Study and Control of a Variable Speed Wind Turbine with a Permanent Magnet Synchronous Generator

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***Abstract*— This paper deals with modeling and simulation of a directly driven wind generator with a full scale converter as interface to the grid. Using the permanent magnet synchronous generator (PMSG). Now-a-days doubly fed Induction generators are being widely used in wind turbine generator system. So, facing drawbacks such as decrease in efficiency, cost and size. If electromagnetic synchronous generator is used which has rotor current, losses increases there by efficiency decreases. So, In order to overcome this drawback, we adopt permanent magnet synchronous generator in which the rotor current is zero and can be used without a gearbox, which also implies a reduction of the weight of the nacelle and a reduction of costs. Therefore, in this work the modeling and control of a PMSG is presented. All the components of the wind turbine and the grid-side converter are developed and implemented in PSIM.**[i]

***Index Terms*— Wind turbine, Permanent magnet synchronous machine, Vector control, DC bus.**

I. INTRODUCTION

The world consumption of energy has known enormous increase these last years, because of the massive industrialization that has tendency to intensify rapidly in some geographical areas in the world, notably in countries of Asia. The risks of shortage of fossil matters and their effects on the climatic change indicate once more the importance of renewable energies. Several sources of renewable energies are under exploitation and search, in order to develop power extraction techniques aiming to improve the reliability, lower the costs (of manufacture, use, and retraining), and to increase the energizing efficiency [1]. In this general context, wind energy is one of the most promising renewable energy resources for producing electricity due to its cost competitiveness compared to other conventional types of energy resources. It takes a particular place to be the most suitable renewable energy resources for electricity production.

In wind energy conversion systems, normally there are two operating modes of wind turbine generators system: fixed speed and variable speed operating modes. In order to extract maximum power wind, the turbine rotor speed needs to be changed proportional to wind speed. This requires variable-speed operation. Most modern wind turbine generators are designed for variable speed operation [2]. Compared with fixed speed operation, variable speed systems offer some advantages including overall efficiency, reduced mechanical stresses and audible noise at low wind speed.

In recent years, numerous topologies of power conditioning systems, varying in cost and complexity, have been developed for integrating PMSG wind turbine systems into the electric grid. In modern PMSG wind turbine generators system designs, the power conditioning systems is typically built using a full-scale power converter made up of a two-stage power conversion hardware topology that meets all the constraints of high quality electric power, flexibility and reliability imposed for applications of modern distributed energy resources [3], [4]. This power conditioning systems design is composed of a back-to-back converter that enables to control simultaneously and independently the active and reactive power flows exchanged with the electric grid, as described in Fig. 1.

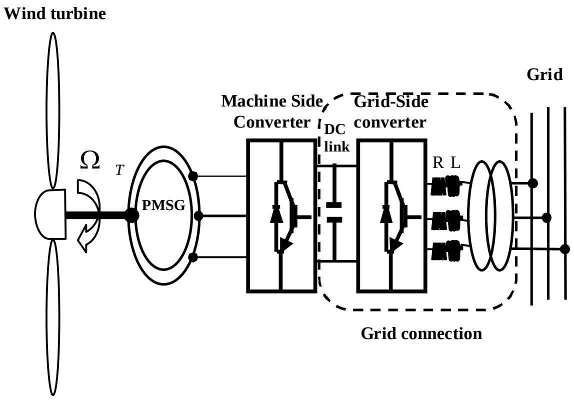

Figure.1. Typical configuration of PMSG based variable speed wind energy conversion system

II. Wind turbine modeling

The device studied, in this part, consists of a wind turbine including blades length R driving a generator via a gearbox with ratio G total kinetic power of the wind which passes through the wind turbine is given by the following equation:

$$P_w = \frac{1}{2}\rho R^2 v^3 \tag{1}$$

R : is the blade radius of the wind turbine (m);
ρ : represent air density (it is 1.25 kg / m in normal atmosphere);
v : is the wind speed (m/s);

