Modeling and Control of Variable Speed Wind Turbine for an Isolated Load

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***Abstract*— This paper describes the modeling and control system of a variable speed wind turbine using Permanent Magnet Synchronous Generator (PMSG) associated to a Pulse Width Modulation (PWM) rectifier connected to isolated load. The turbine is used to drive the PMSG in order to feed the isolated (R,L) load. The main objectives are, maximize the wind power turbine system and control the power delivered to the load, for that we applied the strategies of maximum power point tracking (MPPT) with speed control. The way of computing the flux level from the torque command is developed on the basis of direct current equal to zero. Mathematical relations treating these terms are detailed and studied. The dynamic performances of the turbine, the generator, and the converters are analyzed. The simulation results using Matlab/Simulink have shown that the proposed methodology is an efficient solution of a fully control system.**

***Keywords:* Permanent-magnet synchronous generator (PMSG), Pulse width modulation (PWM), Maximum power point tracking (MPPT), modeling.**

I. Introduction

The development and the exploitation of renewable energies knew a high growth these last years. Among these sources of energies, we find the wind power energy that occupies a particular place. The wind power is a very fluctuating energy, because of significant variations the wind speed that can significantly affect the quality of the voltage and the current in the network or the load where it is connected. Many controls are developed to master and benefit the maximum of this energy [1].

Nowadays, the use of PMSG in wind power has grown increased significantly in the world due to its operation on variable and low-speed, which enables the operation of the turbine at its maximum power coefficient over a wide range of wind speeds in one hand and allows omitting the gear box that influences the efficiency and rises the cost and noise in another hand [2],[3], furthermore, the PMSG has a high efficiency because of the absence of the rotor Joule loses and we avoid the use of brushes. In the used topology the PMSG is connected to the load via converter (the rectifier AC–DC) controlled by PWM to obtain maximum energy capture from the wind, in the same time it allows the PMSG to deliver sinusoidal currents "Fig. 1", contrary to ordinary rectifier. This article presents a synthesis and dynamic performance of the complete wind system, [4].

II. Turbine Model

The wind turbine collects the kinetic energy of the wind and converts it into a torque which turns the blades of the rotor. Three factors determine the relationship between the wind energy and the mechanical energy recovered by the rotor: density of the air, the surface swept by rotor and the wind speed [5]. The evolution of the used power coefficient is given by the following relation [6]:

$$C_p(\lambda,\beta)=\left(0.5-0.0167(\beta-2)\right)\sin\left[\frac{\pi(\lambda+0.1)}{18-0.3(\beta-2)}\right]-0.00184(\lambda-3)(\beta-2) \quad (1)$$

The simulation of "(1)" is shown in "Fig.1"

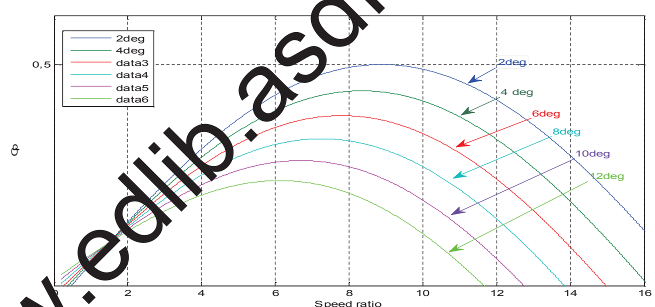

Fig.1. *C p (λ,β)* Characteristics for various values of *β*

The power captured by the wind turbine may be written as [7]:

$$P_m = \frac{1}{2} C_p(\lambda)\rho A V_1^3 \quad (2)$$

The tip-speed ratio is defined as:

$$\lambda = \frac{\Omega_t R_t}{V_1} \quad (3)$$

Where,
A: blade swept area [m²]
ρ: specific density of air [kg/m³]
V_1 : wind speed [m/s]
R_t : radius of the turbine blade[m]
Ω_t: rotating speed [rpm]
C_p : coefficient of power conversion

We fixe the value of pitch angle constant (β equals to two), the value of C_p becomes a function of λ and it reaches the maximum at the particular λ named λ_{opt}.
Hence, to fully utilize the wind energy, λ should be maintained at λ_{opt}, "Fig.2".

