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Variable Structure Control Applied in Wind Turbine Based on Induction Generator

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Abstract- In this paper, the wind electrical conversion system (WECS) is described; the structure of WECS is based on the Induction generator. The global model of the WECS is presented. A study of the electrical parts (Induction machine and static converter) is developed. The goal of this paper is to control the power generated by the WECS to the grid. A strategy of control is developed signed based on the vector control applied to Induction Machine. A new controllers are designed using sliding mode techniques to control active and reactive power. Simulation study was done to prove the validation of the strategy and the method of control used in power control. Conclusions are summarized in the last section.

Keywords- Wind energy, Synchronous generator, Wind turbine, Power control.

1. Introduction

The use of wind energy is increasing these last years. The power generated by the wind varies greatly throughout the day; it depends on the power available in the wind and has the same variation. The need of energy has increased significantly. The use of renewable energies is indispensable. Renewable energies are clean and constitute an alternative to meet the needs of today's society. These energies neglected in the past, find their proper place, obtained through research and studies that are increasingly diverse and multidisciplinary. Consumption of energy has increased in recent years because of massive industrialization which tends to grow more and more, specifically in certain geographic areas as Asian countries [1]. The consequence of the increasing consumption affects significantly the environment and the World reserves of fossil fuel.

Several sources of renewable energy are object of advanced researches, which aim to develop techniques for extracting power with high reliability, lower cost and increased energy efficiency [2-4].

In this paper, we focus on the conversion of wind energy into electrical energy that has become competitive due to three main factors [2]:

- Wind energy is clean, renewable and naturally replenished by nature,
- The development of the wind turbine industry,
- The evolution of semiconductor technology, and new methodologies for control of variable speed turbines.

In this context, the present study focuses on wind energy using Induction generator. The aim of this paper is to present a comprehensive model of a induction generator based on a proposed structure and control strategies to optimize and control the power output transmitted to the network [1], [8].

The organization of this paper is as follow: in the second section, we establish the model of the wind conversion system. The third and fourth section are devoted to vector control of IG and the control strategy of the WECS. In section 5, we develop power controllers based on sliding mode techniques. The sixth section is devoted to the simulation results and finally conclusions are summarized in the last section.

2. Wind Conversion System Model

The WECS described in this article includes the wind turbine, Induction generator, a diode rectifier, a filter and a PWM controlled inverter. In this system, the wind energy is transmitted through the turbine to the three-phase Induction machine and generated in electrical form. This energy is transmitted directly to grid. The control of the power extracted and transmitted to the grid is done by the control of the rotor voltages (Figure 1). Figure (1) shows the equivalent diagram of the electrical portion of the string conversion of wind energy.

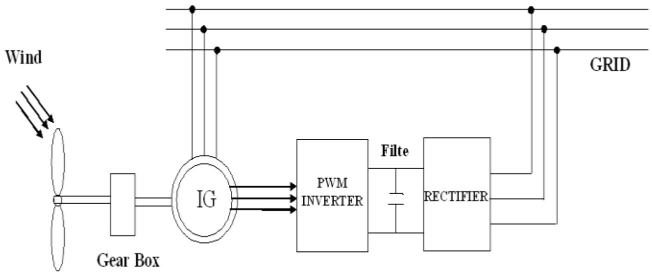


Fig. 1. Wind system based on Induction generator.

2.1. Turbine Model

The turbine power and torque developed are given by the following relation [2,5, 6]:

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda) \quad (1)$$

$$T_m = \frac{P_m}{\Omega} = \frac{1}{2\lambda}\rho\pi R^3 v^2 C_p \quad (2)$$

Which λ presents the ratio between the turbine angular speed and the wind speed. This ratio called the tip speed ration and is defined as:

$$\lambda = \frac{\Omega R}{v} \quad (3)$$

Where: ρ is the air density, R is the blade length, v is the wind speed, C_p is the power coefficient, Ω is the turbine angular speed.

The power coefficient (C_p) presents the aerodynamic efficiency of the turbine and depends on the specific speed λ and the angle of the blades.

It is different from a turbine to another, and is usually provided by the manufacturer and can be used to define a mathematical approximation.

Figure (2) represents the power coefficient C_p as a function of β and λ.

Figure (3) shows the mechanical power as a function of rotor speed of the turbine for different values of wind speed [10].

