Computer Simulation and Analysis of A Doubly Fed Induction Generator with A One Side Directly Connected to The Grid

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***Abstract*— Doubly fed induction generator (DFIG) is one of the most complex electrical structures for a power generating system (such as wind turbine and small hydro power). This paper proposes theory calculations, computer simulation and analysis structure of a DFIG with only one side connected to the grid. The stator of wound rotor induction generator (WRIG) is connected directly to the grid, and the rotor is controlled by a converter connected to an ideal battery. The theory calculation results provide the fundamental information for the initial stages of engineering design both in term of separate components (electrical machine, electronic converter) as well as the whole entire generating system. These properties and calculations determine the composition, technical implementation of the components in the system and the interaction between them. The theory and computer simulation results of a 160 kW WRIG system is also presented to prove the feasibility of the proposed system and method.**

Keywords*— *doubly fed induction generator, vector control, wound rotor induction generator, variable speed constant frequency, computer simulation, energy efficiency.

I. INTRODUCTION

Recently, there are a lot of articles devoted to generation systems which are based on a wound rotor induction generator (WRIG) [1, 2], working either in stand-alone [3] or connected to the grid mode [4]. Nowadays, doubly fed induction generator (DFIG) [5] is one of most complex electrical structure for a generating system, such as wind turbine and small hydro power. The objective of this paper is to provide supplements and development of the publicly accessible information and methodological support required for system engineering design on DFIG with a one side connected directly to the grid based generation systems, which in present, being formed at the new stage of electronics development. The paper's purpose is to provide information that is essential at the initial stages of engineer development for this type of generation system.

The electrical energy production from the mechanical energy generated from the rotational motion on the rotor shaft's DFIG is based on the well-known phenomenon of electromagnetic induction. The main distinctive of DFIG is the ability to create within it a rotating electromagnetic field of the rotor relative to the rotor itself, with the possibility of realizing a consonant or opposite direction of their rotation. Such abilities come from the placement of a two- or three-phase winding on the DFIG rotor that makes it is possible to form a rotating electromagnetic field when switched to the corresponding system of alternating voltages. The rotating direction of the electromagnetic field can be changed by alternating the voltage phases. Obviously, with a variable mechanical rotor speed, the ability to control the rotation frequency of the rotor's electromagnetic field by varying the frequency and alternating phases of voltages stabilizes the rotation of the electromagnetic field relative to the stator, which in turn stabilizes the EMF frequency induced in the stator windings. In other words, with the help of DFIG, a variable-speed-constant frequency system for generating electric power of alternating voltage without additional mechanisms of a constant-frequency drive can be implemented [6].

Such a generation system could be either autonomous or synchronized with the parameters of the power grid operating in conjunction with it. Wind turbine is a natural application of DFIG [7, 8], since its primary source of energy - the wind - is constantly changing in speed, which leads to a change in the frequency of rotation of the wind wheel, if it is not regulated. Another natural application for DFIG is small hydropower.

The structure of a normal DFIG is shown in Fig. 1a, this configuration allows the power electronic converter to deal with approximately 30% of the generated power therefore reducing significantly the cost and being more efficient compared with full converter structure [9-12]. However, this system requires brushes and slip rings, resulting in increasing establishment and maintenance cost [13]. In normal DFIG, the stator of induction machine is directly connected with the grid, and the rotor is connected with the back-to-back converter 1 which controls the torque, power, speed of pulse WRIG. This converter 1 can operate and generate power in variable-speed mode (above and below synchronous speed). The mission of converter 2 is to keep DC link's voltage constant, and can be replaced by an ideal battery (B), this is the structure of DFIG with one side directly connect to the grid (Fig. 1b). Removing the converter 2 and the filters reduces the complexity, and the costs of the system. This structure uses batteries so it is possible to create a magnetic field that makes the system easy to operate in stand-alone mode. This paper only studies the principle and control method of structure shown in Fig. 1b.

The generation system at the point of connecting to the grid must provide active power into the grid, and exchange with the grid reactive power, its control, providing capacitive or inductive character, to solve the problem of compensation of reactive power in the grid. The requirements for a converter and its structure can be determined by analyzing the steady state of WRIG.

