Modeling and optimization of wind turbine driving permanent magnet synchronous generator

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Abstract — **In this work, we propose a control strategy of a variable speed wind generation system with permanent magnet synchronous generator connected to the network using two converters PWM having jointly a DC bus. The aim of this control strategy is to allow the permanent magnet generator to operate for different wind speed in order to optimize the generated power from wind turbine on the one hand, and control the forwarded flows of power, on the other hand.**

Keywords—**Permanent magnet, DC bus, Wind turbine, pulse width-modulated (PWM) power converters**

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 [1]. The risks of shortage of fossil matters and their effects on the climatic change indicate once more the importance of renewable energies [2]. 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 [2, 3]. In this general context, this work carries on the conversion of the wind energy in electric energy that became competitive thanks to three essential factors [16]:
The motivating nature of this energy, the development turbines industry, and the evolution of semiconductors technology, as well as the new methodologies of control of variable speed turbines. Nevertheless, several problems are met, bound to the complexity of wind conversion systems; as the necessity to use gear box between the turbine and the generator, and the instability of wind speed [7, 14]. The use of other wind power structures like for example, permanent magnet synchronous generator (PMSG) with big number of poles, makes variable wind conversion systems more attractive than those with fixed speeds, because of the possibility of extraction of the optimal energy for different speeds of wind, reduction of mechanical constraints by elimination of gear box, which improves reliability of system; and reduction of maintenance expenses [7, 9, 13]. Permanent magnet synchronous machine (PMSG) is characterized by weak inductances, elevated torque, and very weak inertia [11]. All these features offer elevated performances for the generator, important output, and better controllability; which makes this machine real competitor of the asynchronous generator [9, 12]. The principle of horizontal axis wind turbine with variable-speed based on permanent magnet synchronous generator is presented in a first time, following by an analytic model of different components of the conversion chain proposed (Fig. 4). These models are associated to control strategies adopted for the generator in one hand, and the grid link in the other, while passing by the DC bus control. All developed models during this survey, are simulated in Matleb-simulink.

MODELLING OF THE PERMANENT MAGNET GENERATOR CONVERSION CHAIN

A. Modeling of P.M.S.G

In order to get a dynamical model for the electrical generator that easily allows us to define the generator control system, the equations of the generator are projected on a reference coordinate system rotating synchronously with the magnet flux (Fig. 1).
In the synchronous machines with sinusoïdale distribution of conductors, flux ψ_d and ψ_q are linear functions of currents i_d and iq situated on the rotor. And they are given by the equations (1).

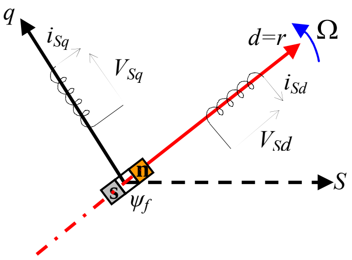

Fig. 1. PARK model for PMSG

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \qquad (1)$$

Where:

L_d : Stator inductance in d-axis**;**

L_q : Stator inductance in q-axis;

L_d and L_q are supposed independent of θ;

ψ_f : Magnets flux;

The wind turbine driven PMSG can be represented in the rotor reference frame as [7, 12, 13]:

$$\begin{cases} V_d = -R_s I_d - L_d \dfrac{d}{dt} I_d + \omega L_q I_q \\ V_q = -R_s I_q - L_q \dfrac{d}{dt} I_q - \omega L_d I_d + \omega \psi_f \end{cases} \qquad (2)$$

The electromagnetic torque is expressed by:

$$C_{em} = \frac{3}{2} P(\psi_d i_q - \psi_q i_d) \qquad (3)$$

After affectation of the expressions of ψ_d and ψ_q, the expression of the electromagnetic torque becomes:

$$C_{em} = \frac{3}{2} P[(L_q - L_d) i_d i_q + i_q \psi_f] \qquad (4)$$

The dynamics of the machine is given by the following mechanical equation:

$$C_m - C_{em} - f\Omega = J \frac{d\Omega}{dt} \qquad (5)$$

With:

C_m : Motor torque applied on the generator;

$f\Omega$: Friction torque;

J: Moment of total inertia of the machine;

f: Friction coefficient;

B. *Modeling of wind turbine*

The wind energy conversion system is complex because of the multiplicity of existing fields, aerodynamic, mechanical, and electric; and factors determining the mechanical power, as wind speed, dimension, and turbine shape.

