Sliding Mode Control of a Doubly- Fed Induction Generator(DFIG) for Wind Energy Conversion System

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Abstract: *The wind energy usage is one of the most important renewable energy with economic justification in the world. Due to the growing needs to the electrical energy, increased environmental pollutions and limitation in the fossils power resources, using of this energy in the power industry is necessary and inevitable. The broad use of wind Turbines in the power systems have caused that this Turbines have a decisive rule in these systems. So because of the better power quality of the Variable speed wind turbines, they are more applicable than the constant speed Turbines. Nowadays Speed control in doubly fed Induction Generator (DFIG) because of the advantages such as: good quality control, high efficiency, Improving power quality, no need to the capacitor banks and cost affectivity are used to have more. This paper presents a speed control of one doubly fed Induction Generator according to the sliding mode controller with the use of simulation in the MATLAB/Simulink environment and the simulation gained results demonstrate the ability of the proposed control strategy.*

Keywords: *Doubly Fed Induction Generator (DFIG), Wind Farm, Variable Speed Wind Turbine, Sliding Mode Control, Power Converter.*

1. INTRODUCTION

At the present time many countries are using of the wind energy as a constant energy. The installed capacity at the wind power is more than 25 GW worldwide. The wind Turbines systems including of the wind Turbines with constant speed armed with one induction generator, variable speed armed with one squirrel cage induction generator and/or synchronous, variable speed with multi-pole permanent magnet synchronous generator and wind turbine with variable speed armed by Doubly fed induction generator (DFIG) which nowadays the most usage of the turbines in the wind farms are based on the Doubly fed induction generator for the reasons that they have some of the outstanding features such as the ability to produce different speed, the ability to control active and reactive power, improvement of power quality, reduce costs related to inverter, etc. [1,2,3]. Variable speed in these turbines will make this ability in them that they can be in broader area of the winds and work in their maximum efficiency. In this system will use of a wound-rotor induction generator that this wounded rotor connect to the network via the sliding rings to a converter machine and the stator machine. One of the most important advantages of DFIG is that equipment of the power electronic is the only carrying a fraction of the total power around 20 to 30%, this means reduction of losses and costs in the electronic power converter. In addition to the providing necessary conditions for electrical network a wind system control zone has duty to provide possible maximum transferring wind energy in the best efficiency, in this regard different controlling methods has been proposed by the researcher[4,5]. In this article for the control of the speed of Doubly Fed Induction Generator from a sliding mode control has been used. Sliding mode control theory is proposed by Utkin at 1977, after that theoretical works and its applications from the sliding mode control have been developed. Since one of the most important benefits of sliding mode control is the “robustness” and this method is a nonlinear control method, so this will be used in the systems which there are uncertainty. This uncertainty may be structural (parameters uncertainty) and/or non-structural, for example is not modelled dynamics. In this control method stability will be gained by holding of states of the system on the sliding base[5,6,7]. This paper offers a control method for inverter machine in order to regulate active and reactive power’s been exchanged between machine and grid, in which the control of the active power is for the wind speed to be adapted in a wind energy inverter system and the control of the reactive power allows to reach a unity power factor between grid and stator.

2. OVERVIEW OF DOUBLY FED INDUCTION GENERATOR

The tremendous progress in the field of development of the wind turbines in order to power production has been started since 1975. The first modern turbine was connected to the grid around 1980. With development of usage of the wind energy and wind power production DFIG is using widely nowadays. The reason which this type of generator is calling as doubly fed induction generator is that, the produced electrical power transfers by two ways, stator as well as rotor. These generators are at the especial attention because of their features which they have in the work with variable wind speed. The use of the wind power plants with variable speed has advantages in the compare with the wind power plants with constant speed. Although the wind power plants with constant speed are able to be connected to the grid directly, but wider energy range will be covered by wind power plants with variable speed, on the other hand they have lesser mechanical stress and lesser noise. Nowadays with development of the power electronics control of all the speeds is possible and cost effective[8,9]. This paper deals with DFIG with variable speed which has important feature in the working with variable wind speed. As it has shown in the figure 1, the structure of a wind power plant designs in which the stator’s orbit of DFIG connect directly and rotor’s orbit of that connect by back to back converter (generator side converter and grid side converter) with slippery rings to the grid. Between two converters a capacitor that is calling as dc link are using as energy saver and to reduce voltage ripple[10,11].

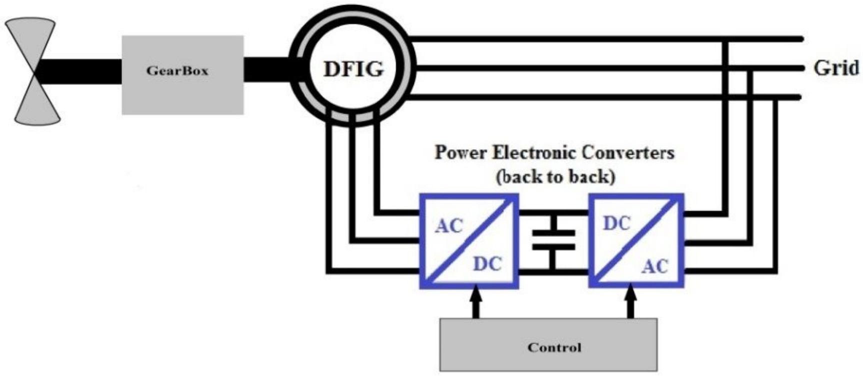

Figure1. A grid connected doubly-fed induction generator and its convertors

At the normal operation mode DFIG can control active and reactive power separately via grid side converter. Furthermore the rotor side converter can take away the need of the soft starter at the time of grid connection. Two subsystems known as mechanical and electrical systems are present that will show the overall control plane of the DFIG. The control systems have been designed for different purposes, but the main goal is to control power to be injected to the grid[12].The active power released to the grid controlling by the rotor side converter, while injected reactive power controlling by both converter (figure 2).