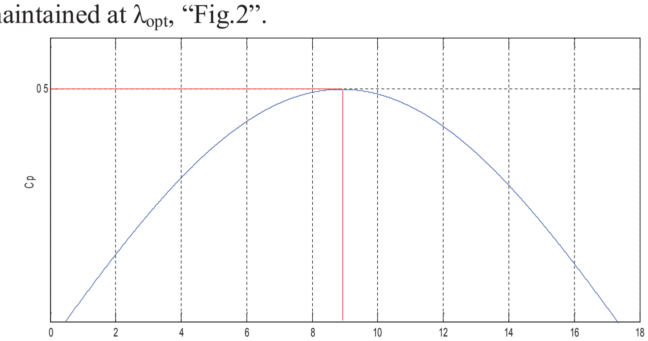

Fig.2. Characteristics of power coefficient

In order to maintain the power coefficient at its maximum we use the MPPT control.

III. MPPT CONTROL

The goal of the (MPPT) strategy is to pick up the maximum power from the wind; it involves following the power curve shown in “Fig.3”, given by:

$$P_{opt} = P_{Max} = \frac{1}{2} C_p^{opt}(\lambda_{opt}) \rho A V_1^3 \qquad (4)$$

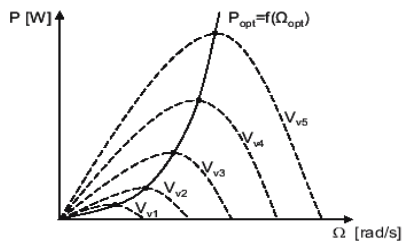

Fig.3. Wind power characteristics in function of mechanical speed

A. MPPT with Speed Control

The speed controller regulates the speed of the rotor by controlling electrical power of the generator (and therefore the torque) according to the optimal speed. In this case the motor torque is controlled to be equals to its reference value:

$$T_{em} = T_{em-ref} \qquad (5)$$

The reference electromagnetic torque T_{em_ref} allows to make the mechanical speed of the generator equals to the reference speed Ω_{ref} by the relation below, [6]:

$$T_{em-ref} = C_{ass}\left(\Omega_{ref} - \Omega_{mec}\right) \qquad (6)$$

Where:

C_{ass}: speed controller.

The reference speed of the turbine corresponds to the optimal value, in our study the specific speed (λ_{opt}=8.7) and the maximum of power coefficient (C_{pMax}=0.5) is given by, [7]:

$$\Omega_{tur-ref} = \frac{\lambda_{opt} V_1}{R} \qquad (7)$$

By developing the proportional integral PI controller, the torque becomes:

$$T_{em-ref} = \left(\frac{b_0 + b_1.S}{S}\right).\left(\Omega_{ref} - \Omega_{mec}\right) \qquad (8)$$

b_0 and b_1 are controller parameters to determinate, S is Laplace magnitude.

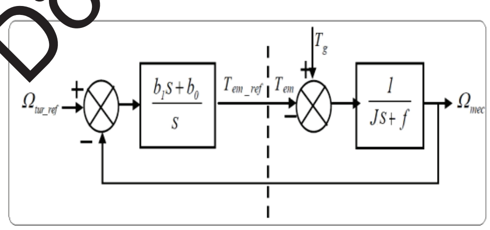

Fig.4. Diagram block of the PI controller

The wind profile can be modeled by a sum of several harmonics, in accordance with [8]-[9]-[10]:

$$V_1(t) = 10 + 0.2\sin(0.1047t) + 2\sin(0.2665t) + \sin(1.2930t) + 0.2\sin(3.6645t) \qquad (9)$$

Where,

V_1 : wind speed [m/s]

t : time [s]

The simulation of the wind profile corresponding to used turbine is shown in “Fig.5”:

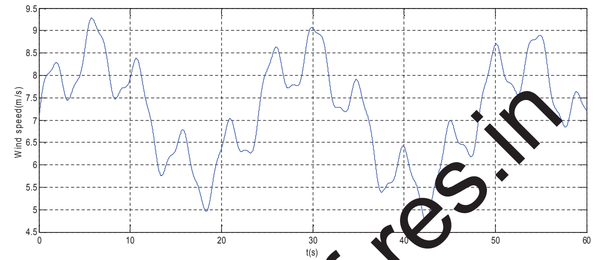

Fig. 5. Wind Profile

Figures “6”, “7”, ”8” and “9” show the simulation results of MPPT strategies by using the wind profile of “Fig.5”.

