Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 4 Issue 5, May - 2017

Integration of Renewable Energy Sources to Power Grid

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***Abstract* - The paper presents a system that can connect wind generator to the grid in Matlab/Simulink/SimPowerSystems. The investigated system consists of the following components: wind generator synchronous type with permanent magnets (PMSG), AC/DC converter, grid inverter, grid and systems for inverter control.**

Keywords - vector control of pmsg, control of grid side inverter, voltage oriented control

I. Introduction

Wind turbines with synchronous permanent-magnets generator (PMSG) are defined like turbines with variable speed. In our days they are used often for turbines with power several kW to 3,5 MW. The wind turbines with PMSG are multi-pole and they are used successfully at very low speeds. Their main priority is the lack of reduction gear, that reduce the mechanical losses [1].

Fig. 1 shows a scheme connecting PMSG to grid. The capacitor divider allows two autonomous systems to control the AC/DC converter and the grid inverter. The PMSG controlling is done by the Field Oriented Control method, just like the grid inverter controlling – by the Voltage Oriented Control. Hereinafter basic theoretical dependences are represented like explaining the operation of basic system components.

A. PMSG model [2].

The operation of the generator in (d,q) coordinate system could be described:

- For the stator voltage:

$$u_{sd} = R_s i_{sd} + \frac{d\psi_d}{dt} - \omega_e \psi_q \quad (1)$$

$$u_{sq} = R_s i_{sq} + \frac{d\psi_q}{dt} + \omega_e \psi_q \quad (2)$$

where u_{sd}, u_{sq} are the stator voltages; i_{sd}, i_{sq} are the stator currents; R_s is the stator resistance; ψ_d, ψ_q are stator flux linkages; ω_e is the rotation speed created by the rotor in $[rad/s]$.

- For the magnetic flux:

$$\psi_d = L_d i_{sd} + \psi_m \quad (3)$$

$$\psi_q = L_q i_{sq}, \quad (4)$$

where L_d, L_q is the stator induction in (d,q) coordinates; ψ_m is permanent flux linkage by the rotor permanent magnets.

- For the electromagnetic torque:

The electromagnetic torque can be obtained by the expression for electromagnetic power:

$$P_{em} = \omega_m T_e = \frac{3}{2}\omega_e\left(\psi_d i_{sq} - \psi_q i_{sd}\right), \quad (5)$$

where ω_m is the mechanical speed to the rotor rotation, which is connected with the rotation speed of the magnetic field:

$$\omega_e = \frac{p}{2}\omega_m, \quad (6)$$

where p is the number of poles. Eventually the electromagnetic torque is:

$$T_e = \frac{3}{2}\frac{p}{2}\left(\psi_d i_{sq} - \psi_q i_{sd}\right) \quad (7)$$

- For the mechanical part

$$T_e = T_L + B\omega_m + T_d + J\frac{d\omega_m}{dt}, \quad (8)$$

where T_L is the load torque; J is the moment of inertia, *B* is viscous friction, *Td* is dry friction torque.

II. PMSG controlling.

As it is noted in the beginning the PMSG controlling method is Field Oriented Control. The controller block diagram is shown in fig.2. In this controller the electromagnetic torque is controlled indirectly by the current of the stator.