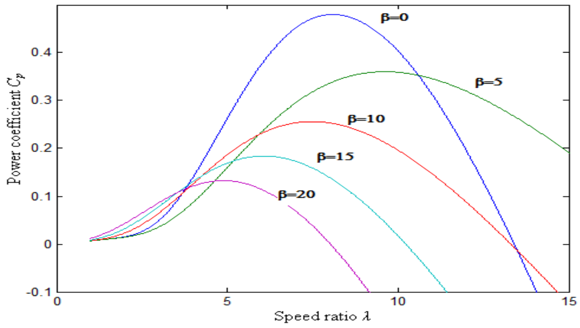


Fig. 2. Power coefficient as a function of and

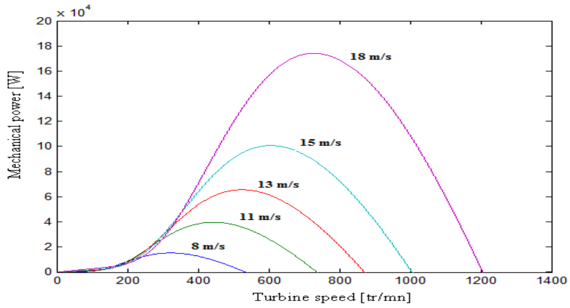


Fig. 3. The characteristics of the mechanical power as function of the turbine

2.2. Generator Model

The generator chosen for the conversion of wind energy is the Induction generator [7-9]. The dynamic model of Induction generator in d-q frame can be represented by the following equations:

The electrical equations are:

$$\begin{aligned} v_{ds} &= \mathrm{R_s}\, i_{ds} + \frac{\mathrm{d}}{\mathrm{dt}}\phi_{ds} - \omega_s\, \phi_{qs} \\ v_{qs} &= \mathrm{R_s} i_{qs} + \frac{\mathrm{d}}{\mathrm{dt}}\phi_{qs} + \omega_s\, \phi_{ds} \\ v_{dr} &= \mathrm{R_r}\, i_{dr} + \frac{\mathrm{d}}{\mathrm{dt}}\phi_{dr} - \omega_r\, \phi_{qr} \\ v_{qr} &= \mathrm{R_s} i_{qr} + \frac{\mathrm{d}}{\mathrm{dt}}\phi_{qr} + \omega_r\, \phi_{dr} \end{aligned} \quad (4)$$

The flux linkage equations are:

$$\begin{aligned} \phi_{ds} &= \mathrm{L_s} i_{ds} + \mathrm{M_{sr}} i_{dr} \\ \phi_{qs} &= \mathrm{L_s} i_{qs} + \mathrm{M_{sr}} i_{qr} \\ \phi_{dr} &= \mathrm{L_r} i_{dr} + \mathrm{M_{sr}} i_{ds} \\ \phi_{qr} &= \mathrm{L_r} i_{qr} + \mathrm{M_{sr}} i_{qs} \end{aligned} \quad (5)$$

The mechanical equation of synchronous generator can be represented as:

$$\mathrm{J}\frac{\mathrm{d}}{\mathrm{dt}}\Omega = T_W - T_e - B\Omega \quad (6)$$

Where the electromagnetic torque is given in d-q frame:

$$T_e = p(\phi_{ds} i_{qs} - \phi_{qs} i_{ds}) \tag{7}$$

In which: $\Omega = \frac{d}{dt}\theta$, $\omega = \frac{d}{dt}\theta_e = p\Omega$, $\theta_e = p\theta$.

Where R_s - stator resistance, L_{ds},L_{qs} - respectively direct and quadrature stator inductances, L_f - field leakage inductance, M_{fd} - mutual inductance between inductor and armature, ϕ_{ds} and ϕ_{qs} - respectively direct and quadrature stator flux, ϕ_{dr} and ϕ_{qr} - respectively direct and quadrature rotor flux, T_W - Wind torque applied to IG rotor, T_e - electromagnetic torque, p - pair number of poles, B - is the damping coefficient, J - is the moment of inertia, ω_s - electrical angular speed of stator, ω_r - electrical angular speed of rotor, ω - electrical angular speed of motor. Ω - mechanical angular speed, θ - mechanical rotor position, θ_e - electrical rotor position.

3. Control Strategy

To control the active and reactive power transmitted to the grid, we proceed to control the direct and quadrature current. It is possible to control the load power by the action on reference voltages of the PWM inverter. These reference voltages can be determinated by the current PI controller.