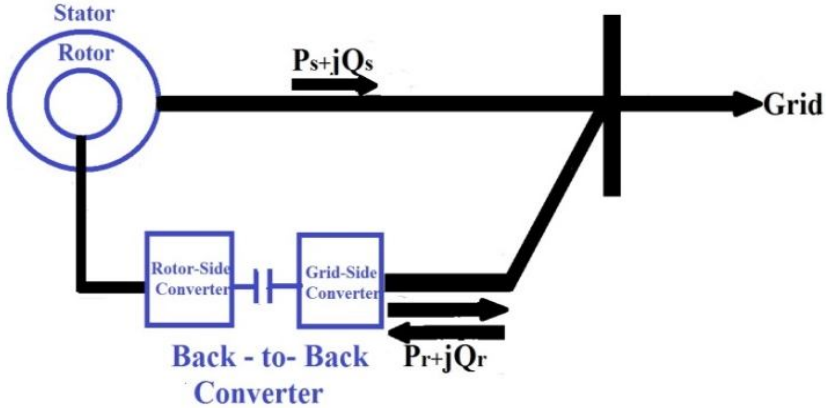

Figure 2.doubly fed induction generator

The electrical system also for the purpose of the protection against overloading has been constructed. The mechanical subsystem for gag of the mechanical power output of the wind turbine by pitch adjustment has been designed. For the reason that, design of the low speed multipolar DFIG is not possible technically, for the DFIG base on the wind energy conversion systems gearboxes are still required. Use of the DFIG will make giving a good power factor to us possible even at the time which machine speed is out of the synchronous speed [12,13].

3. WIND GENERATION SYSTEM MODELING

3.1. MODELING OF THE DFIG

For the DFIG system modeling with variable wind speed the following is needed to be modeled: DFIG, turbine, the control unit as well as design a sliding mode controller which this paper will investigate all respectively. In the rotating field wound rotor induction machine model has shown in the figure 3. [14].

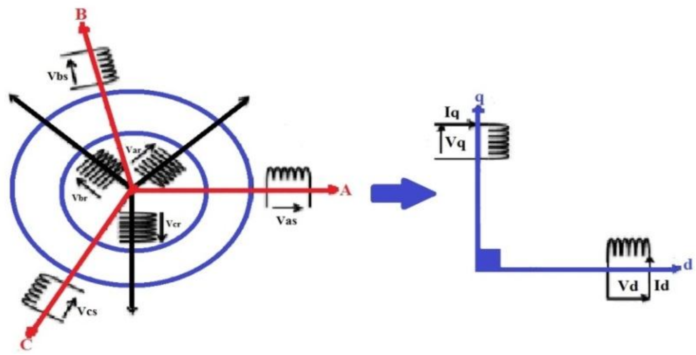

Figure 3. Model of PARK of the DFIG

The equivalent circuit of a doubly fed induction machine with referring to the magnetic losses has shown in figure 4 and the mathematical machine model has been written in order to gaining of a decoupled system from control at a suitable reference field (d-q) with a fixed stator flux. In this case the flowed active and reactive power control between DFIG stator and power grid with use of the sliding mode controller will be synthesized[15,16].

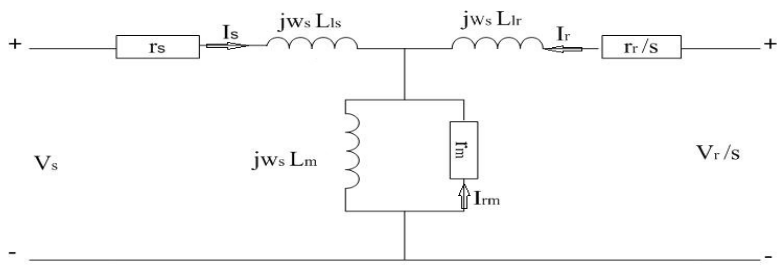

Figure 4. equivalent circuit of DFIG

DIFG classic electrical equation in the park field will be written as follow[4,17]: Stator and rotor voltage equations:

$$V_{ds} = \frac{d}{dt}\Phi_{ds} - \omega_s \Phi_{qs} + r_s i_{ds}$$
$$V_{qs} = \frac{d}{dt}\Phi_{qs} + \omega_s \Phi_{ds} + r_s i_{qs} \qquad (1)$$
$$V_{dr} = \frac{d}{dt}\Phi_{dr} - (\omega_s - \omega)\Phi_{qr} + r_r i_{dr}$$
$$V_{qr} = \frac{d}{dt}\Phi_{qr} + (\omega_s - \omega)\Phi_{dr} + r_r i_{qr}$$

the flux equations for stator and rotor are such as:

$$\Phi_{qs} = (L_{ls} + L_m) i_{qs} + L_m i_{qr}$$
$$\Phi_{ds} = (L_{ls} + L_m) i_{ds} + L_m i_{dr} \qquad (2)$$
$$\Phi_{qr} = (L_{lr} + L_m) i_{qr} + L_m i_{qs}$$

$$\Phi_{dr} = (L_{lr} + L_m)i_{dr} + L_m i_{ds}$$

Torque generated of DFIM Based on stator currents and rotor flux is shown as follows:

$$T_e = \frac{3}{2} P \frac{L_m}{L_r} (\Phi_{dr} i_{qs} - \Phi_{qr} i_{ds}) \qquad (3)$$

here P is the number of pairs of the poles. Mechanical dynamic equation is expressed as follows:

$$J \frac{dw_m}{d_t} + Bw_m = T_e - T_L \qquad (4)$$

Here J and B are Moment of machine inertia and friction coefficient respectively. T_L is the external load torque and ω_m is the rotor's mechanical speed.