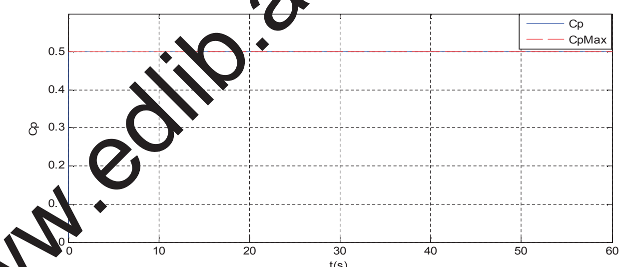

Fig.6. Coefficient of power conversion

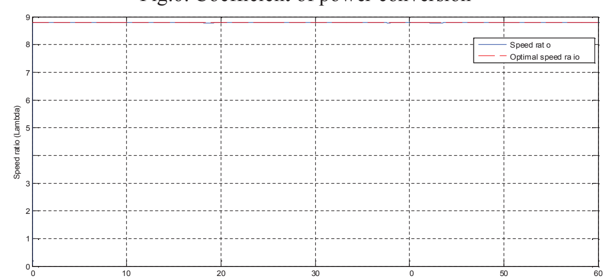

Fig.7. Speed ratio

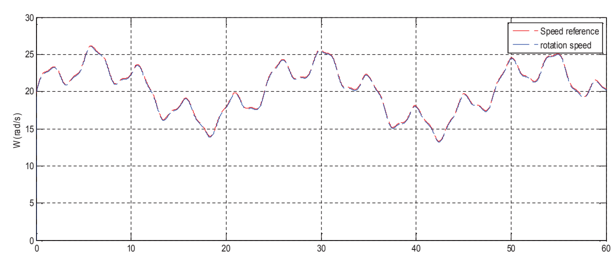

Fig.8. Mechanical and reference speed

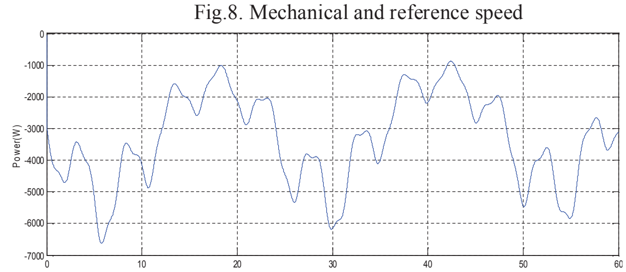

Fig.9. Electric power

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A. Results analysis

We note that the coefficient of power and the speed ratio follow very well their references corresponding to optimal values after a small dynamic, “Fig. 6” and “Fig. 7”, which involves extracting of the maximum power “Fig. 9”. “Fig. 6” shows a good operation of PMSG on optimal rotor speed with a good dynamic performance.

IV. Modeling and Control of PMSG

The voltage equation of the PMSG is expressed at synchronous reference frame by [11]:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} R_s + SL_d & -\omega L_q \\ \omega L_d & R_s + SL_q \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega.\Phi_f \end{bmatrix} \quad (10)$$

Where:
S: differential operator
v_{ds}, v_{qs} : *d-q* axis stator voltage
i_{ds}, i_{qs} : *d-q* axis stator current
$L_d\, L_q$: *d-q* axis inductance
R_s : stator resistance
ω : electric pulsation
Φ_f: magnetic flux of permanent magnet

The electromagnetic torque is expressed as

$$T_{em} = \frac{3}{2} p \left[\left(L_q - L_d \right) i_{ds} i_{qs} + i_{qs} \varphi_f \right] \quad (11)$$

Where

p: number of poles pairs.