Betz proved that the maximum power extractable by an ideal turbine rotor with infinite blades from wind under ideal conditions is 59.26% (0.5926 times) of the power available in the wind. This limit is known as the Betz limit .The extractable power can thus be written as:

$$P_{cap} = C_p(\lambda, \beta).P_w \tag{2}$$

C_P : is the power coefficient which represents the aerodynamic efficiency of the turbine and also depends on speed ratio λ and the pitch angle β, the speed ratio is given by:

$$\lambda = \frac{\Omega_t R}{v} \tag{3}$$

Models for power coefficient have been developed. For example [5] models C_P as a function of the tip speed ratio and the blade pitch angle Λ in degrees as:

$$C_p(\lambda, \beta) = c_1\left(c_2 \frac{1}{\Lambda} - c_3\beta - c_4\beta^x - c_5\right)e^{-c_6\frac{1}{\Lambda}} \tag{4}$$

In this equation, the parameter Λ also depends β and λ.

$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{5}$$

The values of the coefficients, c_1, c_2, c_3, c_4, c_5 and c_6 are given in Table I as:

Table I
Coefficients defining the evolution of C_p

coefficients	*values*
c_1	0.5
c_2	116
c_3	04
c_4	0
c_5	5
c_6	21

The difference between the curves of different wind turbines is small and can be neglected in the dynamic simulations. Knowing the speed of the turbine.

The aerodynamic torque developed (in Nm) can then be calculated:

$$C_{aer} = \frac{P_{aer}}{\Omega_t} = C_p.\frac{\rho.s.v^3}{2}\frac{1}{\Omega_t} \tag{6}$$

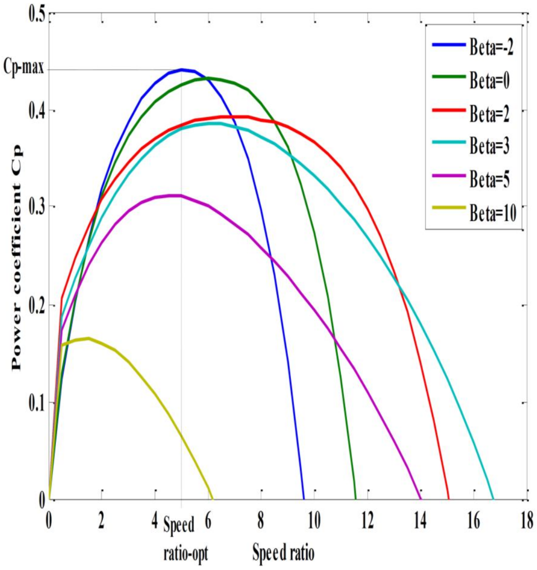

Figure.2 Power coefficient characteristic versus speed ratio λ and pitch angle β

III. Control of permanent magnet synchronous generator PMSG

Fig.3 illustrates the three control functions of the PMSG:

- Maximum power point tracking (MPPT)
- Vector control of PMSG.
- Control of PWM converter.

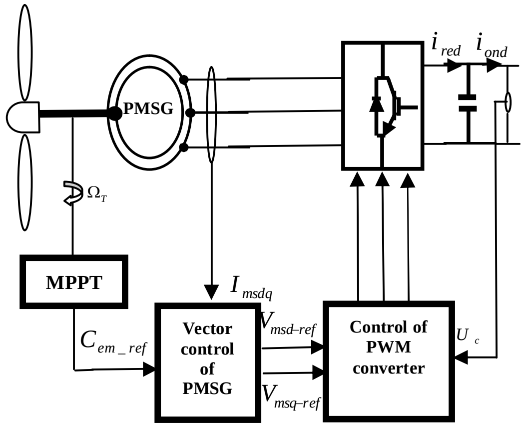

Figure.3 Control of permanent magnet synchronous generator PMSG

A. MPPT

The characteristic of the optimal power of a wind is strongly non linear and in the shape of "bell" [6]. For every speed of wind, the system must find the maximal power what is equivalent in search of the optimal rotational speed. Fig. 2 illustrates the characteristic curves of the wind in the plan power, rotational speed of the turbine. Every dotted line curve corresponds to a speed of wind V_v data.