The total active and reactive power production is as follow:

$$P = V_{ds} i_{ds} + V_{qs} i_{qs} + V_{dr} i_{dr} + V_{qr} i_{qr} \qquad (5)$$

$$Q = V_{qs} i_{ds} - V_{ds} i_{qs} + V_{qr} i_{dr} - V_{dr} i_{qr}$$

3.2. Modeling of the Wind Turbine and Gearbox

Wind Energy Conversion Systems (WECS) are the sets which are using to conversion of the wind energy to mechanical energy. The amount of capacity which is receivable as P_t by wind turbine has direct proportion with power coefficient C_p and also its relationship is as follow:

$$P_t = \frac{1}{2} C_p(\lambda, \beta).\rho_{air}.R^2.V^3 \qquad (6)$$

The ρ_{air} is air density, R is expressed as Blade radius, V consists of air speed, and B is angel of the blade's turbine. The power coefficient curve $C_p(\lambda, \beta)$ for a given speed will be expressed base on the λ . The turbine torque is the ratio of output power to shaft speed w_t and is equal to:

$$T_t = \frac{P_t}{w_t} \qquad (7)$$

The turbine normally connects to the shaft generator by gearbox that the ratio of its gear is equal to G, on the other hand shaft speed of the generator be chosen in such a way at suitable speed area. Regardless of the transfer losses, torque and shaft speed of the wind turbine which is related to the gearbox side is given by the below equation:

$$T_m = \frac{T_t}{G} \quad And \quad \Omega_{mec} = G.\omega_t \qquad (8)$$

which in that T_m is torque of the generator and Ω_{mec} is as wind turbine's mechanical speed. The wind turbine is able to produce a certain amount of the power proportional with wind speed. This amount which is expressing by C_p is a function of wind speed and also it is a function of Pitch angle blades of the wind turbine[4,18]. Although this equations looking simple, C_p is depends on the λ relation that is actually between turbine's angular velocity w_t and wind speed V. this ratio is known as tip speed ratio and is such as:

$$\lambda = \frac{\omega_t.R}{V} \qquad (9)$$

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V. The relation between C_p and λ is shown in the figure 5, as it is clear some of the λ there is a return to C_p that will be maximum and this factor causes maximum of the power for the given wind speed.

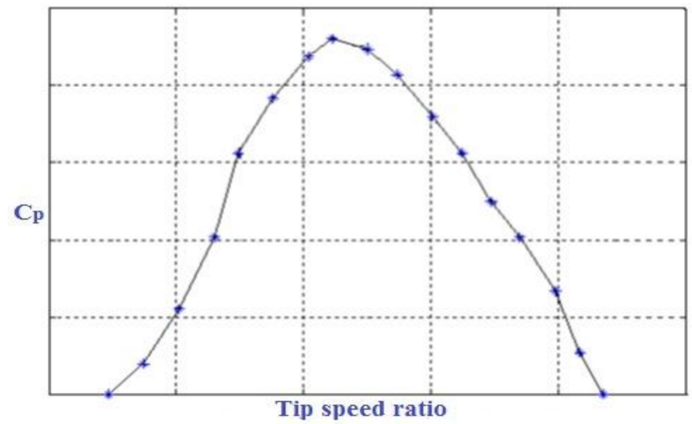

Figure 5. Aerodynamic power coefficient variation C_p against tip speed ratio λ

Figure 6 is showing the simulated overall schematic for the wind turbine, gearbox and shaft.

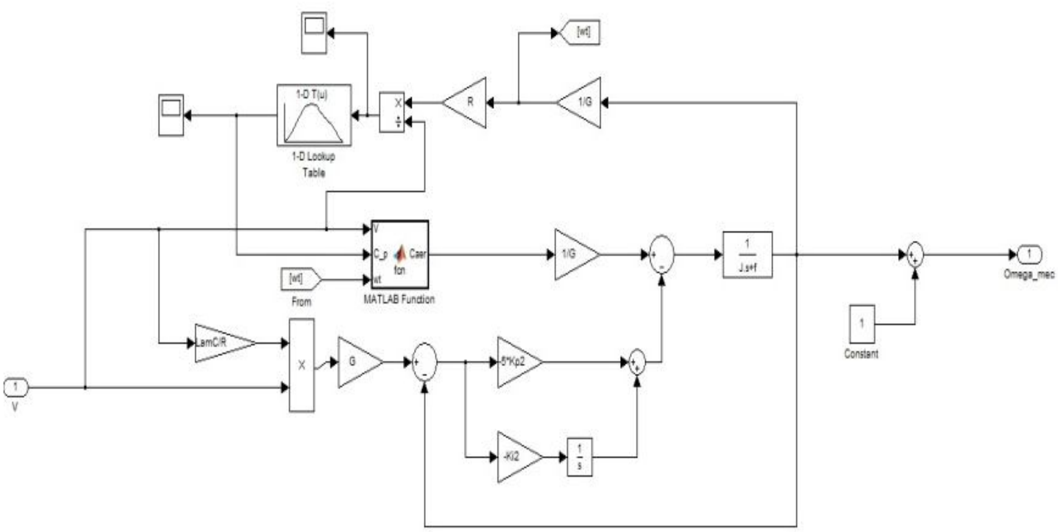

Figure 6. simulated overall schematic for the wind turbine, gearbox and shaft.

4. WIND TURBINE CONTROL BY DFIG

Control of the fixed output DFIG idea is for stator; such as three phase voltage, frequency and output power function that feed network via stator current. Control of the machine is by converter; moreover output active power can be controlled by slope of turbine blades which it is adjusting on the β angel blade. In other words, coefficient of aerodynamic efficiency changes the rotor's blade angel. If the wind speed exceeds the rated value, this angel control is used for output power fixation. The wind turbine with doubly fed induction generator are include two main controls which are involve back to back converter and vane angel control, which we will investigate any each of them[19,20].

4.1. Back to Back Converter Control

The back to back converter is including of four main parts: including of two inverters, that each of them besides switching control have another control as well, which rotor side converter is responsible for voltage control or reactive power and extraction of the optimal power from the wind, network side converter is responsible for control of the DC bus voltage amount, DC which is interface of the two converter and transformer or series reactors which connects the converter to the network.

4.1.1. Rotor Side Converter (RSC) control

The main task of this converter is output power control and terminal voltage of the DFIG. In this method the rotor side converter is similar to common methods use in the doubly fed induction generator. Converter controls will be modeled base on the rotor controlled voltage source, so in the space of two axial d and q the amount of the rotor's d and q axial voltage should be clear.