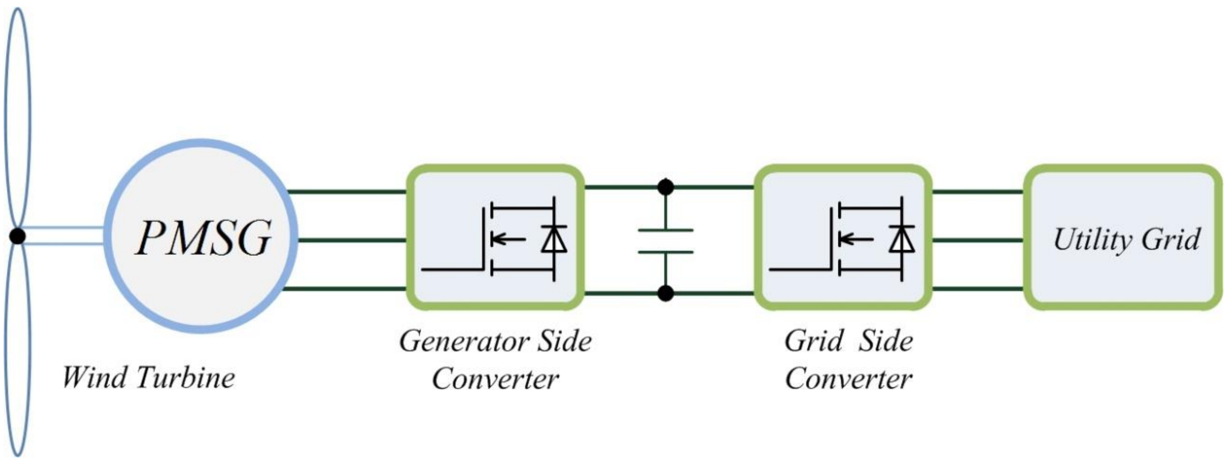

Fig. 1 Connect of wind generator PMSG type to grid

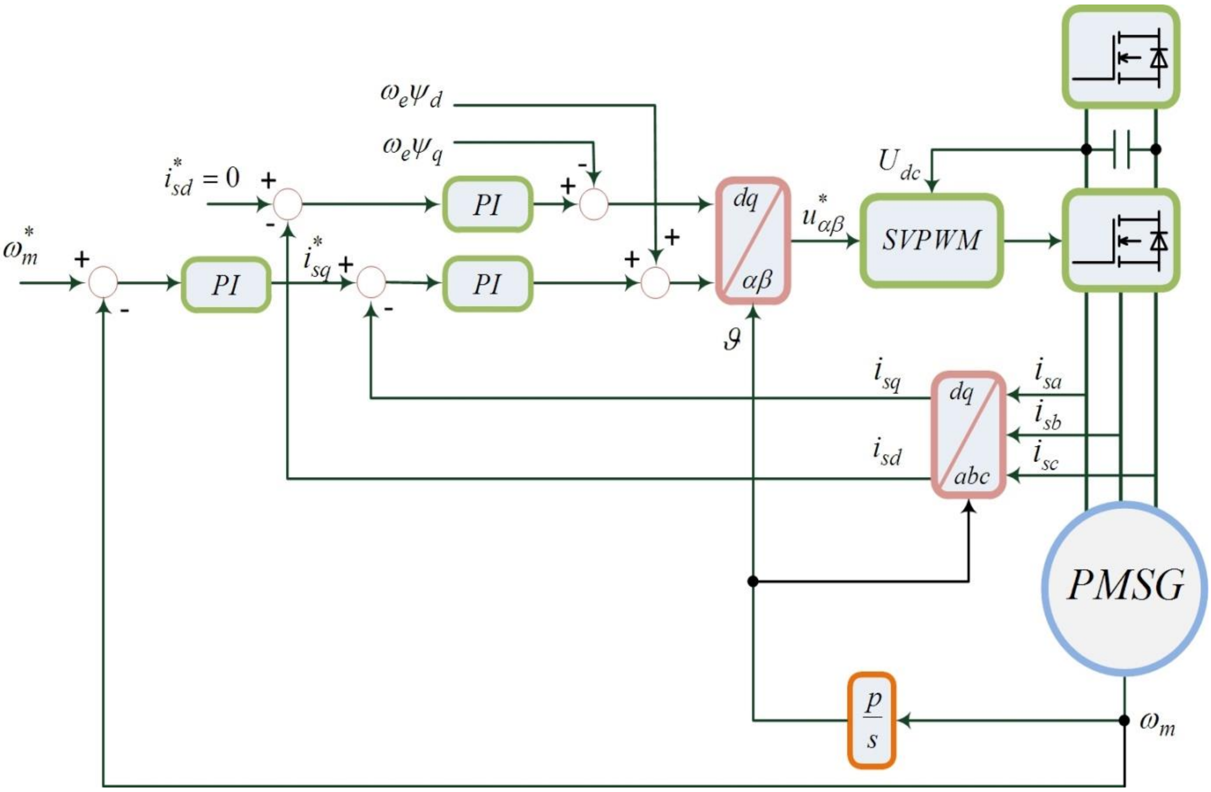

Fig. 2 Field Oriented Control block diagram

The controlling is realized in (d,q) coordinate system according expression:

$$T_e = \frac{3}{2}\frac{p}{2}\psi_m i_{sq} \quad (9)$$

The stator current component i_{sd} is parasitical and do not have to take a part of torque creation, therefore support zero [6].