Input and output variables of the wind turbine can sum up as follows:

1- Wind speed that determines the primary energy to the admission of turbine.

2- Tip-Speed ratio (T.S.R) defined by the ratio of the linear speed in tip of blades of the turbine on the instantaneous wind speed, and given by the following expression [4, 8, 16].

$$\lambda = \frac{\Omega_t R_t}{V} \qquad (6)$$

R: Radius of the wind turbine rotor (m);

V: Velocity of the wind (m/s);

Ω: rotation speed of the turbine (rd/s);

3- Speed of turbine, slant of blades, and angle of wedging.

4- The power cœfficient C_p definite as the ratio of the extracted wind power and the total power theoretically available. It depends of the wind speed, rotation speed of the turbine, and blades parameters of the turbine as incidence angle and wedging angle [4, 8, 16]. It is often represented according to the tip-Speed ratio λ. The maximal theoretical value possible of the power coefficient, named limit of Betz, is of 0.593 [4,8]. The output quantities of the turbine are the power or the torque that can be controlled while varying the previous input quantities.

C. *Model of the gear box*

The role of gear box is to transform the mechanical speed of the turbine to the generating speed, and the aerodynamic torque to the gear box torque according to the following mathematical formulas:

$$G = \frac{C_{aer}}{C_g} \qquad (7)$$

$$G = \frac{\Omega_{mec}}{\Omega_{tur}} \qquad (8)$$

The fundamental equation of dynamics permits to determine the mechanical speed evolution from the total mechanical torque applied to the rotor that is the sum of all torques applied on the rotor:

$$J.\frac{d\Omega_{mec}}{dt} = C_g - C_{em} - C_f \qquad (9)$$

Ω_{tur} : Mechanical speed of the turbine;

Ω_{mec} : Generator speed;

C_{aer} : Torque applied on the shaft of turbine;

C_g : Torque applied on the shaft of the generator;

C_f : resistant torque due to frictions**;**

$$C_f = f.\Omega_{mec} \qquad (10)$$

J: Total inertia brought back on the generator shaft, containing inertia of the turbine, the generator, the two shafts, and the gear box;
f : the total friction coefficient of the mechanical coupling ;

D. *Model of power converter*

Given that the two converters used in the realization of the proposed wind conversion chain have the same structure and control technique, all that is necessary is to model only one. The converter chosen in this part is the one bound to the grid.
To facilitate the modeling and reduce the time of simulation, we model the converter by a set of ideal switches: that means hopeless resistance in the state passing, infinite resistance to the blocked state, instantaneous reaction to control signals.
We define for every switch a function said of "connection" associated to every switch. It represents the ideal orders of commutation and takes the values [14]:
$S_{ic}=1$ when the switch is closed.
$S_{ic}=0$ when the switch is open.

$$S_{ic} \in \{1,2,3\}, \text{ with } \begin{cases} c \in \{1,2,3\} \\ i \in \{1,2\} \end{cases}$$

The c indication corresponds to the cell of commutation, and the index i corresponds to the location of the switch of this cell.
For the three phases of the converter, we define the following conversion functions $\underline{m}$ [6, 14]:

$$\underline{m} = [m_1 \quad m_2] = \begin{bmatrix} 1 & 0 & -1 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} S_{11} \\ S_{12} \\ S_{13} \end{bmatrix} \quad (11)$$

The state of conduction of the converter components can be represented by a matrix of connection composed of three cells of commutation of which the switches control of a same cell are complementary [14].

$$S_{i1} + S_{i2} = 1 \quad \forall i \in \{1,2,3\} \quad (12)$$

The converter's modeling consists in expressing voltages in lines, according to DC bus voltage and switches states.
The modulated voltages are gotten from DC bus voltage and conversion functions according to the expressions [14, 18]:

$$\begin{cases} u_{m13} = m_1.u \\ u_{m23} = m_2.u \end{cases} \quad (13)$$

The modulated simple voltages are stem from the modulated composed voltages according to the following expressions:

$$\begin{cases} v_{m-1} = \dfrac{2}{3}.u_{m13} - \dfrac{1}{3}.u_{m23} \\ v_{m-2} = -\dfrac{1}{3}.u_{m13} + \dfrac{2}{3}.u_{m23} \end{cases} \quad (14)$$