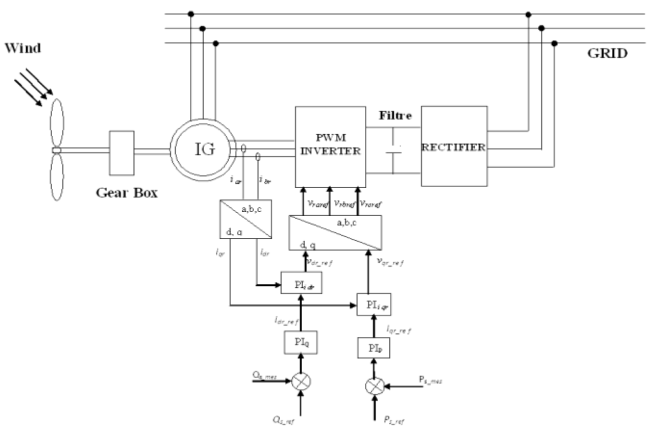


Fig. 4. Diagram block of power and currents Control.

The active and reactive powers generated by Induction machine are given in the Park model by the following relations:

$$\begin{aligned} P_s &= V_{ds} i_{ds} + V_{qs} i_{qs} \\ Q_s &= V_{qs} i_{ds} - V_{ds} i_{qs} \end{aligned} \tag{8}$$

The stator flux vector is orienting according to the d axis in the Park's reference frame. Where: A simplified assumption is made in our case since:

$$\phi_{qs} = 0, \ \phi_{ds} = \phi_s \tag{9}$$

And then

$$V_{qs} = V_s, \ V_{ds} = 0 \tag{10}$$

The equation (8) becomes:

$$\begin{aligned} P_s &= V_{qs} i_{qs} \\ Q_s &= V_{qs} i_{ds} \end{aligned} \tag{11}$$

From equation (4, 5, 11) we can obtain, The equation (11) becomes:

$$\begin{aligned} P_s &= -V_s \frac{M}{L_s} i_{qr} \\ Q_s &= -V_s \frac{M}{L_s} i_{dr} + \frac{V_s \phi_s}{L_s} \end{aligned} \tag{12}$$

The control of the active and reactive power (P_{grid}, Q_{grid}) is achieved using conventional PI controllers. The block diagram is shown in Figure (5). The reference voltages in park model are obtained by current PI regulators. The Three-phase reference voltages (u_{ar}, u_{br}, u_{cr}) are calculated by Park transformation and got in the voltage-source PWM inverter.

4. Vector Control

The self-control operation of the Induction machine results in a rotor field oriented control of the Active and reactive power in the machine. The principle is to maintain the active and reactive power in a decoupled axis. The active power in the machine is controlled independently by the quadrature rotor current and the reactive power by the direct rotor current. Substituting (5) in (4) and using the equation (9), the rotor voltage can be rewritten as follow:

$$\begin{aligned} v_{dr} &= R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - g\omega_s \sigma L_r i_{qr} \\ v_{qr} &= R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + g\omega_s \sigma L_r i_{dr} + g\frac{MV_s}{L_s} \end{aligned} \tag{13}$$

Where: $\sigma = 1 - \frac{M^2}{L_r L_s}$, $g = 1 - \frac{\omega_s}{\omega_r}$

In the same conditions, it appears that the v_{dr} and v_{qr} equations are coupled. A decoupling system is established, by introducing the compensation terms v_{qr} and Fem_q in which

$$\begin{aligned} Fem_d &= g\omega_s \sigma L_r i_{qr} \\ Fem_q &= -g\omega_s \sigma L_r i_{dr} - g\frac{MV_s}{L_s} \end{aligned} \tag{14}$$

5. Sliding Mode Control

Consider a nonlinear system which can be represented by the following state space model in a canonical form [3, 18]:

$$x^{(n)}(t) = f(x(t),t) + g(x(t),t)u + d(t)$$
$$y(t) = x(t) \tag{15}$$

Where $x = \left[x(t)\ \dot{x}(t) \ldots x^{(n-1)}(t) \right]^T$ is the state vector, $f(x(t),\, t)$ and $g(x(t),\, t)$ are nonlinear functions, u is the control input, $d(t)$ is the external disturbances. The objective of the control is to determine a control law u(t) to force the system output y(t) in (15) to follow a given bounded reference signal yd(t), that is, the tracking error $e(t) = y_d(t) - y(t)$ and its forward shifted values, defined as

$$e^{(i)}(t) = y_d^{(i)}(t) - y^{(i)}(t)$$
$$= x_d^{(i)}(t) - x^{(i)}(t), \quad (i = 1, \ldots, n\text{-}1) \tag{16}$$

should be small. The design of SMC involves two tasks. The first one is to select the switching hyperplane to prescribe the desired dynamic characteristics of the controlled system. The second one is to design the discontinuous control such that the system enters the sliding mode and remains in it forever [3, 14].