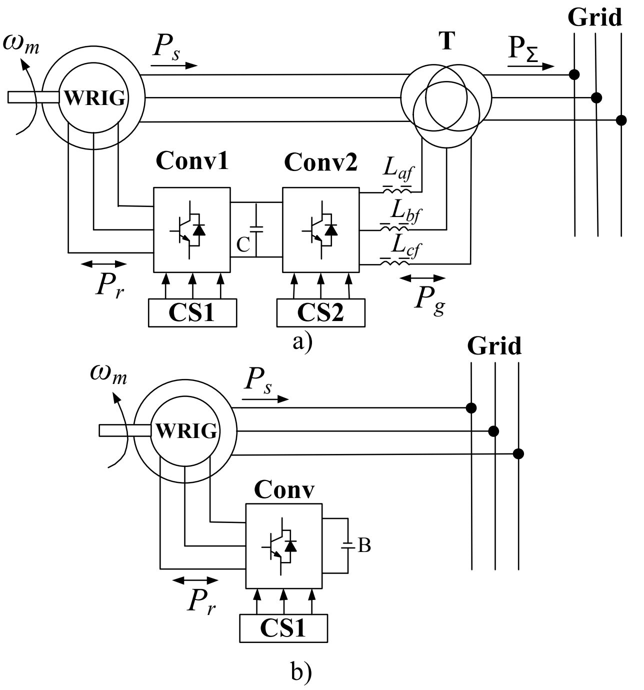

Fig. 1. Structure system WRIG connected directly with the grid
a) DFIG; b) DFIG with one side.

II. RESEARCH ON STEADY STATE OF THE WRIG

The steady state equivalent electric circuit referring the rotor to the stator of WRIG can be simplified presented in Fig. 2, ignoring the loss of magnetic [14].

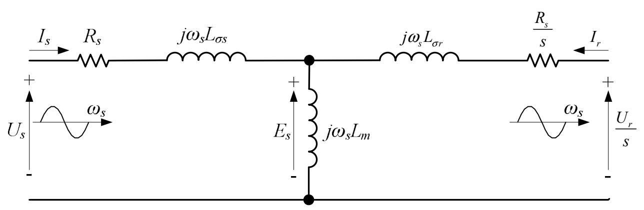

Fig. 2. One-phase steady state equivalent electric circuit of the WRIG referred to the stator.

Electrical models of WRIG are presented in (1) – (7):

$$\frac{\dot{U}_r}{s} - \dot{E}_s = \left(\frac{R_r}{s} + j\omega_s L_{\sigma r}\right)\dot{I}_r \tag{1}$$

$$\dot{U}_s - \frac{\dot{U}_r}{s} - (R_s + j\omega_s L_{\sigma s})\dot{I}_s + \left(\frac{R_r}{s} + j\omega_s L_{\sigma r}\right)\dot{I}_r = 0 \tag{2}$$

$$\dot{E}_s = j\omega_s L_m(\dot{I}_s + \dot{I}_r) \tag{3}$$

$$\dot{\Psi}_s = L_s\dot{I}_s + L_m\dot{I}_r \tag{4}$$

$$\dot{\Psi}_r = L_m\dot{I}_s + L_r\dot{I}_r \tag{5}$$

$$\dot{U}_s - R_s\dot{I}_s = j\omega_s\dot{\Psi}_s \tag{6}$$

$$\dot{U}_r - R_r\dot{I}_r = js\omega_s\dot{\Psi}_r \tag{7}$$

Energy indicators in steady state of the WRIG, can be calculated using expressions (8) - (14):

$$P_s = 3\,\mathrm{Re}\{\dot{U}_s \cdot \dot{I}_s^*\} \tag{8}$$

$$Q_s = 3\,\mathrm{Im}\{\dot{U}_s \cdot \dot{I}_s^*\} \tag{9}$$

$$P_r = 3\,\mathrm{Re}\{\dot{U}_r \cdot \dot{I}_r^*\} \tag{10}$$

$$Q_r = 3\,\mathrm{Im}\{\dot{U}_r \cdot \dot{I}_r^*\} \tag{11}$$

$$M_{em} = 3p\frac{L_m}{L_s}\mathrm{Im}\{\dot{\Psi}_s \cdot \dot{I}_r^*\} \tag{12}$$