By using the vector control, q-axis is aligned with the magnetic flux, then

$$T_{em} = \frac{3}{2} p . i_{qs} \varphi_f = K . i_{qs} \quad (12)$$

The q-axis current component can be used for the speed control of the generator by using the reference from MPPT control, and the d-axis current is set to zero [12].

V. Model Of PWM Rectifier

Contrary to the traditional rectifiers, PWM rectifiers are controlled by opening and closing semiconductors in a way allows obtaining the imposed references according to needs. Thus, we have a total control of the converter [13],[14].
This rectifier is controlled to keep the voltage of the continuous bus at a wished value of reference, by using a closed loop control as it is shown in “Fig.10”.

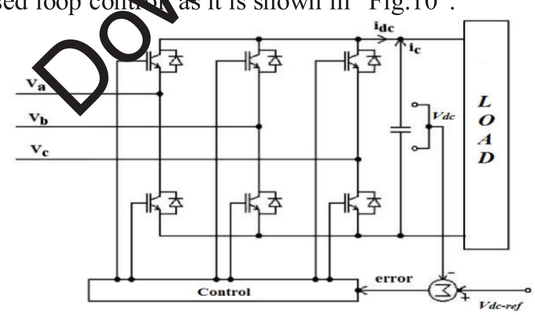

Fig.10. Basic topologies of a rectifier of voltage

We can simplify modeling and reduce the time of simulation by modeling the rectifier with ideal switches, these switches being complementary; their state is defined by the following function [1]:

$$S_j = \begin{cases} +1, S_j & -1 \\ -1, \overline{S_j} & +1 \end{cases} \quad (13)$$

The simple input voltages and the output current can be written in function of S_j, V_{dc} and the input currents i_{sa}, i_{sb}, i_{sc}.

$$i_{sa} + i_{sb} + i_{sc} = 0 \quad (14)$$

The compound input voltages of the rectifier can be described by

$$\begin{aligned} U_{Sab} &= (S_a - S_b) * V_{dc} \\ U_{Sbc} &= (S_b - S_c) * V_{dc} \\ U_{Sca} &= (S_c - S_a) * V_{dc} \end{aligned} \quad (15)$$

Voltage equations of the three-phase system balanced without connection to neutral point can be written as follows:

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = R_s \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + L_s \frac{d}{dt} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} \quad .(16)$$

With:

$$\begin{aligned} U_{sa} &= \frac{2S_a - S_b - S_c}{3} V_{dc} \\ U_{sb} &= \frac{2S_b - S_a - S_c}{3} V_{dc} \\ U_{sc} &= \frac{2S_c - S_a - S_b}{3} V_{dc} \end{aligned} \quad (17)$$

Finally, we deduce the equation from coupling the AC and DC sides:

$$C.\frac{dV_{dc}}{dt} = \left(S_a.i_a + S_b.i_b + S_c.i_c \right) - I_L \quad (18)$$

The diagram in d-q reference frame is presented in figure “11”.

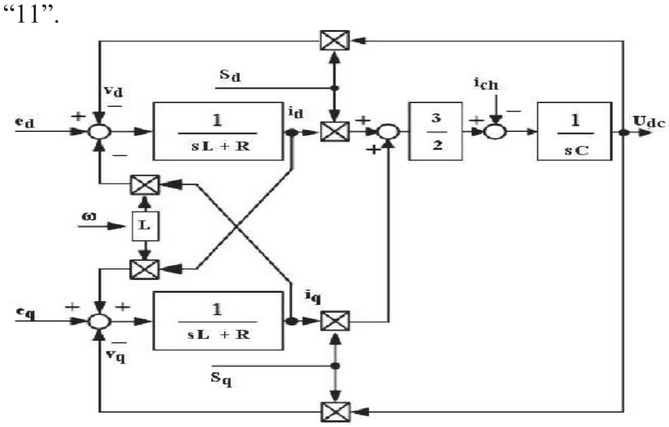

Fig. 11. Diagram of the PWM rectifier in d-q reference frame.