In this paper, we use the sliding surface proposed par J.J. Slotine,

$$s(x,t) = \left(\frac{d}{dt} + \lambda \right)^{n-1} e(t) \tag{17}$$

In which $e = x_d(t) - x(t)$, λ is a positive coefficient, and n is the system order.

It remains to be shown that the control law can be constructed so that the sliding surface will be reached. Then, a sliding hyperplane can be represented as $s(x,t) = 0$.

Consider a Lyapunov function:

$$V = \frac{1}{2} s^2 \tag{18}$$

From Lyapunov theorem we know that if $\dot{V}$ is negative definite, the system trajectory will be driven and attracted toward the sliding surface and remain sliding on it until the origin is reached asymptotically [6]:

$$\dot{V} = s\,\dot{s} \tag{19}$$

The simplified 1st order problem of keeping the scalar $s(x,t)$ at zero can be achieved by choosing the control law u(t). A sufficient condition for the stability of the system is

$$\frac{1}{2}\frac{d}{dt} s^2 \le -\eta |s| \tag{20}$$

where η is a positive constant.

The equation (20) is called reaching condition or sliding condition. s(t) verifying (20) is referred to as sliding surface, and the system's behaviour once on the surface is called sliding mode.

If the control input is so designed that the inequality (20) is satisfied, together with the properly chosen sliding hyperplan, the state will be driven toward the origin of the state space along the sliding hyperplane from any given initial state. This is the way of the SMC that guarantees asymptotic stability of the systems. The process of sliding mode control can be divided in two phases, that is, the approaching phase and the sliding phase. The sliding mode control law u(t) consists of two terms, equivalent term ueq(t), and switching term us(t).

In the sliding phase, where $s(x,t) = 0$ and $\dot{s}(x,t) = 0$, the equivalent term ueq(t) is designed to keep the system on the sliding surface. In the approaching phase, where $s(x,t) \neq 0$, the switching term us(t) is designed to satisfy the reaching condition (20). While in sliding phase we have:

$$\dot{s}(x,t) = 0 \tag{21}$$

By solving the above equation formally for the control input, we obtain an expression for u called the equivalent control ueq, which can be interpreted as the continuous control law that would maintain $\dot{s}(x,t) = 0$ if the dynamics were exactly known. In order to satisfy sliding conditions (13) and to despite uncertainties on the dynamic of the system, we add a discontinuous term across the surface $s(x,t) = 0$, so the sliding mode control law u(t) has the following form:

$$u = u_{eq} + u_s$$
$$u_s = -K_f \operatorname{sgn}(s(x,t)) \tag{22}$$

where K_f is the control gain.

For a defined function :

$$\operatorname{sgn}(\varphi) = \begin{cases} 1, & if\ \varphi > 0 \\ 0, & if\ \varphi = 0 \\ -1, & if\ \varphi < 0 \end{cases} \tag{23}$$

The controller described by the equation (15) presents high robustness, insensitive to parameter fluctuations and disturbances [1, 3, 4, 20, 21], but it will have high-frequency switching (chattering phenomena) near the sliding surface due to function involved. These drastic changes of input can be avoided by introducing a boundary layer with width ε [3, 4, 21]. Thus replacing $\operatorname{sgn}(s(t))$ by $sat(s(t)/\varepsilon)$ in (20), we have

$$u = u_{eq} - K_f\, sat(s(x,t)/\varepsilon) \tag{24}$$

Where

$\varepsilon > 0$,

$$sat(\varphi) = \begin{cases} \operatorname{sgn}(\varphi) & if |\varphi| \ge 1 \\ \varphi & if |\varphi| < 1 \end{cases}.$$