$$P_m = \frac{M_{em} \cdot \omega_m}{p} \tag{13}$$

$$\eta = \frac{P_s + P_r}{P_м} \tag{14}$$

where: $\dot{U}_s, \dot{U}_r, \dot{E}_s, \dot{I}_s, \dot{I}_r$ – Stator and rotor voltages (V), EMF in the stator (V), stator and rotor currents (A); $\dot{I}_s^*, \dot{I}_r^*$ – Vector conjugate currents of stator and rotor (A); $\dot{\Psi}_s, \dot{\Psi}_r$ – Stator and rotor fluxes (Wb); $R_s, R_r, L_{\sigma s}, L_{\sigma r}$ – Stator and rotor resistances (Ω), stator and rotor leakage inductances (H); L_m – Mutual inductance (H); $L_s = L_{\sigma s} + L_m$ – Stator inductance (H); $L_r = L_{\sigma r} + L_m$ –Rotor inductance (H); ω_s – Angular frequency of the voltages and current of the stator windings (rad.s^{-1}); s – Slip; p – Pairs of poles; P_s, P_r – Stator and rotor active powers (W); Q_s, Q_r – Stator and rotor reactive powers (VA); M_{em} – Electromagnetic torque in the shaft of the machine; P_m – Mechanical power (W); η –Efficiency of generator.

From the steady state equivalent circuit (1) – (14), it is possible to derive the vector diagram of the WRIG hence to determine operating conditions. This session shows how the vector diagram is deduced, by using the WRIG's equations. Table 1 shows parameters of a 160 kW WRIG. All these parameter values are from the library of *MATLAB/Simulink*.

TABLE I. MACHINE PARAMETERS 160 KW (ALL DATA FROM LIBRARY MATLAB/SIMULINK)

Parameter	Value	Features
f_s	50	Nominal frequency of stator (Hz)
p	2	Pairs of poles
n	1500	Synchronous speed (rev/min)
P_{sn}	160	Nominal stator three phase active power (kW)
U_{sn}	220	Nominal stator voltage per phase in RMS (V)
I_{sn}	255	Nominal stator current each phase in RMS (A)
M_n	1020	Nominal torque (Nm)
R_s	$13.79 \cdot 10^{-3}$	Stator resistance (Ω)
$L_{\sigma s}$	$0.152 \cdot 10^{-3}$	Stator leakage inductance (H)
L_m	$7.69 \cdot 10^{-3}$	Magnetizing inductance (H)
R_r	$7.72 \cdot 10^{-3}$	Rotor resistance referred to the stator (Ω)
$L_{\sigma r}$	$0.152 \cdot 10^{-3}$	Rotor leakage inductance referred to the stator (H)
$L_s=L_{\sigma s}+L_m$	$7.842 \cdot 10^{-3}$	Stator inductance (H)
$L_r=L_{\sigma r}+L_m$	$7.842 \cdot 10^{-3}$	Rotor inductance (H)
J	2.9	Inertia (kg.m^2)

A. Calculation for the above synchronous speed mode

The generator is supposed to be delivering to the grid P_s=-144 kW at U_s=220 V, f_s=50 Hz, and s=-0.3 (above synchronous speed) with condition Q_s=0 VA.

Vector of stator voltage and current when Q_s=0 VA:

$$\dot{U}_s = 220 \cdot e^{j0}\ \text{V}$$

$$\dot{I}_s = \frac{P_s}{3 \cdot \dot{U}_s} = 218 \cdot e^{j180}\ \text{A}$$

From (6), the stator flux can be calculated as:

$$\dot{\Psi}_s = \frac{\dot{U}_s - R_s \dot{I}_s}{j\omega_s} = 0.71 \cdot e^{-j90}\ \text{Wb}$$

From (4), the rotor current is found as:

$$\dot{I}_r = \frac{\dot{\Psi}_s - L_s \dot{I}_s}{L_m} = 240.88 \cdot e^{-j22.53}\ \text{A}$$

