cos\left(z_R\alpha - \gamma(k-1)\right), \tag{5}$$

Where
α – turning angle of the rotor;
γ – tooth step in radians;
a_0 – constant component,
a_1 – component of the first harmonic which equals

$$a_0 = \frac{\lambda_{\max} + \lambda_{\min}}{2}; \; a_1 = \frac{\lambda_{\max} - \lambda_{\min}}{2} \tag{6}$$

Where λ_{max} – maximum value of the magnetic conductivity,

λ_{min} – minimum value of the magnetic conductivity.

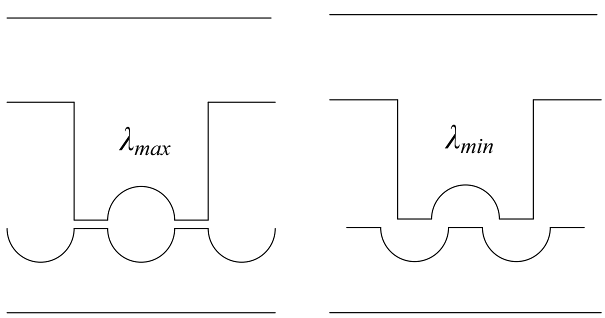

Fig. 3. The placement of the pole extension and the rotor, where magnetic conductuctivity λ reaches its maximum or minimum values

The equations, which express magnetic flux linkage for each phase, are

$$\Psi_A = w_{k1}\begin{pmatrix} \lambda_1(w_{k1}i_A + w_{k2}i_a)+ \\ +\lambda_7(w_{k1}i_A - w_{k2}i_a)+ \\ \lambda_4(w_{k1}i_A + w_{k2}i_b)+ \\ +\lambda_{10}(w_{k1}i_A - w_{k2}i_b)+ \end{pmatrix} = $$
$$= 4a_0 w_{k1}^2 i_A + 2a_1 w_{k1} w_{k2} i_a \cos(Z_R\alpha) + ;$$
$$+ 2a_1 w_{k1} w_{k2} i_b \cos(Z_R\alpha - 90^0)$$

$$\Psi_B = w_{k1}\begin{pmatrix} \lambda_3(w_{k1}i_B + w_{k2}i_a)+ \\ +\lambda_9(w_{k1}i_B - w_{k2}i_a)+ \\ \lambda_6(w_{k1}i_A + w_{k2}i_b)+ \\ +\lambda_{12}(w_{k1}i_B - w_{k2}i_b)+ \end{pmatrix} = $$
$$= 4a_0 w_{k1}^2 i_B + 2a_1 w_{k1} w_{k2} i_a \cos(Z_R\alpha - 120^0) + ;$$
$$+ 2a_1 w_{k1} w_{k2} i_b \cos(Z_R\alpha - 210^0)$$

$$\Psi_C = w_{k1}\begin{pmatrix} \lambda_2(w_{k1}i_C + w_{k2}i_a)+ \\ +\lambda_8(w_{k1}i_C - w_{k2}i_a)+ \\ \lambda_5(w_{k1}i_C + w_{k2}i_b)+ \\ +\lambda_{11}(w_{k1}i_C - w_{k2}i_b)+ \end{pmatrix} = $$
$$= 4a_0 w_{k1}^2 i_C + 2a_1 w_{k1} w_{k2} i_a \cos(Z_R\alpha - 240) + ; \qquad (7)$$
$$+ 2a_1 w_{k1} w_{k2} i_b \cos(Z_R\alpha - 330^0)$$

$$\Psi_a = w_{k2}\begin{pmatrix} \left(\sum_{k=1}^{6}\lambda_k\right) w_{k2}i_a + (\lambda_1 - \lambda_7) w_{k1} i_A + \\ +(\lambda_3 - \lambda_9) w_{k1} i_B + \\ +(\lambda_2 - \lambda_8) w_{k1} i_C \end{pmatrix} = ;$$
$$= 6a_0 w_{k2}^2 i_a + 2a_1 w_{k1} w_{k2} i_A \cos(Z_R\alpha) +$$
$$+ 2a_1 w_{k1} w_{k2} i_B \cos(Z_R\alpha - 120^0) +$$
$$+ 2a_1 w_{k1} w_{k2} i_C \cos(Z_R\alpha - 240^0)$$

$$\Psi_b = w_{k2}\begin{pmatrix} \left(\sum_{k=1}^{6}\lambda_k\right) w_{k2}i_b + (\lambda_4 - \lambda_{10}) w_{k1} i_A + \\ +(\lambda_6 - \lambda_{12}) w_{k1} i_B + \\ +(\lambda_5 - \lambda_{11}) w_{k1} i_C \end{pmatrix} = $$
$$= 6a_0 w_{k2}^2 i_b + 2a_1 w_{k1} w_{k2} i_A \cos(Z_R\alpha - 90^0) +$$
$$+ 2a_1 w_{k1} w_{k2} i_B \cos(Z_R\alpha - 210^0) +$$
$$+ 2a_1 w_{k1} w_{k2} i_C \cos(Z_R\alpha - 330^0)$$

The component a_0 refers to the self inductance, but a_1 refers to the mutual inductance [9, 10].