5.1. Active Power Controller

The direct current error is defined by:

$$e_{Ps} = P_{sref} - P_s \quad (25)$$

For n=1, the direct current control manifold equation can be obtained by:

$$s(P_s) = P_{sref} - P_s \quad (26)$$

Substituting the expression of ids given by equation (1) and (4) in equation (26) we obtain :

$$\dot{s}(P_S) = \dot{P}_{sref} - \dot{P}_S$$

$$\dot{s}(P_s) = \dot{P}_{sref} + V_s \frac{M}{L_s} \dot{i}_{qr} \quad (27)$$

During the sliding mode and in permanent regime, we have $s(P_S)=0,\ \dot{s}(P_S)=0,\ V_{qs}^{n}=0$ .The control voltage vqref is defined by:

$$v_{qref} = v_{qs}^{eq} + v_{qs}^{n} \quad (28)$$

Where:

$$v_{qs}^{eq} = -\dot{P}_{ref} \frac{\sigma L_s L_r}{V_s M} + R_r i_{qr} + g\omega_s \sigma L_r i_{dr} + g \frac{M V_s}{L_s} \quad (29)$$

$$v_{qs}^{n} = K_P \operatorname{sgn}(s(P_s)) \quad (30)$$

Kd - positive constant, $\sigma = 1 - \frac{M^2}{L_r L_r}$, $g = 1 - \frac{\omega_s}{\omega_r}$

5.2. Reactive Power Control

The quadrature current error is defined by:

$$e_{Qs} = Q_{sref} - Q_s \quad (31)$$

For n=1, the quadrature current control manifold equation can be obtained by:

$$s(Q_s) = Q_{sref} - Q_s \quad (32)$$

Then, we have

$$\dot{s}(Q_s) = \dot{Q}_{sref} - \dot{Q}_s \quad (33)$$

Substituting the expression of iqs given by equation (1) and (4) in equation (33) we obtain :

$$\dot{s}(Q_s) = \dot{Q}_{sref} + V_s \frac{M}{L_s} \dot{i}_{dr} \quad (34)$$

During the sliding mode and in permanent regime, we have $s(Q_S)=0,\ \dot{s}(Q_S)=0,\ v_{dr}^{n}=0$ .The control voltage vqref is defined by:

$$v_{dref} = v_{dr}^{eq} + v_{dr}^{n} \quad (35)$$

Where:

$$v_{ds}^{eq} = -\dot{Q}_{ref} \frac{\sigma L_s L_r}{V_s M} + R_r i_{dr} - g\omega_s \sigma L_r i_{qr} \quad (36)$$

$$v_{dr}^{n} = K_Q \operatorname{sgn}(s(Q_s)) \quad (37)$$

Kq - positive constant.

6. Simulation Results

6.1. Description of the System

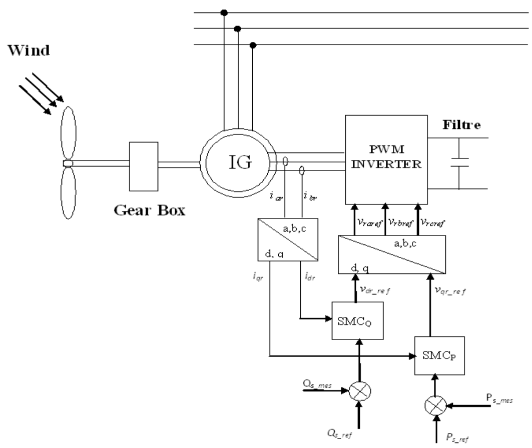


Fig. 5. Control of active and reactive power.

The system described in the present study is shown in Figure (5). The system consists of Induction generator, diode rectifier, filter, inverter, the wind turbine, Gear box, and the grid. The IG generates alternative current which is transmitted to the grid. The power is extracted from the wind, using wind turbine. The active and reactive powers are controlled by the rotor voltages.

The all rectifier, filter and Inverter connected to the grid are used to supply and control the rotor voltages. To control the power transmitted to the grid we use the sliding mode technique.

6.2. Simulation and Results

In this section, we have simulated, in Matlab-Simulink, the system described in Figure (6). IG Parameters are: Rated output power 7,5 kW, Rated phase voltage 400V, f =50Hz, p=2, R_r=0.62Ω, R_s=0.455Ω, L_r=0.081H, L_s=0.084H, M_{sr}=0.078H, J=0.3125 kg.m^2 ,f=0.00673 N.m/s. For simplicity, we have supposed that the inverter is perfect. First, we have simulated the system as it is described in figure (4) and (5), respectively, with classical controllers PI and sliding mode controllers ; wind speed taken is about 10m/s. In second time, we have taken the system with sliding mode controllers for variable wind speed between 8 and 11m/s. To extract the maximum power from the wind, the desired active power is the one delivered in the wind turbine.