Thus from (5), the rotor flux can be derived:

$$\dot{\Psi}_r = L_m \dot{I}_s + L_r \dot{I}_r = 0.727 \cdot e^{-j84.71}\ \text{Wb}$$

And from (7) – the rotor voltage:

$$\dot{U}_r = R_r \dot{I}_r + js\omega_s \dot{\Psi}_r = 66.88 \cdot e^{-j173.97}\ \text{V}$$

Using the obtained results, the rotor active and reactive power can be found:

$$P_r = 3\,\text{Re}\{\dot{U}_r \cdot \dot{I}_r^*\} = -42.447\ \text{kW}$$

$$Q_r = 3\,\text{Im}\{\dot{U}_r \cdot \dot{I}_r^*\} = 23.107\ \text{kVA}$$

This shows that the machine is being magnetized through the rotor.

Electromagnetic torque in the WRIG's shaft:

$$M_{em} = 3p\frac{L_m}{L_s}\text{Im}\{\dot{\Psi}_s \cdot \dot{I}_r^*\} = -929.27\ \text{N·m}$$

From the calculated results, the vector diagram is depicted in Fig. 3.

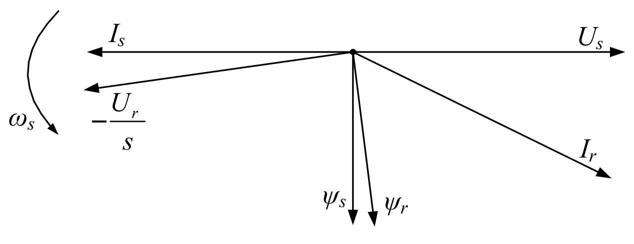

Fig. 3. Vector diagram of WRIG with s = -0,3, Q_s= 0 VA, P_s = -144 kW.

B. Calculation for the below synchronous speed mode

The initial conditions of the calculation are the same as for the rotation of the rotor with a frequency above synchronous speed, except for the value s=0.3.

The algorithm for determining all the calculated values is the same:

$$\dot{U}_s = 220 \cdot e^{j0}\ \text{V}$$

$$\dot{I}_s = \frac{P_s}{3 \cdot \dot{U}_s} = 218 \cdot e^{j180}\ \text{A}$$

$$\dot{\Psi}_s = \frac{\dot{U}_s - R_s \dot{I}_s}{j\omega_s} = 0.71 \cdot e^{-j90}\ \text{Wb}$$

$$\dot{I}_r = \frac{\dot{\Psi}_s - L_s \dot{I}_s}{L_m} = 240.88 \cdot e^{-j22.53}\ \text{A}$$

$$\dot{\Psi}_r = L_m \dot{I}_s + L_r \dot{I}_r = 0.727 \cdot e^{-j84.71}\ \text{Wb}$$

$$\dot{U}_r = R_r \dot{I}_r + js\omega_s \dot{\Psi}_r = 70.17 \cdot e^{j4.58}\ \text{V}$$

$$P_r = 3\,\text{Re}\{\dot{U}_r \cdot \dot{I}_r^*\} = 45.13\ \text{kW}$$

$$Q_r = 3\,\text{Im}\{\dot{U}_r \cdot \dot{I}_r^*\} = 23.107\ \text{kVA}$$

$$M_{em} = 3p\frac{L_m}{L_s}\text{Im}\{\dot{\Psi}_s \cdot \dot{I}_r^*\} = -929.27\ \text{N·m}$$

From the calculated results, the vector diagram is depicted in Fig. 4.

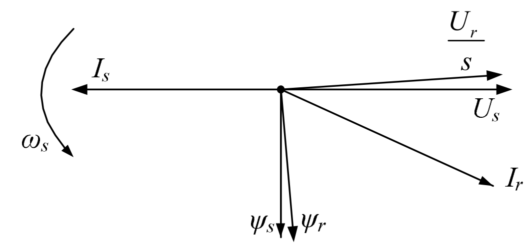

Fig. 4. Vector diagram of WRIG with s = 0,3, Q_s= 0 VA, P_s = -144 kW.