During the simulations is used synchronous generator *6 kW* power with following parameters:
$R = 0.425\Omega$, $L = 0.835mH$, $\psi_m = 0.433V.s$, $J = 0.0197kg.m^2$, $B = 0.001189N.m.s$, $p = 10$.

A. *Q-axis current controller design (controlling of electromagnetic torque T_e).*

The feedback loop (FBL) by current for i_{sq} is shown in fig.3 [2]. The figure contain:

$$G_{pi}(p) = K_{pc} + \frac{K_{ic}}{p} \quad (10)$$

$$G_{conv}(p) = \frac{1}{0.5T_{pwm}s + 1} \quad (11)$$

$$G_{pl} = \frac{1}{L_{sq}s + R_s}, \quad (12)$$

Where T_{pwm} is the rectifier switching period.

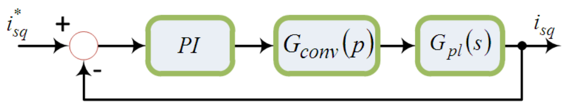

Fig. 3 FBL by i_{sq} current

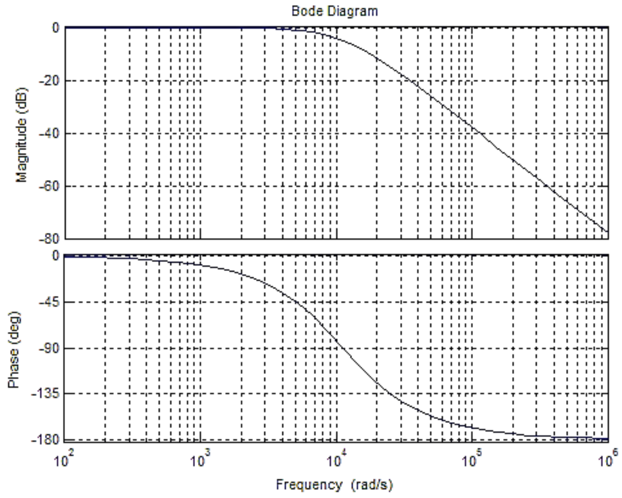

Fig. 4 Frequency characteristics of closed system

B. *D-axis current controller design (controlling of magnetic flux linkage ψ).*

This feedback support the stator flux linkage constant through i_{sd}, which has to be zero [3]. Since $L_{sd} = L_{sq}$ coefficients of i_{sd} controller are the same like of i_{sq} controller.

C. *Speed controller design.*

In fig.5 is presented the speed feedback. p_b is the number of poles pairs and ω_r - mechanical speed. In the figure contain following transfer functions:

$$G_{pi}(p) = K_{p\omega} + \frac{K_{i\omega}}{p} \quad (13)$$

$G_{clp}(p)$ is a transfer function of current loop.

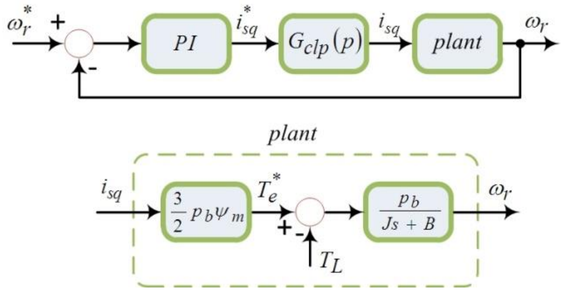

Fig. 5 Speed feedback outline [2]