IV. THE GENERATED POWER OF MULITPOLE INDUCTION GENERATOR WITH SECONDARY WINDING ON THE STATOR

To calculate the output power of the induction machine it is necessary to obtain the currents $\dot{I}_1$, $\dot{I}'_2$, $\dot{I}_0$ according to the slip s. Therefore the power S_1 generated to the grid and active power P_2 generated to the secondary load R_L equals

$$\dot{S}_1 = m_1 \dot{U}_1 \dot{I}_1^* = P_1 + jQ_1 ; \qquad (8)$$
$$P_2 = m_2 I_2'^2 R_L , \qquad (9)$$

where
m_1 – number of phases in the primary winding;
m_2 – number of phases in the secondary winding.

The efficiency factor η equals

$$\eta = \frac{P_1 + P_2}{P_1 + P_2 + \Delta P_1 + \Delta P_m + \Delta P_2 + \Delta P_{mech}} , \qquad (10)$$

(2)

where
$\Delta P_1 = m_1 I_1^2 R_1$ - electrical losses in the primary windings;
$\Delta P_m = m_1 I_0^2 R_m$ - magnetizing losses;
$\Delta P_2 = m_2 I_2^2 R_2$ - electrical losses in the secondary windings;
ΔP_{mech} – mechanical losses in the shaft and bearings [8].

Within the increase of the slip s of the generator, it is important to keep the same value of the current I_2. This can be done by changing the load resistance R_L. Within the increase of the slip s, increases the load resistance R_L and the power P_2 generated in the secondary circuit.

V. CONCLUSIONS

1) The equivalent circuit diagram of the multipole induction machine with the secondary winding on the stator is the same as for conventional induction machines, the number of phases in secondary winding must be greater than 1.

2) With the flux linkage matrix equation is possible to obtain the necessary values of the equivalent circuit diagram, from where the output power can be calculated.

3) The generated power for the slip s = – (1…2) can be transferred through the primary and secondary windings. There are extended limits for raising the output power if the rotation speed of the generator is increasing.

4) The two phase secondary winding provides electromagnetic symmetry, which significantly reduces the presence of THD in the primary winding.

5) This machine is designed in a way that it can be applied in the applications where slow rotation speed is required, like wind power stations and small hydro power plants.

REFERENCES

[1] Ackerman T., Wind Power in Power Systems. Royal Institute of Technology Stockholm, Sweden, John wiley & Sons, Ltd. 2005, 694 pages.
[2] Daskova J., Kamolins E., Levins N. Multipolar directly driven wind generators. Latvian journal of Physics and Technical sciences, No.4, 2004. pages 41 – 47. *(in Latvian)*
[3] The new generation of wind energy converters. Pitch Wind Systems AB, Sweden, 2001.
[4] Kamolins E., Levins N., Pugachev V., Ribickis L. Specific features of reluctance step motors, No.5, 2005. pages 27 – 35. *(in Latvian)*
[5] Pugachev V., Levin N., Ribickis L., Manonov M., A multipolar inductor generator of annular design for windmills. Riga RTU Power and electrical engineerings 4, 10. 2003. gads, 10 – 15 pages.
[6] Nordex N54/1000 kW MK3, Technical Overview Svindblek 7323 Give Denmark, 1996, 4 pages.
[7] Voldek A., Electrical machines. Energia 1974, 640 pages. *(in Russian)*
[8] Kopilov I., Klokov B., Morozkin V., Tokarev B. Design of electrical machines, Moskva, VSh. 2005. 768 pages. *(in Russian)*
[9] Postnikov I. Design of electrical machines, GITL USSR, Kiev 1952. 736 pages. *(in Russian)*
[10] Levin N., Serebriakov A. Electrical machines and drives, 3.ed, Electrical drives based on the motors with static windings, Riga 1976, 192 pages.
[11] Dilevs G., Levins N., Pugachevs V., Ribickis L. Double fed induction generator. Patents application P – 03 – 101, 20.09.2007, 8 pages.