4.1.2. Grid Side Converter (GSC) control

Since DFIG base on the wind system is sensitive to the voltage changes, disturbed grid voltage conditions should be considered in the quality design of GSC. As noted the most important task of grid side converter is regulate bus voltage regardless of the rotor power flow side, so V_{dc} should be compared with its reference amount and applies to a PI controller to take the amount of the flow at the grid side converter. Control of the GSC by use of the merged Sliding mode controller (SMC) and PI controller under grid disturbances for the dynamical control performance evaluation of DFIG has been done in this paper.

4.2. Vane angle Control

According to the C_p- λ curve shown in figure 5, in order to maximum power extraction of the wind, zero helix angels should always be considered unless the rotor speed is greater than the allowable. So, for the control of vane angel only the velocity difference between the maximum speeds should apply to a PI controller and area of changes can be limited between zero and maximum angel. Also it should be noted, speed changes of the vane angel should not be more than a clear amount.

5. DESIGN OF SLIDING MODE CONTROL ALGORITHM

The sliding mode control is a nonlinear control method which guarantees the control strategy in the face of uncertainty. In this case the system stability is obtained by keeping the system's states on the sliding surface. The sliding mode controller is a variable structure controller which switches with high-frequency between several control rules. Basically, the variable structure controller is including of several different continues environs that can map plant state to a control surface, while switching between different environs by shown plant state is determined by a function switching Controller implements a nonlinear control rule in order to drive and keep the state of the system on a favourable hyper surface. A special issue about control plan is that define a sliding surface with property guaranteed of stability and attractiveness[21]. The sliding mode method has high flexibility, also it is effective and very strong method (quite robust), and on the other hand it needs relatively less information about the system and also is insensitive to the parametrical changes of the system. The sliding mode controller doesn't need to the mathematical models accurately like classical controllers but needs to know the range of parameter changes for ensuring sustainability and condition satisfactory [22]. The block diagram of the SMC in a variable speed wind turbine application in this paper is shown in Figure. 7

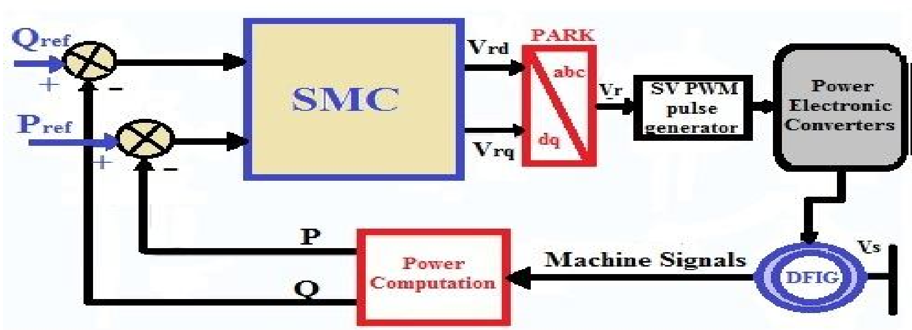

Figure 7. Block diagram of a sliding mode control of a DFIG.

The sliding mode control method is including of the competent of the calculation of equivalent and discontinuous variable control from a favourable surface of the selected sliding mode[23,24].

$$S(\phi_{dr}) = \overset{*}{\phi}_{dr} - \phi_{dr} , S(\phi_{qr}) = \overset{*}{\phi}_{qr} - \phi_{qr} \qquad (10)$$

Reference fluxes ϕ_{qr}, ϕ_{dr} will be defined in accordance with the objectives control of stator current. In the sliding mode regimen of the system dynamic in the sliding mode is subjecting to the following conditions: $\dot{S}(\phi) = 0$ and we have for the ideal sliding mode: $S(\phi) = 0$. Reference stator voltage components in order to sliding mode conditions define as follow: Reference stator voltage components in order to sliding mode conditions define as follow:

$$V_{dreq} = \overset{*}{\phi}_{dr} + \frac{1}{Tr}\phi^{*}_{dr} - W_r\phi^{*}_{rq} - \frac{1}{T_r} l_m i^{*}_{ds} \qquad (11)$$

$$V_{qreq} = \overset{*}{\phi}_{qr} + \frac{1}{Tr}\phi^{*}_{qr} + W_r\phi^{*}_{dr} - \frac{1}{T_r} l_m i^{*}_{qs}$$

V_{dreq} and V_{qreq} are component of the rotor voltage respectively. The stator currents sliding surface will be calculated based on the below equations:

$$S(i_{ds}) = \overset{*}{i}_{ds} - i_{ds} , S(i_{qs}) = \overset{*}{i}_{qs} - i_{qs} \qquad (12)$$

The reference rotor flux in the sliding mode regimen is determined by below equation:

$$\phi^{*}_{dr} = \frac{\sigma l_r}{W_s l_m}\left(\frac{r_s}{\sigma} i_{ds}{}^{*} - W_s i^{*}_{sq} - \frac{1}{\sigma}u - \frac{r_s}{\sigma w_s} i_{qs}{}^{*}\right) \qquad (13)$$

$$\phi^{*}_{qr} = \frac{\sigma l_r}{W_s l_m}\left(-\frac{r_s}{\sigma} i_{qs}{}^{*} - W_s i^{*}_{ds} - \frac{r_s}{\sigma w_s} i_{ds}{}^{*}\right)$$

where σ is the total leaking constant and determines as below: $\sigma = l_s(1-\frac{l^2{}_m}{l_s l_r})$ .Rotor voltage of references defines as follow:

$$V^*{}_{qr} = V_{qreq} - V_{qrn}\,, V^*{}_{dr} = V_{dreq} - V_{drn} \qquad (14)$$

where n shows discrete components of the rotor voltage of reference. The designed control unit has shown by MATLAB/Simulink software at the below figure.