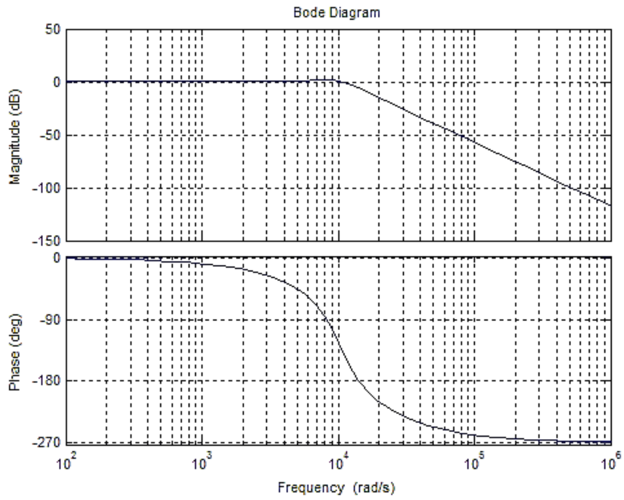

Fig. 6 Frequency characteristics of speed feedback closed system

D. *Power grid modeling.*

The power grid is modeled like source of three-phase symmetrical voltage with effective value of the phases 220 [7] and frequency 50 Hz.

$$V_a = E_m\cos(\omega t), \quad (14)$$

$$V_b = E_m\cos(\omega t - \frac{2\pi}{3}), \quad (15)$$

$$V_c = E_m\cos\left(\omega t - \frac{4\pi}{3}\right), \quad (16)$$

where E_m is the amplitude of phase voltage, and ω is angular frequency.

III. Grid Inverter Controlled Through Voltage Oriented Control.

The grid inverter controlling is realized in (d,q) coordinate system too. Controlling functional scheme is shown in fig.7.