Table 2 presents the theory results in cases of P_s=0.6P_{sn} and P_s=0.3P_{sn} with different values of slip.

TABLE II. CALCULATION RESULTS

s	P_s (W)	P_r (W)	Q_r (V.A)	M_{em} (N.m)	P_m (W)	η (%)
0.3		14787	19023		-33753.2	98.4
0.2		9965	12682		-38575.1	98.6
0.1		5143	6341.1		-43397	98.8
0	-48000	321	0	-306.97	-48218.8	98.9
-0.1		-4501	6341.1		-53040.7	99
-0.2		-9323	12682		-57862.6	99.1
-0.3		-14144	19023		-62684.5	99.1
0.3		29768	20597		-67812.8	97.7
0.2		20080	13731		-77500.4	98
0.1		10393	6865.6		-87187.9	98.2
0	-96000	705	0	-616.73	-96875.5	98.4
-0.1		-8982	6865.6		-106563	98.5
-0.2		-18670	13731		-116251	98.6
-0.3		-28357	20597		-125938	98.7
0.3		45135	23107		-102179	96.8
0.2		30538	15405		-116776	97.2
0.1		15941	7702.4		-131373	97.5
0	-144000	1344	0	-929.27	-145970	97.7
-0.1		-13253	7702.4		-160567	98
-0.2		-27850	15405		-175164	98.1
-0.3		-42447	23107		-189761	98.3