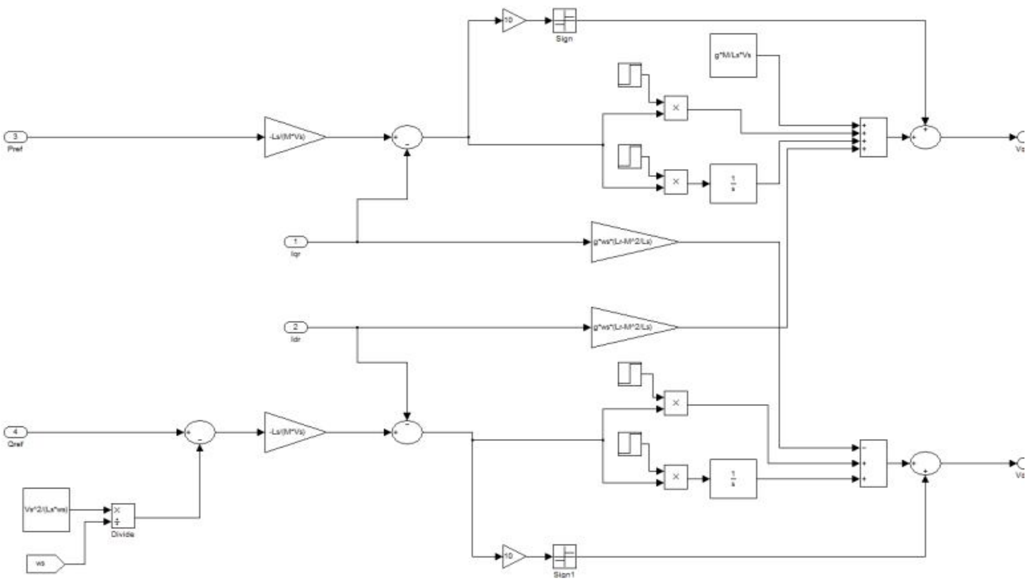

Figure 8. Diagram of the control strategy

A simple form of control operation is a relay function by sliding mode theory. Design of the control unit is expressed by use of equation (15) which in that we see fusion of sliding control unites and PI.

$$U_{dq} = U_{PI} + K * sign(S_{dq}) \qquad (15)$$

6. Simulation Results and Discussion

To verify the proposed method, simulation results of a DFIG generator sample has shown by MATLAB /Simulink software in this section. In this section the performance of the DFIG system is analysed under grid voltage fluctuations. The wind turbine is of doubly fed induction generator type. The sliding mode controller has been achieved base on the stator flux orientation reference in order to control of the active and reactive powers by direct component and stator flows second degree and via desired power flow between grid and generator in the MATLAB environment (figure.9).