Figure (6) shows the Response of the system with PI regulators. Figure (7) shows the Response of the system with sliding mode regulators.

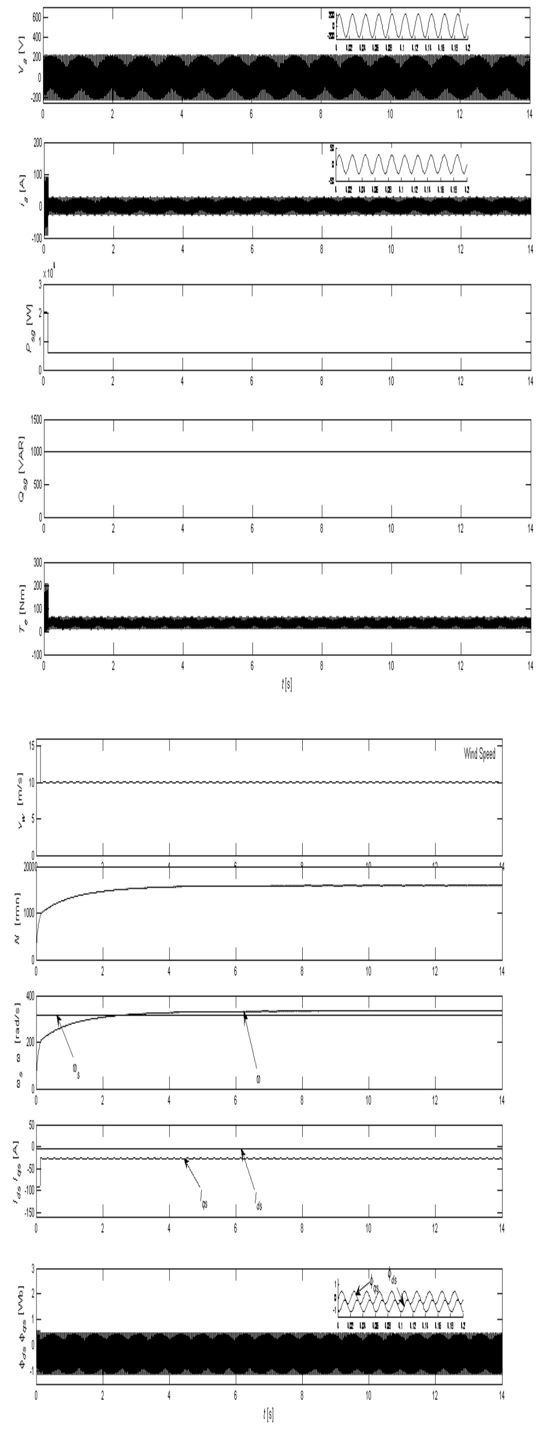


Fig 6. Response of the system with PI controllers.