The modulated current is gotten from the filter currents and conversion functions:

$$i_{m-res} = m_1.i_{t1} + m_2.i_{t2} \quad (15)$$

E. *DC bus Modeling*

The capacitor current is stem from a node where circulates two modulated currents by every converter:

$$i_c = i_{m-mac} - i_{m-res} \quad (16)$$

i_{m-mac} : Current provided by the generator
i_{m-res} : Current modulated by the converter MLI_2
DC bus is modeling by knowledge of capacitor terminals voltage gotten while integrating the following differential equation:

$$\frac{du}{dt} = \frac{1}{C}.i_c \quad (17)$$

Where: $u = \int \dfrac{du}{dt} + u(t_0)$ (18)

$u(t_0)$ is the voltage value to t_0 instant.

III. STRATEGIES OF CONTROL

A. *Vector control of* **PMSG**

The strategy of applied vector control consists in imposing a reference of the direct current I_{sd} to zero. This choice is justified in the goal to avoid the demagnetization of the permanent magnets due to the armature reaction according to the *d* axis [5, 7].
The electromagnetic torque is given therefore by the following expression:

$$C_{em} = \frac{3}{2} P.\psi_f i_{sq} \quad (19)$$

We propose to make use of PI regulators in the control structure. The mathematical model equations of the permanent magnet synchronous machine can be written as:

$$\begin{cases} V_{sd}(p) = R_s.I_{sd}(p) + P.L_s.I_{sd}(p) - \omega.\psi_{sq}(p) \\ V_{sq}(p) = R_s.I_{sq}(p) + P.L_s.I_{sq}(p) + \omega.\psi_{sd}(p) \end{cases} \quad (20)$$

The coupling terms $E_{dq} = \omega.\psi_{sdq}$ are considered as measurable disruptions.

The transfer function of the machine can be written in the form:

$$G_s(p) = \frac{I_{sd,q}(p)}{V_{sd,q}(p) + E_{d,q}(p)} = \frac{1}{R_s} \cdot \frac{1}{1 + T_e . p} \quad (21)$$

With $$T_e = \frac{L_s}{R_s} \quad (22)$$

B. MPPT

The characteristic of the optimal power of a wind is strongly non linear and in the shape of "bell" [3]. For every speed of wind, the system must find the maximal power what is equivalent in search of the optimal rotational speed.
Figure 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 *Vv* data.

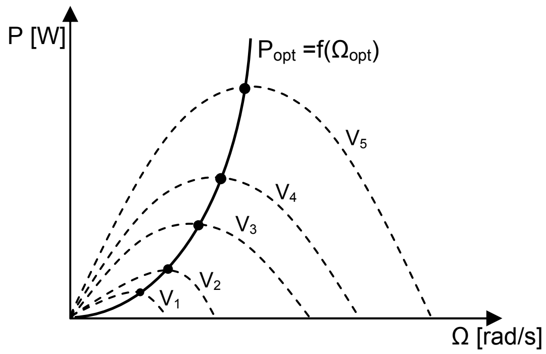

Fig. 2. Feature of wind turbine in the plan power, rotational speed

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:

$$C_{em-ref} = \frac{1}{2} \cdot \frac{C_{p\,max}}{\lambda_{opt}^3} . \rho . \pi . R^5 . \frac{\Omega_{mec}^2}{G^3} \quad (23)$$

The expression (23) can be written as:

$$C_{em-ref} = K_{opt} . \Omega_{mec}^2 \quad (24)$$

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 figure 3.

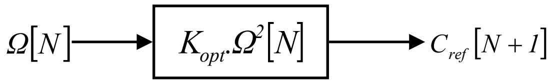

Fig. 3. Reference torque according to the rotational speed

C. Regulation of powers

The active and reactive powers passed through the grid are given in Park model by the following relations [10]:

$$P = v_{pd} . i_{td} + v_{pq} . i_{tq} \quad (25)$$

$$Q = v_{pq} . i_{td} - v_{pd} . i_{tq} \quad (26)$$

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

$$i_{td-ref} = \frac{P_{ref} . v_{pd-mes} + Q_{ref} . v_{pq-mes}}{v_{pd-mes}^2 + v_{pq-mes}^2} \quad (27)$$

$$i_{tq-ref} = \frac{P_{ref} . v_{pq-mes} - Q_{ref} . v_{pd-mes}}{v_{pd-mes}^2 + v_{pq-mes}^2} \quad (28)$$