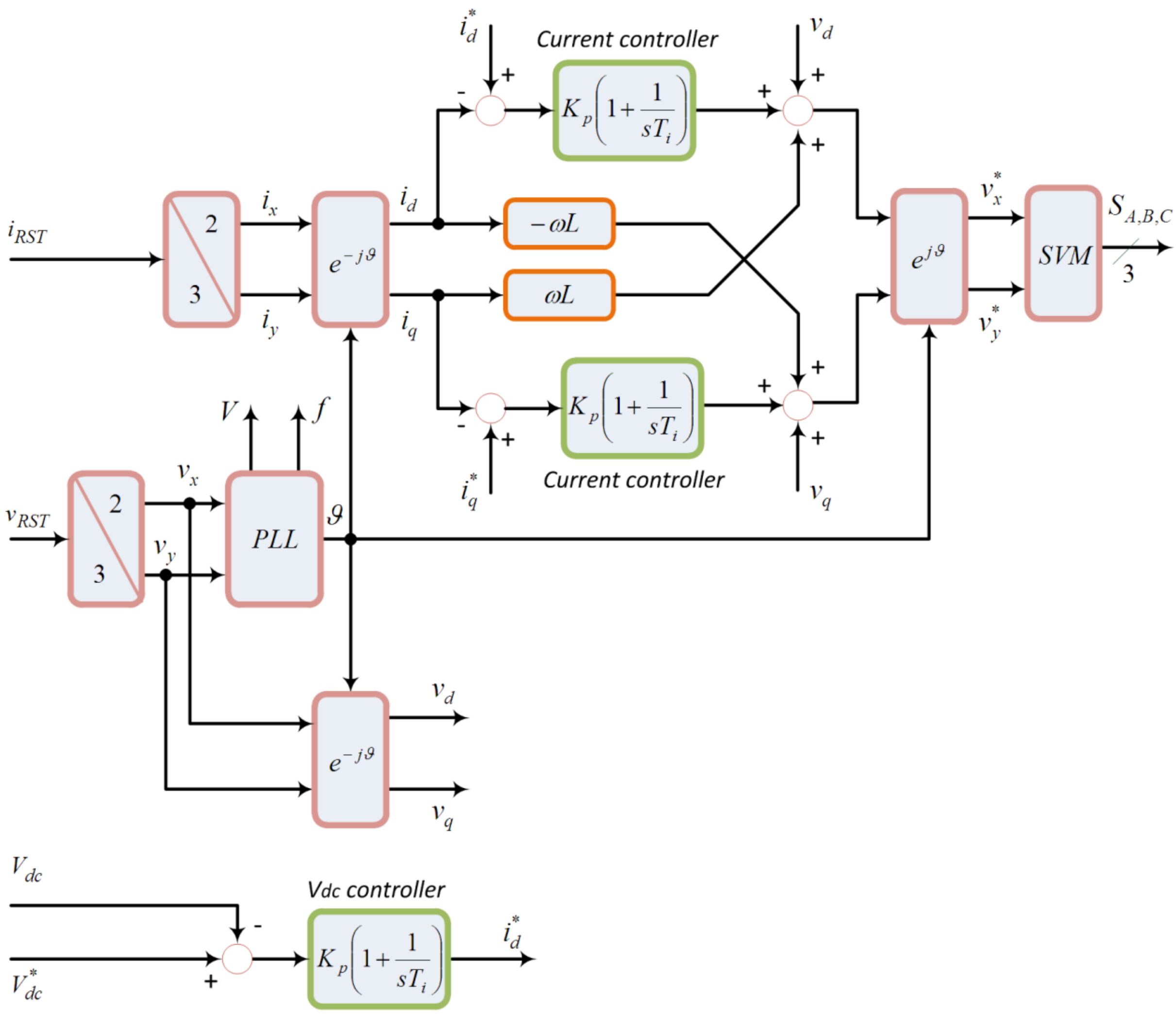

Fig.7 Voltage Oriented Control block diagram

Phase Locked Loop block helps to determine phase, frequency and amplitude of the utility voltage. The phase is used in coordinate transformations. On the scheme are shown 2 feedbacks – by current (internal feedback) and by voltage (external feedback). Thereby the voltage at the inverter input V_{dc} is supported constantly. It is known that V_{dc} should be $Vdc \geq 1.6V_{ll}$ [5], where V_{ll} is the effective value of linear grid voltage.

A. *Phase Locked Loop (PLL) system.*

The PLL block diagram is shown in fig.8 [7], in fig.9 are shown V_a graphics and the PLL determine phase.

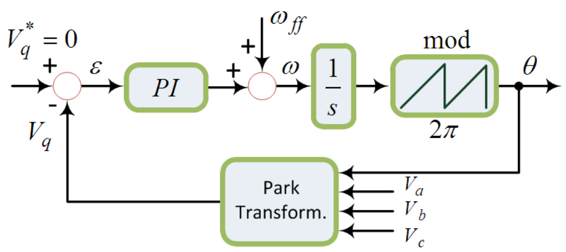

Fig. 8 Phase Locked Loop

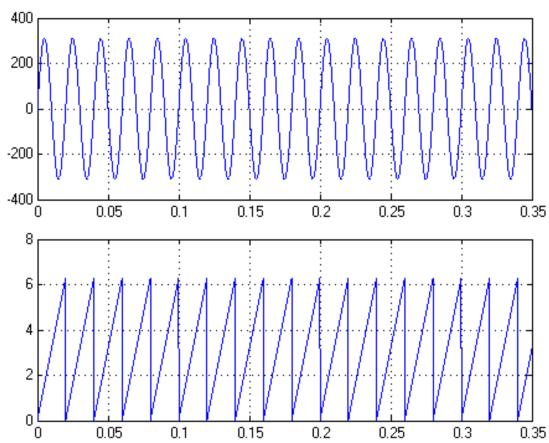

Fig.9 The voltage of phase a and the phase angle θ

B. *Grid inverter controller.*

The grid inverter control is made by method of space vector pulse width modulation. At these algorithms the reference act the PWM through vector in (α, β) coordinate system which vector is realized by the inverter.

It is known that three-phase inverter has 8 basic states (basic vectors). (fig. 10) [10] The output voltages of the inverter are composed by these eight basic states. 6 of that positions are active and divide (α,β) plane to 6 sectors. Depending on the sector where the reference is, it is realized through relevant basic vectors and the calculation of basic vectors work times.

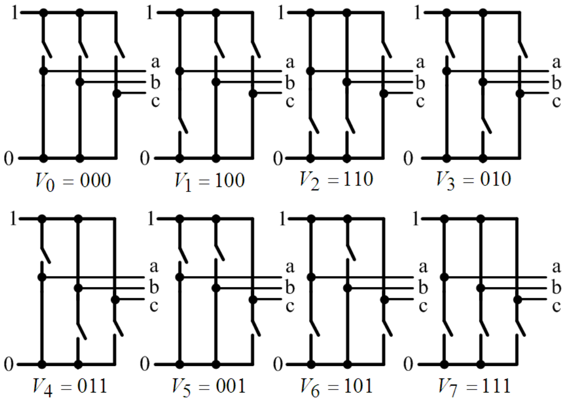

Fig. 10 Basic states of inverter

A variety of algorithms for vector pulse-width modulation is determined by different sequence and method of work time realizing [14].