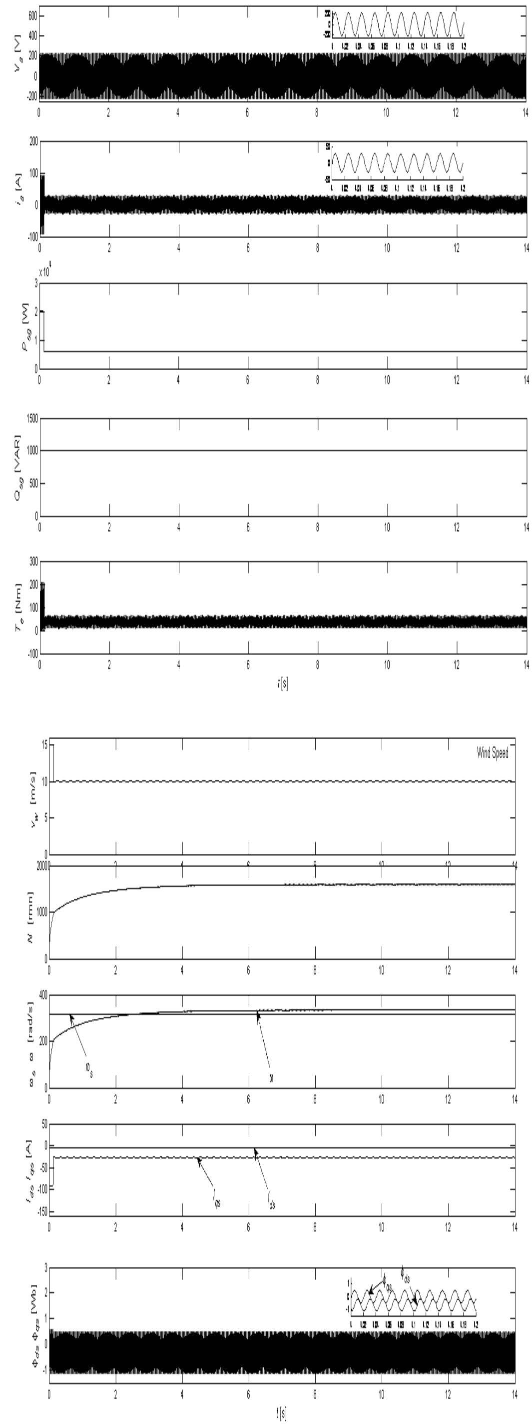


Fig. 7. Response of the system with Sliding mode controllers.

Figure (8) shows a comparison when using PI regulators and sliding mode regulators.

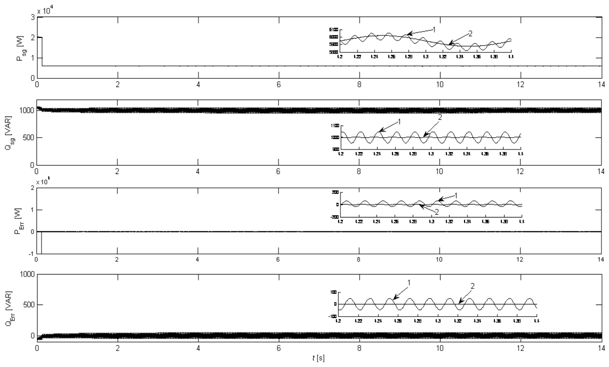
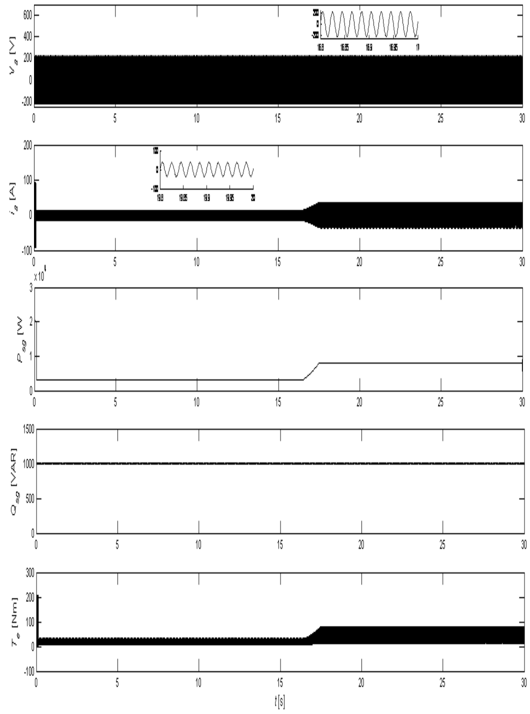


Fig. 8. Comparison between the response of the system when using power PI controller and power sliding mode controller.



The wind speed in Figures (6) and (7) is about 10m/s. In figure (7) the sliding mode controllers gives best performances in tracking the desired trajectory with no overshoot and with a negligible steady state error. The desired active power is the maximal power extracted from the wind and transmitted in mechanical form to all the turbine and induction generator. In figure (8) a comparison with the PI regulators, shows that the use of Sliding mode techniques allowed us to have high performances to follow the desired trajectory. In figure (9), a variation of wind speed, increase the power generated by the Induction generator, the desired active power is calculated each time from the maximal power extracted from the wind turbine.

6.3. Robustness

In order to test the robustness of the sliding mode method, we have studied the effect of the parameters uncertainties on the performances of the power control. Two cases are considered: the Rotor resistances and the inductances. To illustrate the performances of control, it has simulated the same system described in Figure (5) in the case of variable wind speed between (8 to 11m/s).