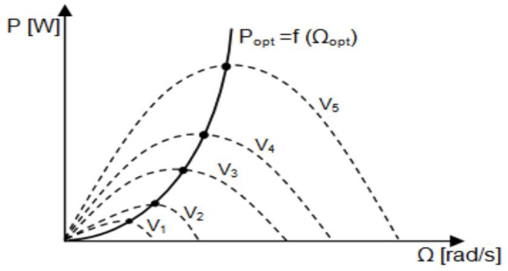

Figure 4: Feature of wind turbine in the plan power, rotational speed.

An ideal functioning of the wind system requires a perfect follow-up of this curve. To approach of this goal, a specific control known by the terminology: Maximum Power Point Tracking (MPPT) must be used. The strategy of this control consists in controlling electromagnetic torque in order to adjust the mechanical speed in order to maximize the generated electric power. So that the extracted power is maximal, we associate to the parameter λ its optimal value λ_{opt} corresponds to the maximum of power coefficient $C_{p\max}$. The value of the reference electromagnetic torque is then adjusted to the following maximal value:

$$C_{aer-ref} = \frac{C_{p\max}}{\lambda^3_{opt}} \cdot \frac{\rho . s . R^5}{2} \frac{\Omega^2{}_{mec}}{G^3} \qquad (7)$$

This expression can be written as:

$$C_{aer-ref} = K_{opt} . \Omega^2{}_{mec} \qquad (8)$$

The MPPT algorithm controlled with the help of the measured rotational speed in *N* stage, determine the reference torque in *N+1* stage of the way shown on Fig 5.

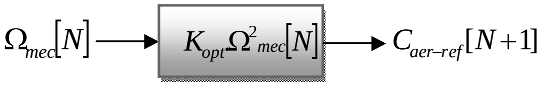

Figure 5. Reference torque according to the rotational speed.

B. Vector control of PMSG.

Control of AC machines is difficult because the mathematical model of the system is strongly coupled. All control devices are conceived with the aim of finding the ease and quality setting naturally offers DC machine. The similarity between the PMSG and DC machine is made possible by the vector control; the aim of this control is the decoupling of axes d-q. The model of the PMSG in the d-q synchronous reference frame is given by.

$$\begin{cases} V_{msd} = R_s . i_{msd} + L_{sd} . \dfrac{di_{msd}}{dt} - L_{sq} . \omega_r . i_{msq} \\ V_{msq} = R_s . i_{msq} + L_{sq} . \dfrac{di_{msq}}{dt} + L_{sd} . \omega_r . i_{msd} + \psi_f . \omega_r \end{cases} \qquad (9)$$

$$C_{em} = p\left(\left(L_{sd} - L_{sq} \right) i_{msq} . i_{msd} + \psi_f . i_{msq} \right) \qquad (10)$$

i_{msd} , i_{msq} : The stator currents
V_{msd} , V_{msq} : The stator voltages
R_s : Stator resistance
L_{sd} , L_{sq} : Stator inductances
ψ_f : Permanent magnetic flux
p : Number of pole pairs
$\omega_r = \frac{d\theta_r}{dt} = p \frac{d\theta_m}{dtdt}$: Represents the electrical speed of the rotor.
C_{em} : Electromagnetic torque

Among the strategies applied to vector control of a synchronous machine, which consists in imposing a direct current reference i_{msd} equal to zero is the most widely used. This choice is justified in order to avoid demagnetization of permanent magnets of the armature reaction along the axis of *d* [7]. The electromagnetic torque is given by.

$$C_{em} = \psi_f . i_{msq} \qquad (11)$$

To control the generator power, it is enough to control the PMSG electromagnetic torque C_{em}, by regulation of the stator current and to know the rotational speed of the shaft.

C. Control of PWM converter.

The connection matrix PWM converter is given by the matrix equation.

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{U_c}{3} . \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} . \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \qquad (12)$$

Where V_{an}, V_{bn} and V_{cn} are the average phase voltages and f_a , f_b and f_c are the switches status at each leg respectively.