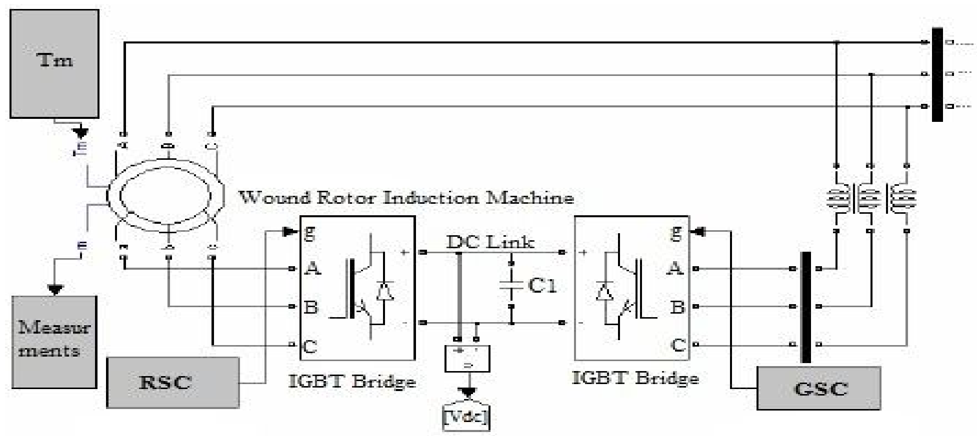

Figure 9. configuration of wind turbine and DFIG system with MATLAB

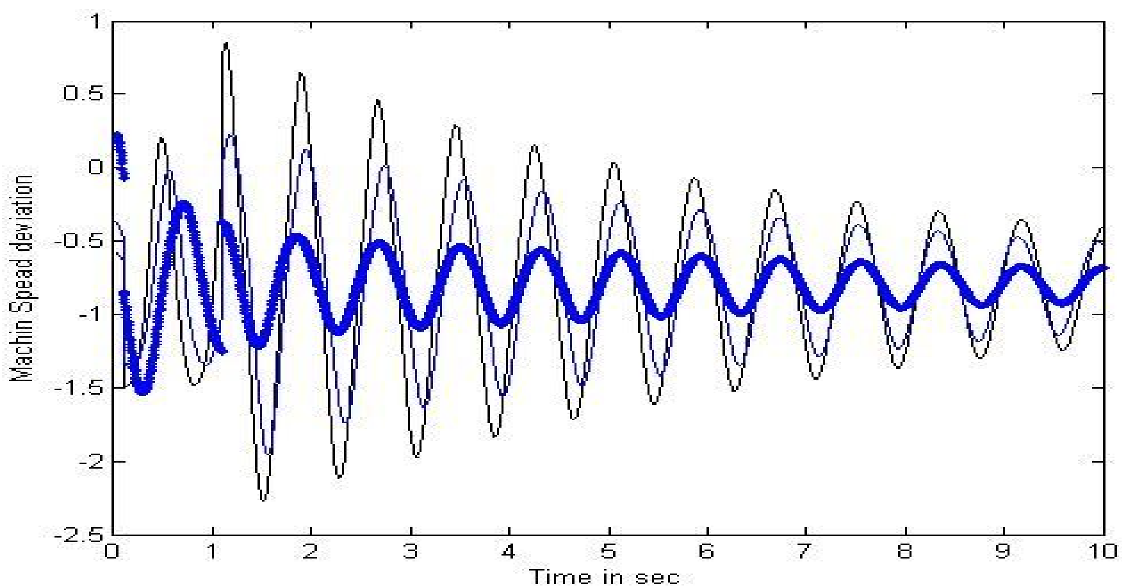

Figure10. Machin Speed Deviation per Sec

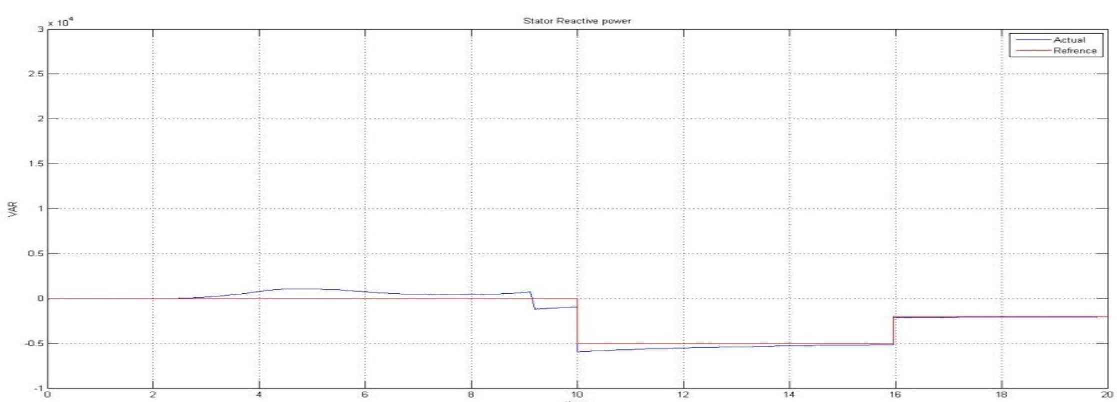

Figure 11. stator reactive power

Figure 11, As it has shown it is related to the stator reactive power along with reference amount as well as the real amount which this amount convergent very fast to the reference amount.

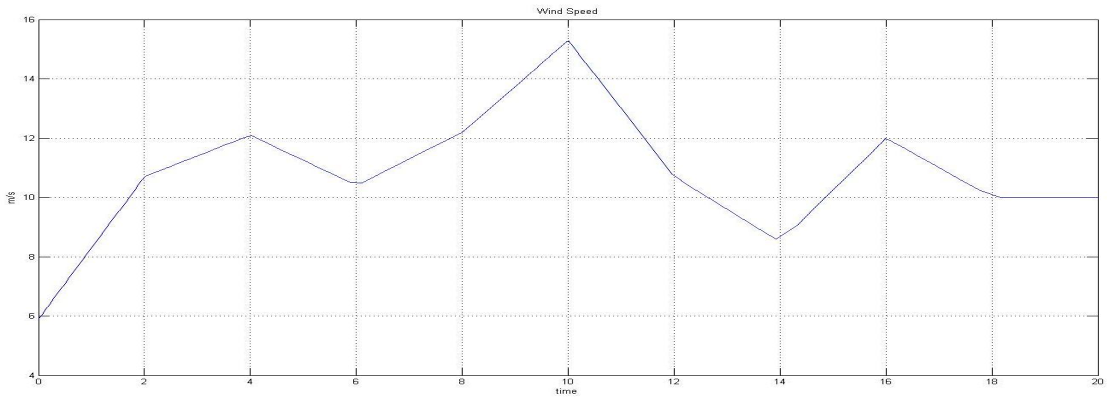

Figure 12. Variable speed of wind Turbine

Figure 12, It is related to variable speed according to the time related to the wind turbine.

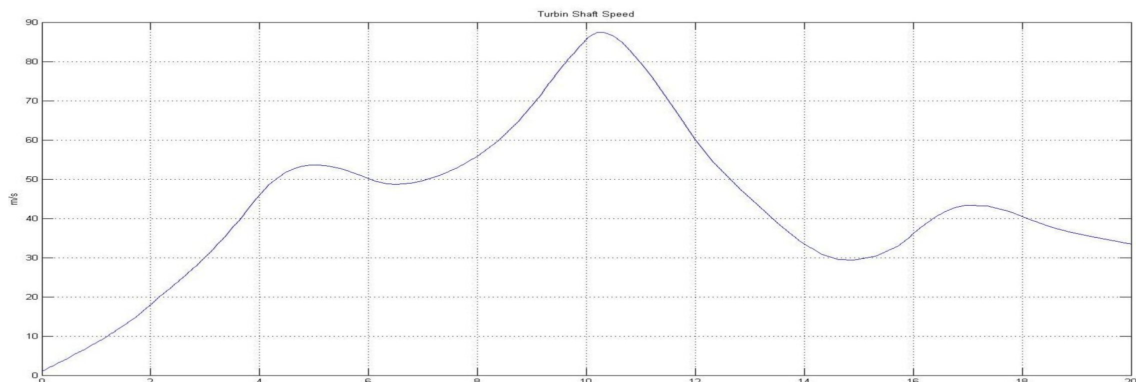

Figure 13. Shaft speed of wind Turbine

Figure 13, The speed of the turbine shaft has been demonstrated which this speed is proportional with wind speed.