The PWM technique stands on the comparison between two signals, the first is called reference signal represents the image of the wished sinusoid in the output of the inverter; the second is called triangular signal, defines the rate of the commutation the inverter switches, as it is shown in figure “12”.

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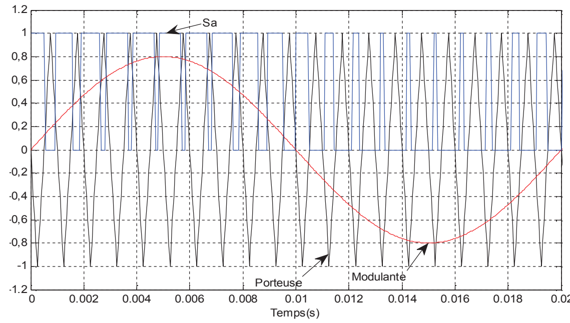

Fig.12. PWM generation of the switch S_a.

The control of the system is presented in figure “13.

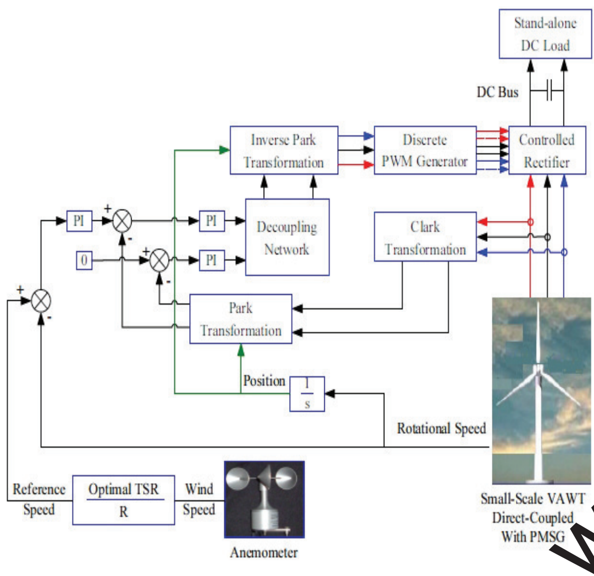

Fig.13. The control diagram of the wind turbine system.

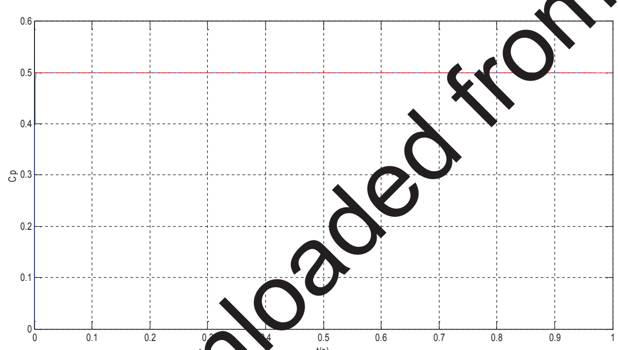

Fig.14. Power coefficient.

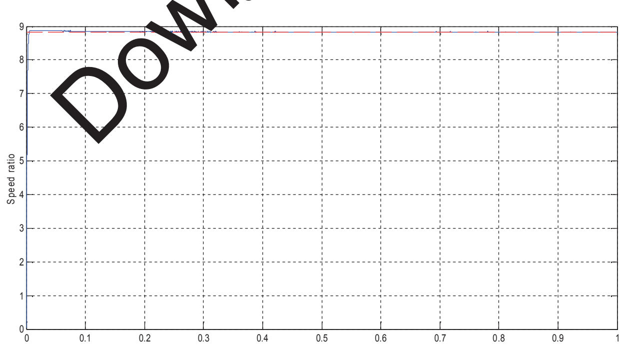

Fig.15. Speed ratio.