C Design of current feedback and voltage feedback.

The voltage feedback support constantly the input inverter voltage and produced reference. i_d^* to the current loop. By this is decided active power flow. i_q is decided reactive power and usually supports zero.

The current loop has similar type like 2.1, fig.3, with the difference that *R* is active resistance of grid and *L* is its induction.

In fig. 11 is shown close system with voltage feedback [13], and in fig. 12 are shown frequency characteristics

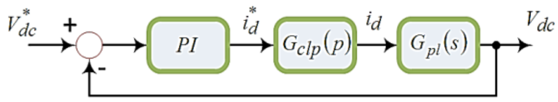

Fig. 11 Voltage feedback

In the figure $G_{clp}(p)$ is transfer function of the current loop, and $G_{pl}(p)$ is transfer function between i_d and V_{dc}:

$$G_{pl}(p) = \frac{1}{C_{dc}s}, \quad (16)$$

where C_{dc} is separating capacitor value.

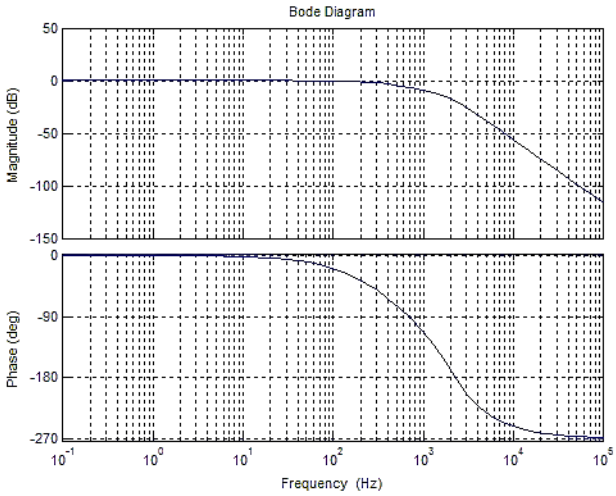

Fig. 12 Frequency characteristics of voltage feedback system

IV. Simulations

In fig. 13 is shown the block diagram formed in *Simulink*, and in fig. 15 ÷ fig. 21 the results of conducted simulations through changing of the load torque by the way shown in fig. 14 (nominal PMSG speed is 150 *rad/s*, and nominal load moment is 40 *N.m*) are shown