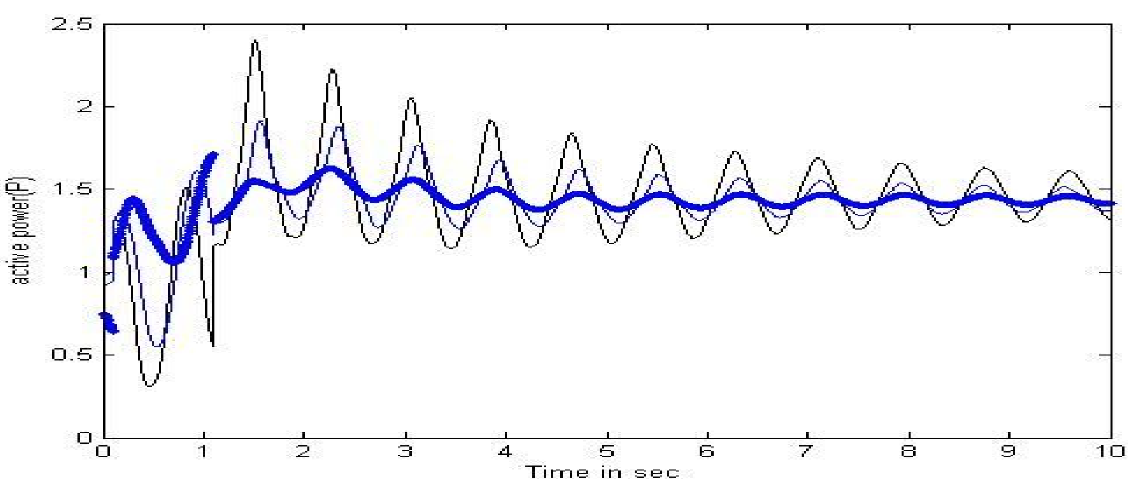

Figure 14.Active power of rotor

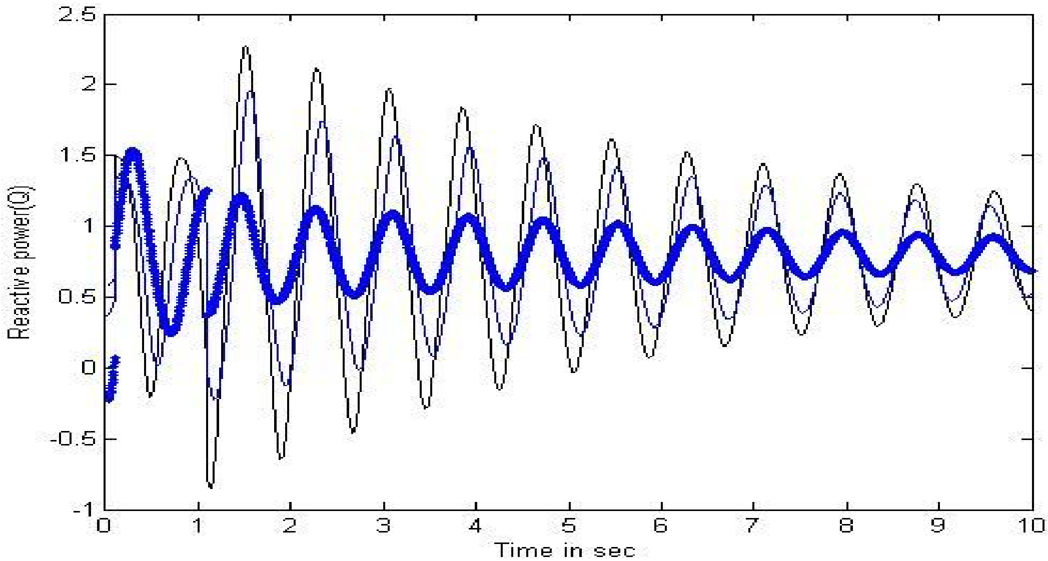

Figure 15. Reactive power of rotor

Figure 14, 15: these figures are related to active and reactive powers of rotor but these are unwanted powers and much less can be better.