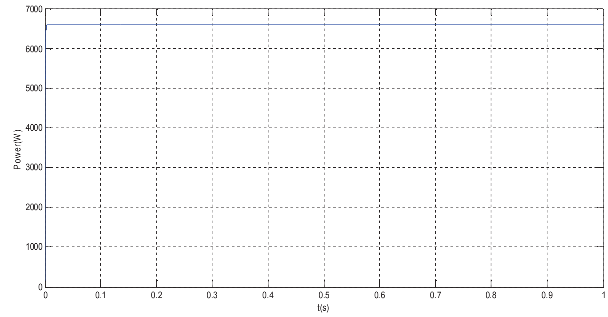

Fig.16. Electromagnetic power.

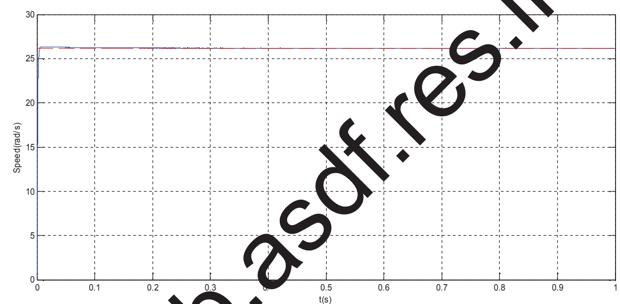

Fig.17. Mechanical and reference speed.

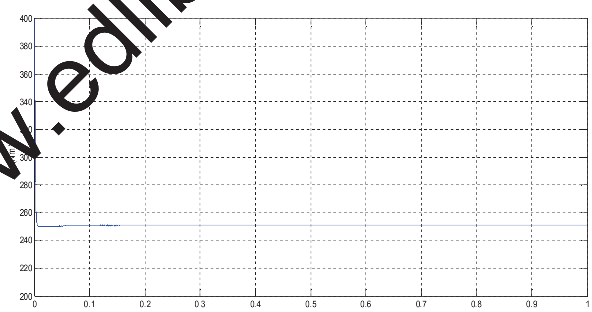

Fig.18. Torque.

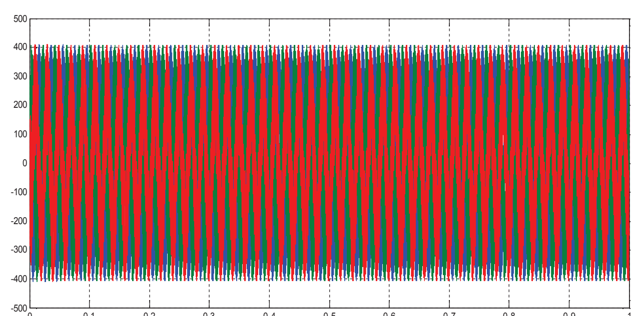

Fig.19. Stator voltages.

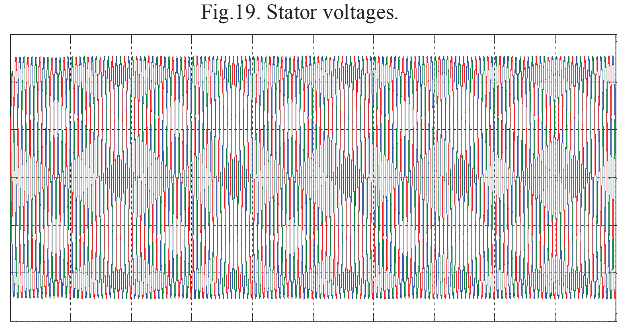

Fig.20. Stator currents.

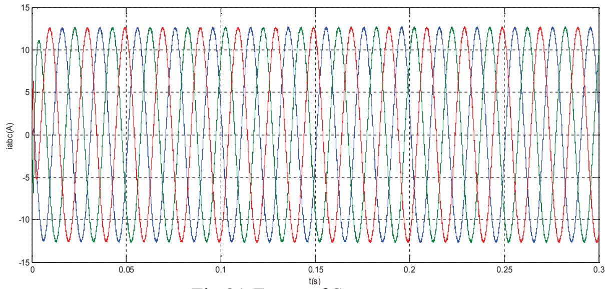

Fig.21.Zoom of Stator currents.