D. DC bus regulation

While neglecting losses in the capacitor, in the converter and in the filter compared with the power passed through the grid, it is sufficient to know the available power stemmed from the rectifier P_{dc} and the power to stock in the capacitor $P_{cond\text{-}ref}$ to determine the necessary reference power.

$$\boldsymbol{P_{ref} = P_{dc\text{-}}\, u_{cap} . i_{c\text{-}ref}} \quad (29)$$

E. Limits of functioning

Given that the rectifier MLI1 has a voltage elevator nature; its DC bus must be of voltage sufficiently high to assure the piloting of the generating to maximal speed (Fem).
The association synchronous machine - MLI rectifier with six switches - battery must satisfy a DC bus voltage level sufficiently high so that the control of the machine can be achieved. In the case of strong values of wind speed, the boundary-marks voltage of the generator becomes high according to the rotational speed as indicates the equation 30.

$$E_{ab}^{max} = \sqrt{3} p . \Omega . \psi_f \quad (30)$$

The control condition of the rectifier defined by the relation 31 imposes the minimum of voltage of DC bus side according to the boundary-marks maximal composed voltage of the machine.

$$U_{cap} \geq E_{ab}^{max} \quad (31)$$

Then: $$U_{cap} \geq \sqrt{3} p . \Omega . \psi_f \quad (32)$$

While supposing that the system works to the optimal point, then the optimal rotational speed according to the wind speed is defined by the equation (6). The minimal DC bus voltage can, so determined according to the wind speed:

$$U_{cap} \geq \sqrt{3}\, p.\psi_f.\frac{\lambda_{opt}}{R}.V_v \qquad (33)$$

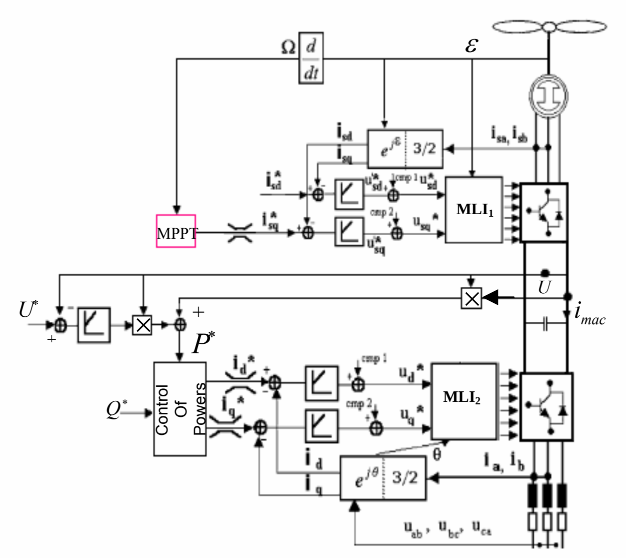

Fig. 4. Global diagram of control of the permanent magnet synchronous generator

IV. RESULTS AND DISCUSSION

The power coefficient C_p of the turbine used during this simulation is represented according to λ on the figure 5. It takes its maximal value when λ=7,5. This value is superior to the limit of BETZ because of the polynomial approximation of features of the wind turbine studied [12].

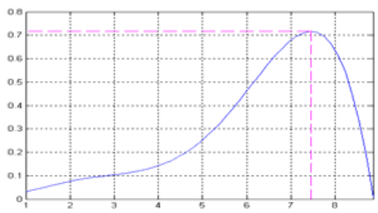

Fig. 5. Characteristics $C_p = f(\lambda)$

The figure 6 illustrates the variations of the tip-speed ratio for a wind speed that varies from 6m/s to 8m/s at the instant t=20(s) according to an echelon. It is clear that the tip-speed ratio stabilizes at a value of 7.5 what maintains an optimal value for the coefficient of power, held account that the initial speed of the turbine is 20(rd/s).