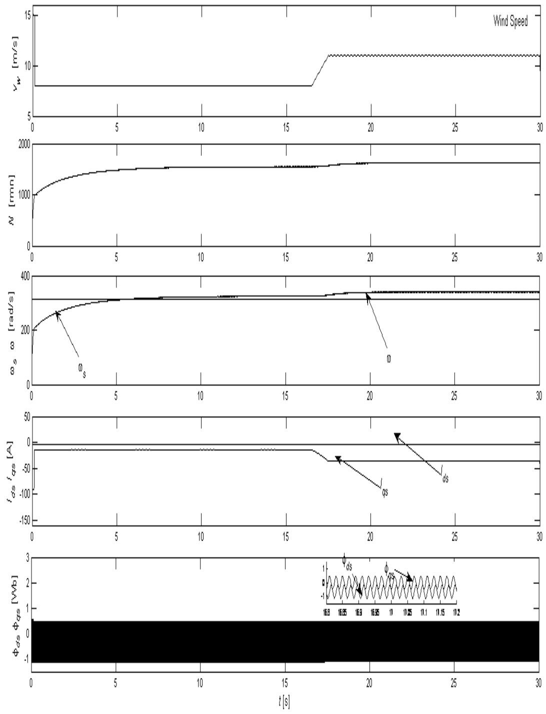


Fig. 9. Response of the system with regulation and a Variable wind speed Sliding Controller.

Figure (10) and figure (11) show the tests of robustness realized by using sliding mode controllers, respectively, with different values of the Rotor resistances (-50%, Nominal, +50%), and with different values of the machine inductances (-50%, Nominal, +50%). The results of figure (10) and figure (11) show a decrease or increase of the Resistances and the Inductances doesn't have any effects on the performances of the technique used. With using sliding mode techniques we have reached high performance in tracking the desired trajectory and reject any effects of disturbances.

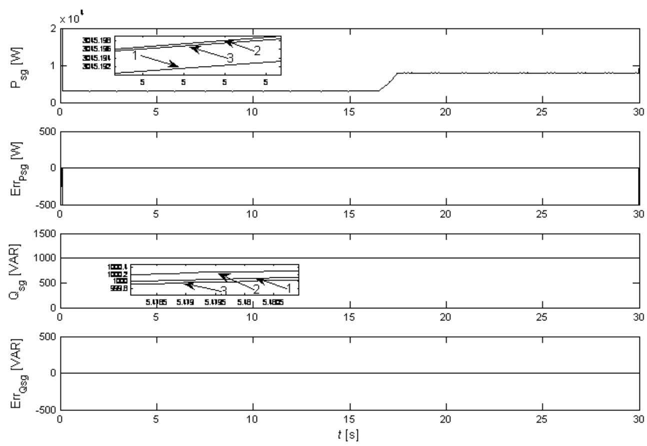


Fig. 10. Test of robustness for different values of the Rotor resistances: 1)-50%, 2) nominal case, 3) +50%.

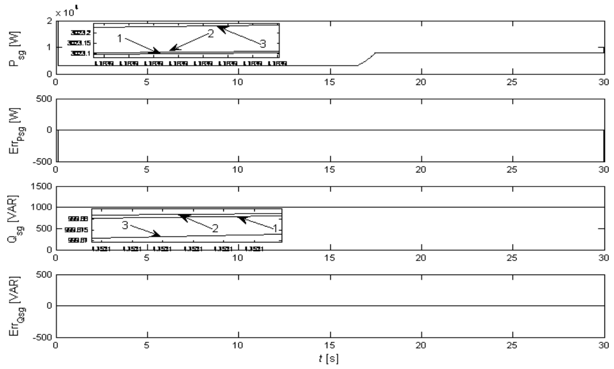


Fig. 11. Test of robustness for different values of the inductances: 1)-50%, 2) nominal case, 3) +50%.

7. Conclusion

In this paper, we have described the different structures of wind turbines based on the Induction generator; we have established a model of the wind conversion chain, consisting of an Induction generator, a rectifier (diode bridge), a filter, a three-phase PWM inverter. We have subsequently built a device for controlling the chain of the proposed conversion. The overall system is tested for two different cases of wind speeds. The simulation results show the possibility of extracting the maximal power from the wind, the control of the power generated to the grid by controlling the rotor voltages and the high performances of the controller based on sliding mode techniques. With using these techniques we have reached high performances in tracking the desired trajectory and increasing the robustness of our controllers.

In the future work, this study will be validated by an experimental study.

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