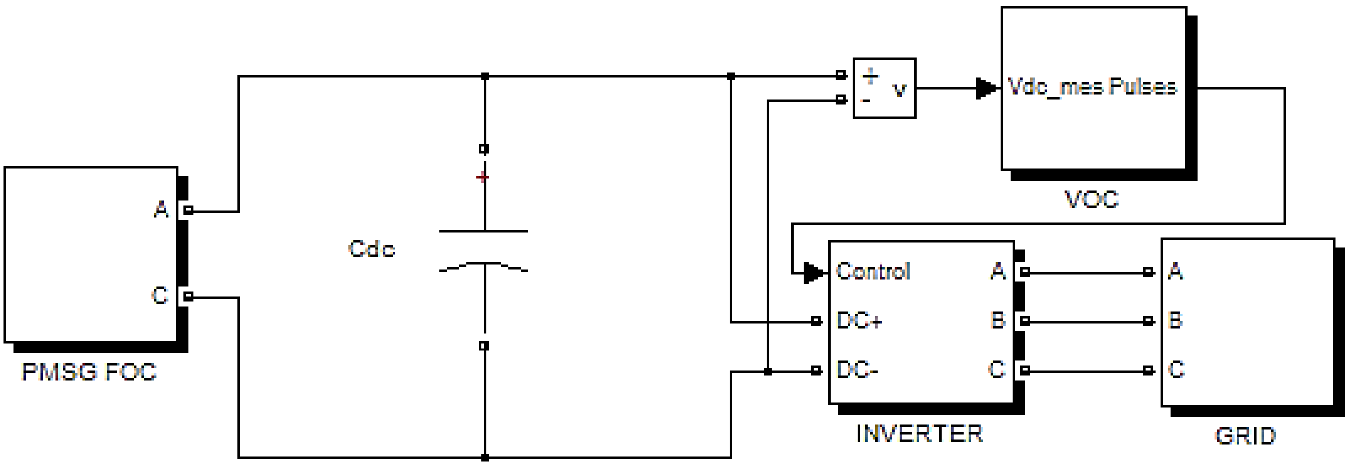

Fig. 13 *Simulink* block diagram of PMSG connecting to the grid

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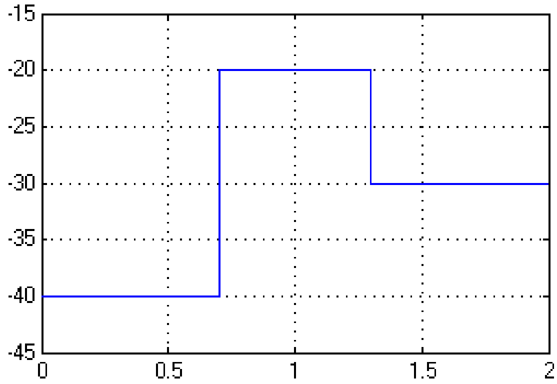