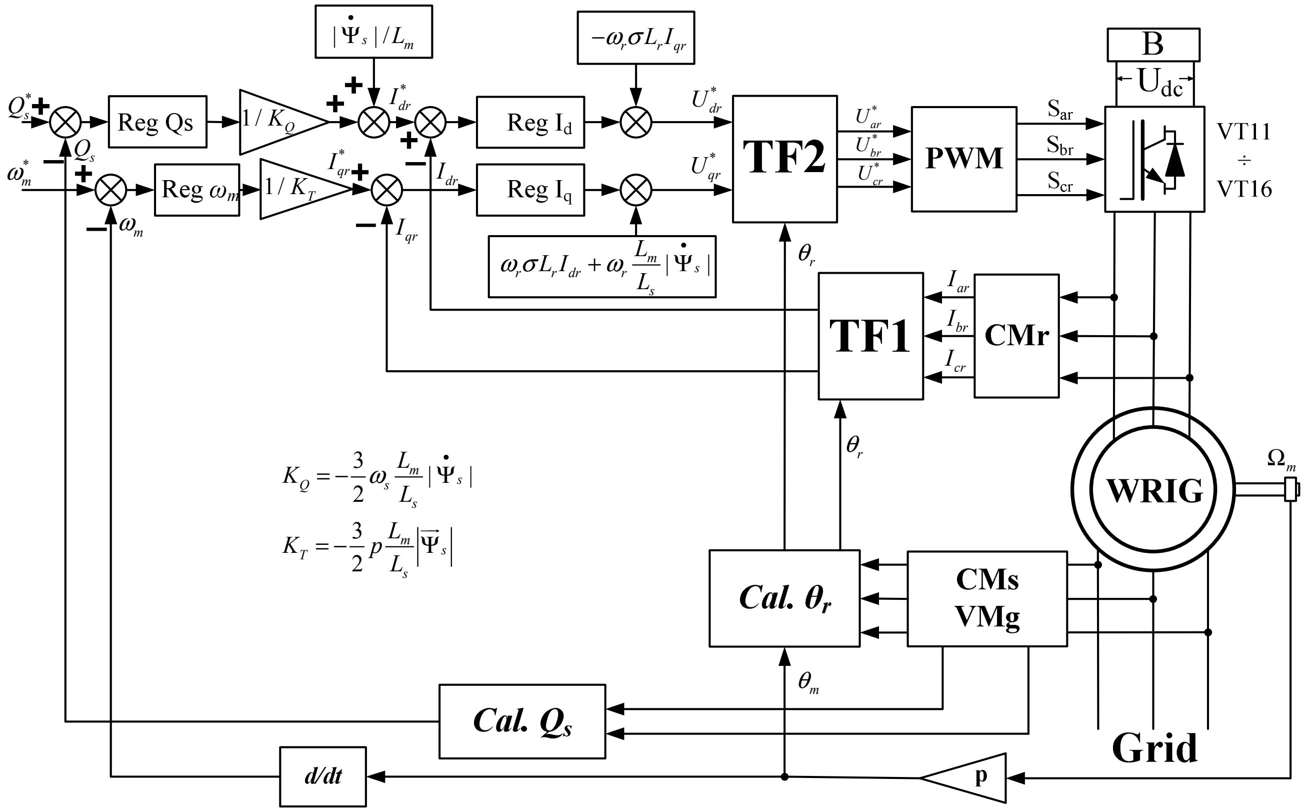

Fig. 5. Structure diagram vector control of the DFIG one side directly connected to the grid:
TF1, TF2– Transformation frame from *abc* to *dq* and from *dq* to *abc*; PWM – Pulse width modulation; B – Battery;
Reg I_d, Reg I_q – Regular current rotor in axes *d* and *q*; Reg Q_s, Reg ω_m – Regular reactive power stator, mechanical speed;
CMr, CMs– Current measurement rotor, stator; VMg – Voltage measurement grid; Cal Q_s – Calculation reactive power stator; Cal θ_r – Angle calculation.

III. Vector Control Strategy

Controlling algorithms are crucial in implementation the properties of converter in the dynamic and steady operation modes of the generating system. One of the widely used algorithms is the separate control of WRIG's active and reactive power, which is implemented in the general case by means of vector control of the transistor switch converter.

In order to form initial ideas about this control algorithm, consider an example of the structure of a simplified simulation computer simulation model of a generation system with active and reactive power control WRIG, which has the parameters given in Table 1.

It is known that in the synchronous reference frame *dq* [15], under stator flux orientation, in which the *d* axis coincides with the stator flux vector Ψ_s, the stator reactive power is proportional to the direct rotor current on the *d* axis (15), and the stator active power or the torque is proportional to the quadrature rotor current on the *q* axis (16):

$$Q_s = \frac{3}{2}(U_{qs}I_{ds} - U_{ds}I_{qs}) = -\frac{3}{2}\omega_s \frac{L_m}{L_s}|\dot{\Psi}_s|\left(I_{dr} - \frac{|\dot{\Psi}_s|}{L_m}\right) \qquad (15)$$

$$M_{em} = \frac{3}{2}p\frac{L_m}{L_s}(\Psi_{qs}I_{dr} - \Psi_{ds}I_{qr}) = -\frac{3}{2}p\frac{L_m}{L_s}|\dot{\Psi}_s|I_{qr} \qquad (16)$$

The value of the stator flux WRIG, without taking into account the voltage drop in the stator resistance, is determined by the parameters of the grid at constant AC voltage, so the stator flux is constant:

$$|\dot{\Psi}_s| \cong |\dot{U}_s|/\omega_s \qquad (17)$$

From equations (15), (16), (17) it deduces that the controlling of the active and reactive power of an WRIG during operation with grid, can be realized with the help of components' regulators of the generalized rotor current vector along with the *q* and *d* axes, respectively $-I_{qr}^*, I_{dr}^*$. The structural scheme of such a solution is presented in Fig. 5.

IV. Computer Simulation Model

The implementation of current regulators need feedback on the instantaneous values of the I_{qr}, I_{dr} components. They are measured by the rotor current measurement (CMr), the signals from which are converted into the values of the components of the generalized current vector in the two-phase coordinate system *d, q* (TF1). At the output of current regulators, signals of a generalized rotor voltage vector are formed U_{qr}, U_{dr}, which, by means of coordinate (TF2) and vector transformations, are converted into control signals for transistors converter. Fig. 6 shows the structural-functional diagram of the computer simulation model of the generating system in the *MATLAB/Simulink* program. The model implements the block diagram is shown in Fig. 5.