The current i_{red} is expressed in function of phase currents:

$$i_{red} = f_a . i_a + f_b . i_b + f_c . i_c \qquad (13)$$

Fig.6 shows the description of the sine triangle PWM control. The level switching edge is produced at every moment the sine wave intersects the triangle wave. Thus the different crossing positions result in variable duty cycle of the output waveform.

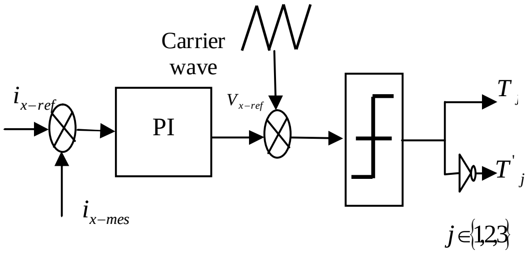

Figure 6. Schematic diagram of sine triangle PWM

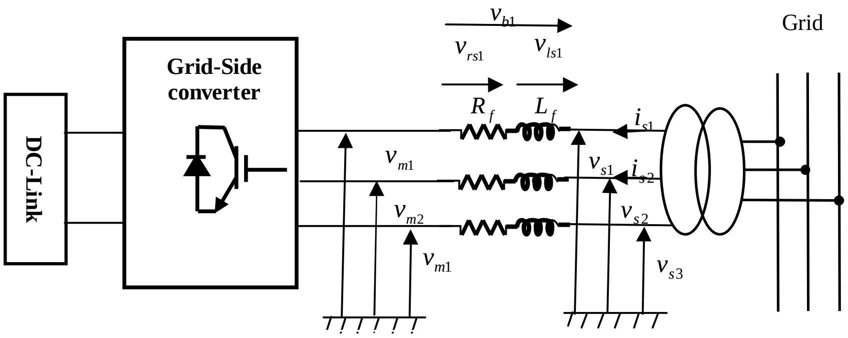

Fig.7 Grid connection studied

IV. Connection to the grid

The provided energy by the PMSG-based variable-speed wind turbine and transmitted on DC current is applied to a multilevel converter which makes it possible to control the continuous voltage and the active and reactive powers exchanged with the grid [8] [9]. An inductive filter *RL* has been designed to limit harmonic current injection into the grid Fig7.

A. *Control of the powers exchanged with the AC grid*

The active and reactive powers passed through the grid are given in Park model by the following relations:

$$P_g = v_{sd}.i_{sd} + v_{sq}.i_{sq} \quad (14)$$

$$Q_g = v_{sd}.i_{sq} - v_{sq}.i_{sd} \quad (15)$$

By inversion of these relations, it is possible to impose some references for the active power p_{g-ref} and reactive power Q_{g-ref} while imposing the following reference currents:

$$i_{sd-ref} = \frac{p_{g-ref}.v_{sd-mes} + Q_{g-ref}.v_{sq-mes}}{v^2{}_{sd-mes} + v^2{}_{sq-mes}} \quad (16)$$

$$i_{sq-ref} = \frac{p_{g-ref}.v_{sq-mes} - Q_{g-ref}.v_{sd-mes}}{v^2{}_{sd-mes} + v^2{}_{sq-mes}} \quad (17)$$

B. *Controlling the DC bus voltage:*

The electrical equations of DC bus voltage are given by this expression.

$$U_c = \frac{1}{C}\int_{t_0}^{t_0+\Delta t} i_C + U_C(t_0) \quad (18)$$

So:

$U_c(t_0)$: is the value of the DC voltage at the initial time.

The capacitor current is given by:

$$i_C = i_{red} - i_{ond} \quad (19)$$

With:

i_{red} : rectified current;

i_{ond} : ripple current;

Adjusting the DC bus is composed of a control loop to maintain a constant DC bus voltage, with PI controller C_{i_C} and generating the reference current to be injected into the capacitor.

$$i_{C-ref} = C_{i_C}\left(U_{C-ref} - U_C\right) \quad (20)$$

V. Simulation results

Simulations have been performed using a wind generator based on a permanent magnet synchronous machine $(800KW)$ connected to the network. This chain conversion was simulated for a profile of mean wind around (12m / s) for a period of 20s Fig.8.