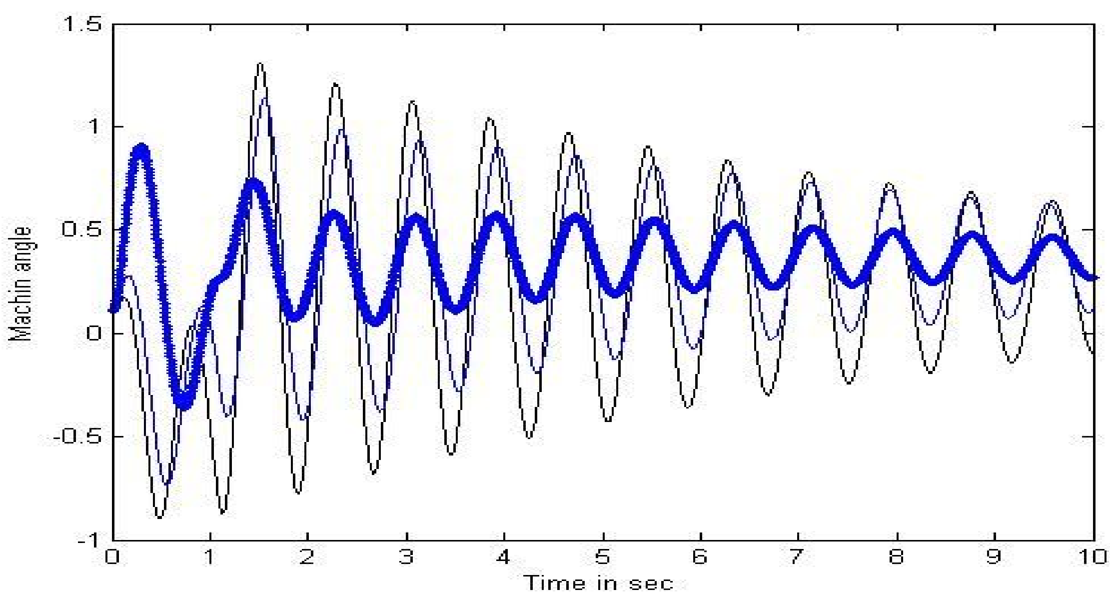

Figure 16. Machin angle per Sec

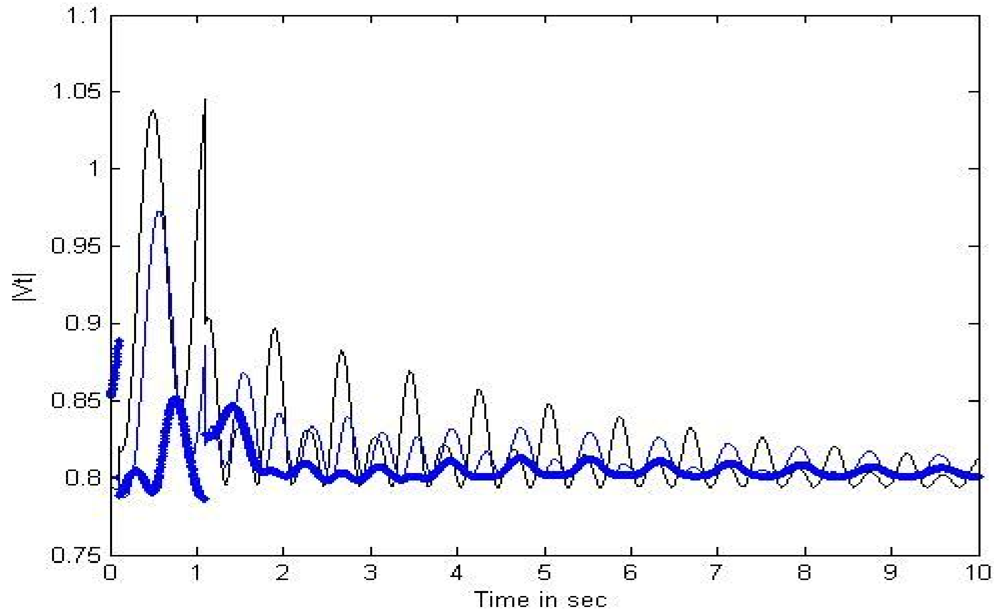

Figure 17. DFIG Terminal voltage

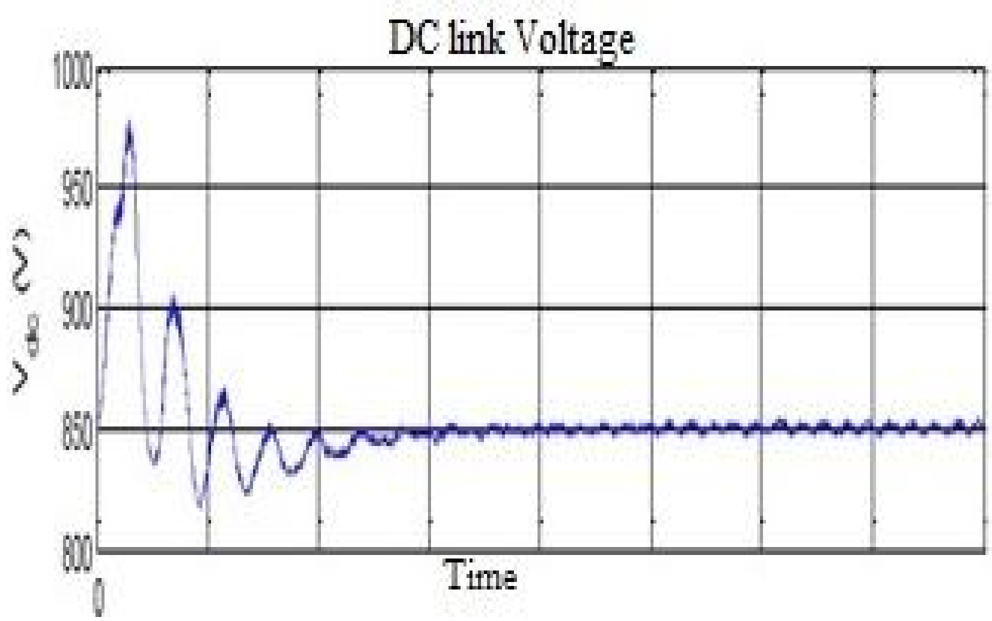

Figure 18. DC link Voltage under balanced grid

7. CONCLUSION

In this paper a complete system for electrical energy production by use of the doubly fed induction generator (DFIG) has been done via wind turbine. The studied system has been formed of a DFIG with stator and rotor, which in that stator has connected to the grid directly and rotor has connected to the grid via two converter, machine converter and grid converter. Control of the machine inverter provides at the first a set of active and reactive powers exchanged between the grid and the machine. With the consideration of turbine variable velocity state and design controller for DFIG in form of using of the sliding mode, we have reached to the favourable results in spite of the uncertain system active and reactive powers.

NOMENCLATURES

P_{aeor}	The wind available power,
T_t	Wind turbine torque (Nm),
V	Wind speed (m/s),
R	Blade radius (m),
ρ_{air}	Air density,
β	Pitch angle,
P	Number of pole pairs,
C_p	Power coefficient,
ω_t	Wind turbine angular speed (shaft speed) (rad/s),
Ω_{mec}	Wind turbine Mechanical speed (rad/s) ,
λ	Tip speed to wind speed ratio of the Wind Turbine,
G	Mechanical speed multiplier (gearbox) ,
J	Moment of inertia,
B	Coefficient of viscous friction,
$V_{ds}, V_{qs}, V_{dr}, V_{qr}$	Stator and rotor voltage components in the d-q reference frame,
$I_{ds}, I_{qs}, I_{dr}, I_{qr}$	Stator and rotor current components in the d-q reference frame,
$\Phi_{ds}, \Phi_{qs}, \Phi_{dr}, \Phi_{qr}$	Stator and rotor flux components in the d-q reference frame,
ω_s, ω_r	Stator , Rotor Pulsation,
T_m, T_e	Mechanical and electromagnetic torques respectively,
L_s , L_r	Stator and rotor inductances,
L_m	Magnetizing inductance
r_s, r_r	Stator and rotor resistances,
T_L	External load torque
ω_m	Rotor mechanical speed
P, Q	active and reactive grid powers
σ	total leaking constant

APPENDIX: PARAMETERS

Rated Power(DFIG)	1.5MW
V_s (Stator Voltage) (DFIG)	300/690V
B (Coefficient of viscous friction) (DFIG=+Turbine)	0.071 / *.N. m .s/ rd*
r_s (Stator Resistance) (DFIG)	0.012 ohm
r_r (Rotor Resistance) (DFIG)	0.021ohm
R(Blade radius)(Turbine)	2m
L_s (Stator Inductance) (DFIG)	13.732mH
L_m (Mutual Inductance) (DFIG)	13.528mH
L_r (Rotor Inductance) (DFIG)	13.703mH
J(Moment of inertia) (DFIG=+Turbine)	50kg.m2
P (Poles Pairs) (DFIG)	2
Rated Speed(DFIG)	100rad/s
F (Nominal frequency) (DFIG)	50Hz

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