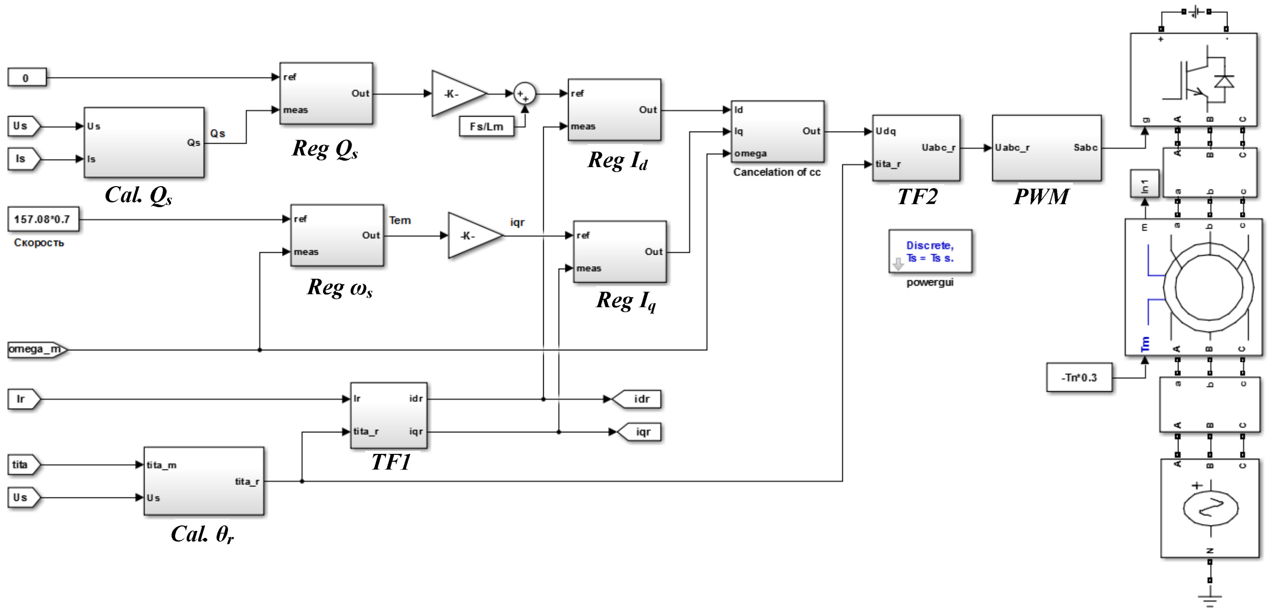

Fig. 6. Structure-functional diagram of the computer simulation model.

Fig. 7 to Fig. 10 present the simulation results, previously calculated, of the steady state of operation of the generating system based on WRIG (Table 2). The values of both calculation results correlate with each other with sufficient accuracy. The values of voltages, currents, capacities obtained during the calculations are the initial information for the further selection of the converter element base and its design.

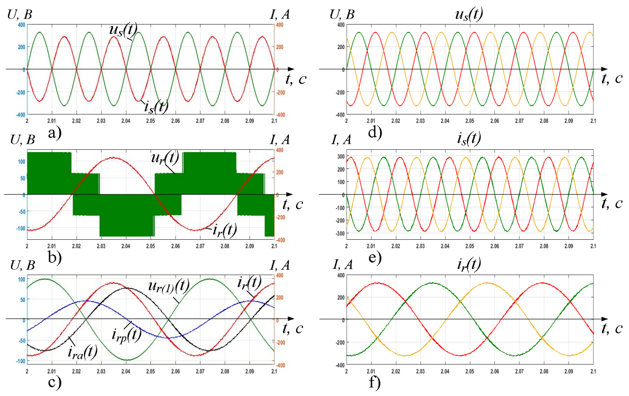

Fig. 7. Oscilloscope of currents and voltages DFIG at s=-0,3:
a) Voltage $u_s(t)$ and current $i_s(t)$ phase A of stator;
b) Voltage $u_r(t)$ and current $i_r(t)$ phase a of rotor;
c) Fundamental harmonic voltage $u_{r(1)}(t)$ and current $i_r(t)$ phase a of rotor, active $i_{ra}(t)$ and reactive $i_{rp}(t)$ components current of rotor;
d) Three-phase voltage of stator (f = 50 Hz);
e) Three-phase current of stator (f = 50 Hz);
f) Three-phase current of rotor (f = 15 Hz).