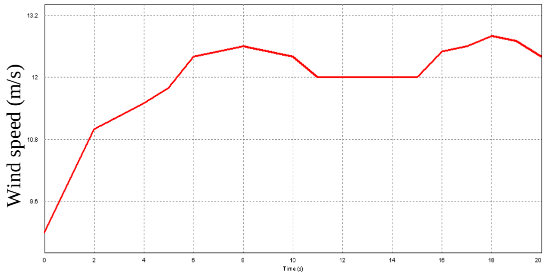

Figure.8 Wind speed profile

Fig.9 shows the active power delivered by the wind and the active power sent to the grid connection, we see that the two powers following which shows the good performance of the system. Fig.10 shows the reactive grid power. So the generation system can operate at unit power-factor, absorbs or provides reactive power, Fig.11 shows the first-phase line current and line voltage .The modulated voltage is shown in Fig.12 .The DC bus voltage is represented in Fig.13 which demonstrates that this voltage is perfectly constant equal to 1500 V and thus proves the effectiveness of the established regulators.

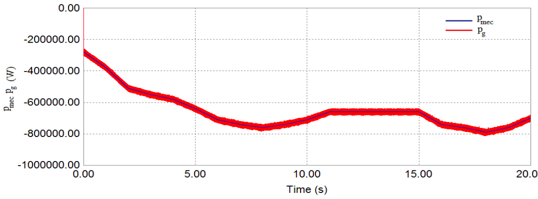

Figure.9. Wind power P_{mec} *and active power transited to the grid connection* P_g .

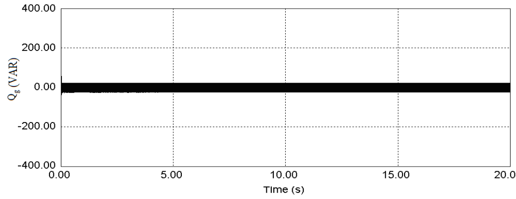

Fig.10 Reactive power transmitted to the grid connection

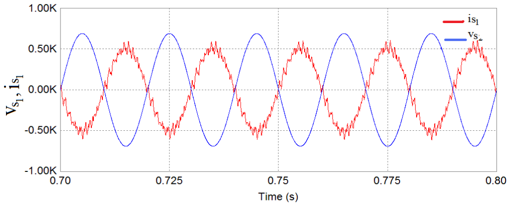

Figure.11 Voltage and current of the first phase of the grid connection.

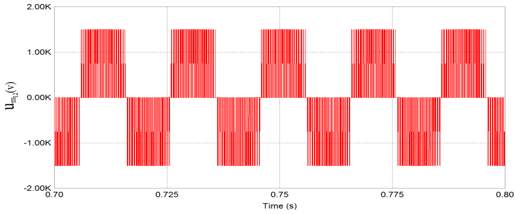

Figure.12. Modulated voltage u_{m12} .

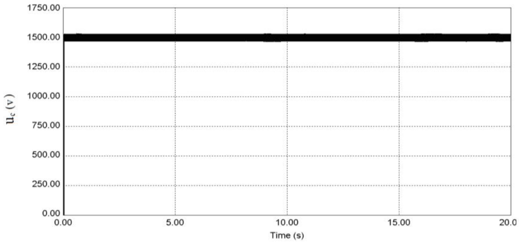

Figure.13. DC bus voltage u_c .

VII. Conclusion

The aim of this paper has been the study and control of a direct-driven PMSG used in variable speed wind-energy system connected to the grid. This wind system was modelled using d-q rotor reference frame and is interfaced with the power system through an inverter and a filter modeled in the power system reference frame. The control strategy developed insured power optimization with conventional MPPT strategy. The inverter control allowed, through grid current regulation, to achieve a decoupled active and reactive power control for operate with unitary power factor.

The simulation results showed the effectiveness of the control strategy adopted.

VI. RÉFÉRENCES

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