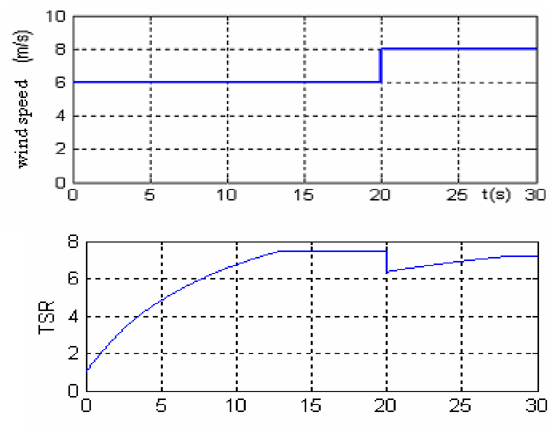

Fig. 6. Variations of tip-speed ratio according to wind speed

Figures 7.a, 7.c represent respectively the current i_{sa} of the phase (a) input rectifier MLI_1 and the current i_{ta} of the phase (a) output inverter MLI_2, for a wind speed of 6m/s. These same currents are represented on the figures 7.b and 7.d for a wind speed of 8m/s. The three phases of current output inverter MLI_2 are illustrated on the figure 7.e for the entire simulation interval.

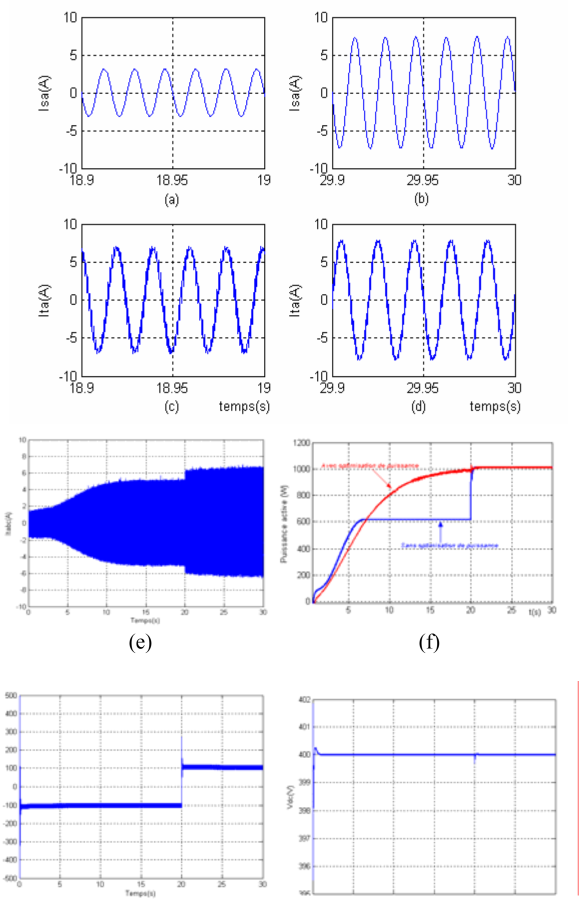

Fig. 7. Results of simulation

From the previous figures, we can observe the influence of the wind speed, and therefore the kinetic energy of wind on the amplitudes of currents. With the increase of the wind speed, the values of currents become more important either of generating side, or grid side. The method used to optimize the power extracted of wind is validated by the illustrated results of simulation on the figure 7.f. It is clear that the power provided to the grid with optimization is more important than one provided without optimization, notably in the case where the wind speed is insufficient.

The figure 7.h represents DC bus voltage that is maintained constant to 400(V). As soon as the capacitor is putting into charge, it undergoes some variations around 400(V) caused by the load transient current, in fact that the capacitor is previously charged to 400(V). A light variation noted to the instant 20(s) caused by the abrupt variation of the generator current, and therefore, the current produced by the rectifier MLI1.

The performances of the reactive power control strategy are validated by the gotten results. While choosing a reference of -100(VAR) before the instant 20(s), and a reference of 100(VAR) after, the reactive power is gotten without meaningful fluctuations of the DC bus voltage.

IV. CONCLUSION

The results of simulation permitted to consider the objectives fixed by these control strategies. With this end in view it was possible to examine the validity of the power optimization algorithm on the active power and specific speed curves that is maintained to the optimal value in steady state, and to observe wind speed influence on current, voltage, and power that become more important with the increase of the wind speed. The performances of DC bus regulation strategies and reactive power control have been put in evidence through the results of simulation.

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