Fig.14 Load torque changing applied to generator shaft

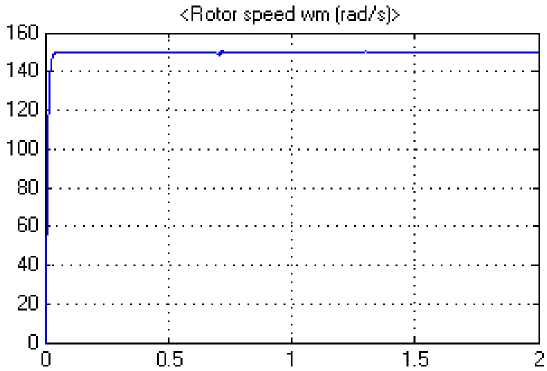

Fig. 15 Generator speed diagram

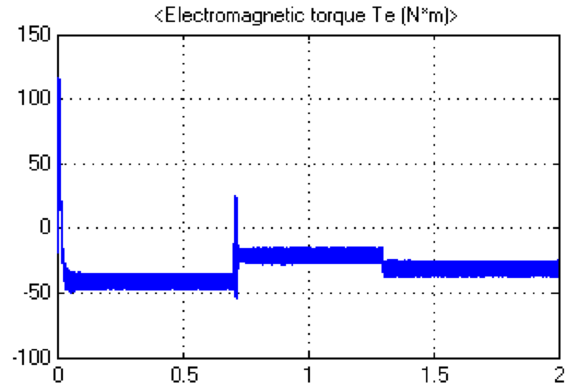

Fig. 16 Electromagnetic torque changing

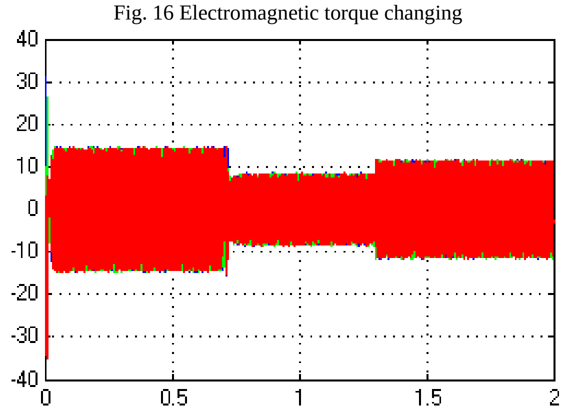

Fig. 17 Generator current

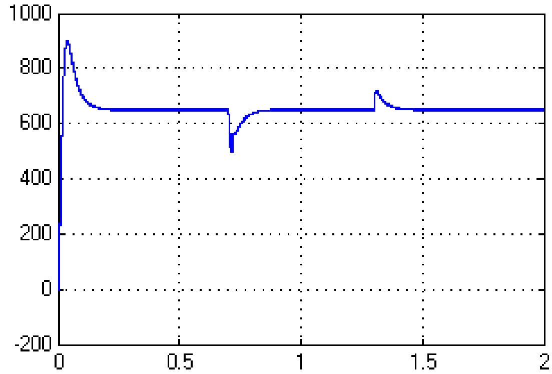

Fig. 18 Input voltage of grid inverter

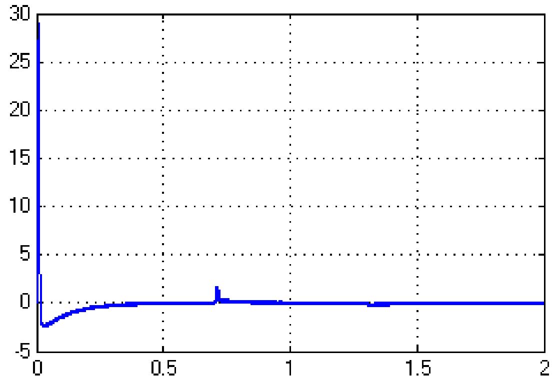

Fig.19 Current component i_q into the grid

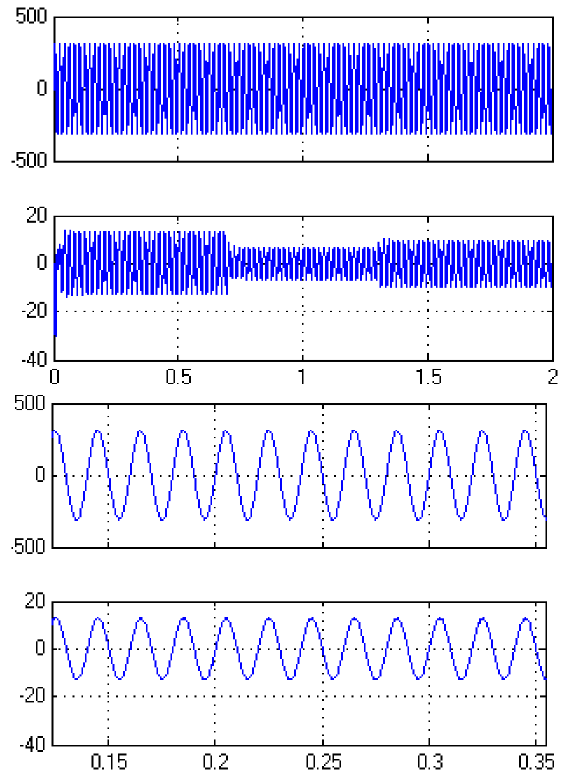

Fig. 20 Phase *a* voltage and current into the grid

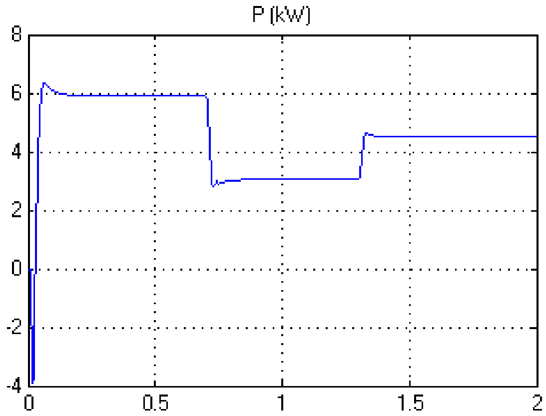

Fig. 21 Power devoted to the grid

V. Conclusions

In the formed diagram is not include the wind turbine model and the wind action. Like input is examined directly the load torque applied to the generator shaft.

From speed diagram in fig.15 is shown that through speed feedback generator speed remains constant at load torque changing. The generator speed could be changed on purpose getting maximum power at different wind speeds. In fig. 18 we can see that the input voltage of grid inverter stays constantly and support the needed level. In fig. 19 we could conclude that in the grid cannot produce reactive power. The same conclusion we could make in fig. 20, where phase *a* voltage and phase *a* current are in phase. In fig. 21 is shown the devoted power to the grid diagram.

Based on its value we could draw a conclusion for system correct and energy conversion. It is interesting to mark that in practice there is no difference grid inverter controlling of wind generator and photovoltaic generator to grid connecting.

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