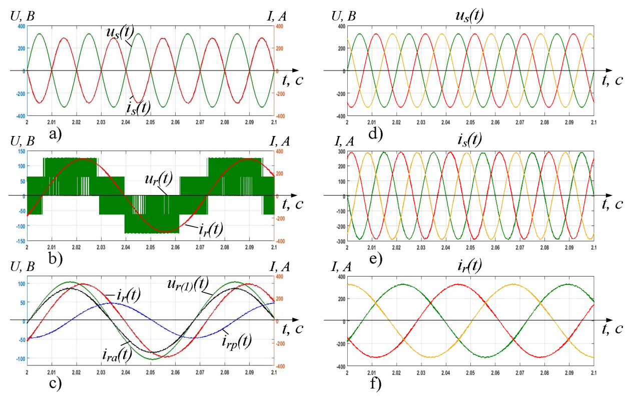

Fig. 8. Oscilloscope of currents and voltages DFIG at s=0,3:
a) Voltage $u_s(t)$ and current $i_s(t)$ phase A of stator;
b) Voltage $u_r(t)$ and current $i_r(t)$ phase a of rotor;
c) Fundamental harmonic voltage $u_{r(1)}(t)$ and current $i_r(t)$ phase a of rotor, active $i_{ra}(t)$ and reactive $i_{rp}(t)$ components current of rotor;
d) Three-phase voltage of stator (f = 50 Hz);
e) Three-phase current of stator (f = 50 Hz);
f) Three-phase current of rotor (f = 15 Hz).

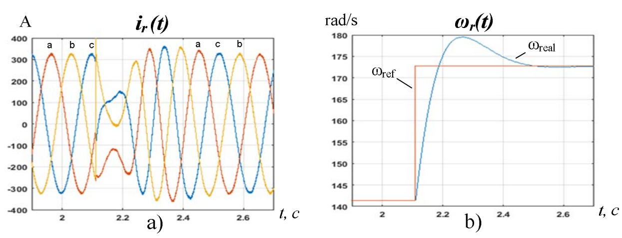

Fig. 9. Oscilloscope of rotor currents and angular frequency of rotor when speed transfer from s=0,1 to s=-0,1:
a) Rotor currents $i_r(t)$;
b) Angular frequency of rotor: ω_{ref} – reference frequency; ω_{real} – real frequency.

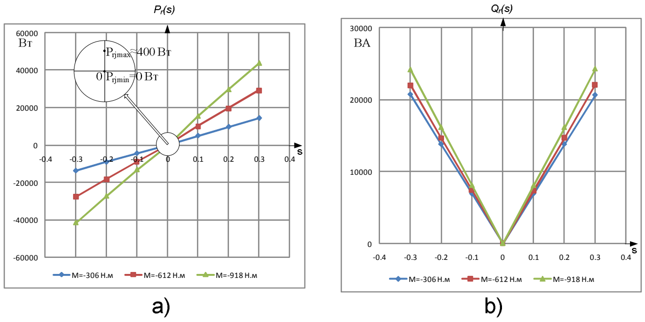

Fig. 10. Steady state curves at fixed $Q_s = 0$ at different torques and speed: a) Rotor active power b) Rotor reactive power.

V. Conclusion

This paper has presented a doubly fed induction generator (DFIG) with a one side, in which the stator is directly connected to the power grid and the rotor is connected to a converter, fed by ideal battery. The proposed vector control in the stator flux reference frame can be used in controlling the generated power.

The performed theory calculations and the obtained results of computer simulation model of steady state of a wound rotor induction generator –WRIG, what conditions of rotation frequency and generated power allow the determination of requirements for the structural and algorithmic organization of a converter in the application.

The results of the study WRIG allows to obtain the source data for the calculation and selection of electronic components of the converter.

The experiments in computer simulation of a 160-kW DFIG with one side structure, the operations of the proposed structure and control methods have been confirmed.

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