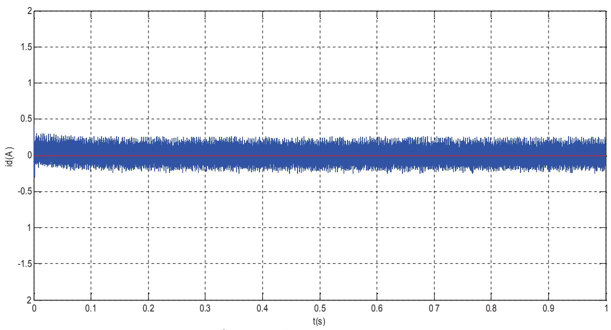

Fig.22. Generator current i_d.

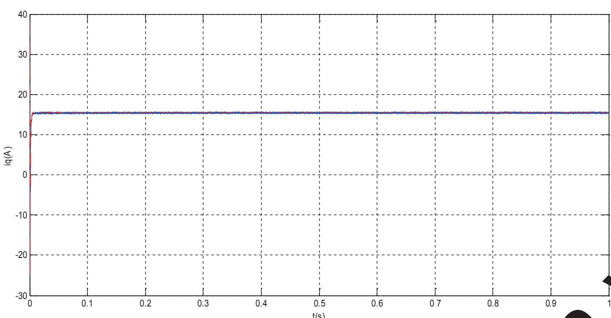

Fig.23. Generator current i_q.

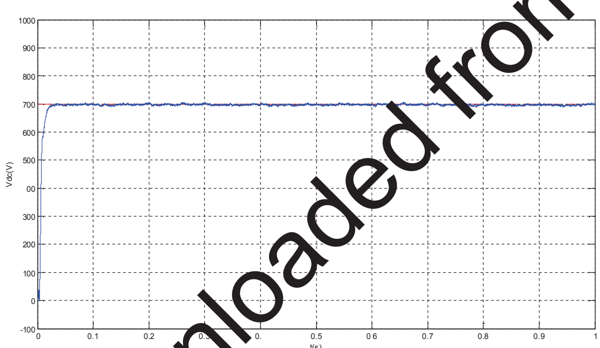

Fig 24. DC link voltage.

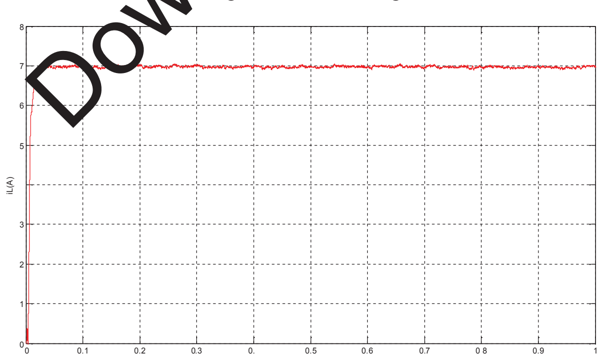

Fig.25. Load current.

A. Analysis of Simulation Results

"Fig. 14" and "Fig. 15" show that the power coefficient and the speed ratio are adjusted to their references which involve that the captured power is maximal ("Fig. 16"), "Fig. 14" shows a good following of the speed rotor its reference which controlled by the torque shown in "fig.18" . We note that the stator voltages and currents are sinusoidal that improve the performances of PMSG (Figures "19", figures "20" and figures "21"). The current i_q "Fig. 22", but i_d remains null, "Fig. 23", which involves that the torque is controlled by the current i_q which is calculated by the MPPT control therefore vector control is assured. "Fig. 24" shows that the DC bus is well adjusted to its reference, which allows a stable supplying to the load, "Fig. 25" .

VI. Conclusion

This work enabled us to study the operating mode of the wind energy system (model of variable speed turbine, models permanent magnet synchronous generator (and model of PWM rectifier).Various controls were developed (MPPT, vector control, PWM) in order to pick up the maximum power from the wind and deliver sinusoidal currents from the controlled rectifier which doesn't allow in ordinary rectifier. The obtained results by simulation show that the output of the system is very encouraging.¶

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