Sliding Mode Control Of Permanent Magnet Synchronous Motor Fed By Wind Turbine Generator Taking Saturation Effect Into Account

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Abstract— **In this paper, we present the voltage build up process and the terminal voltage control of an isolated wind powered induction generator driven by a variable speed wind turbine using rotor flux oriented vector control. A description of the studied system is provided, and a simulation study is presented. The model used for the autonomous induction generator is a diphase one obtained by application of the Park transform. Theis model permits, when adopting some simplifying hypotheses, taking account the saturation effect. Wind powered isolated induction generators have an input, wind, that is not controllable, but they can be set to operate within a given variation of speed. Unlike a grid connected induction generator, in an isolated case, there should be a control system that keeps the DC bus voltage at a constant value when the speed of the rotor varies. The paper presents the control system to maintain the DC bus voltage at a constant value. This DC voltage is utilized for feeding an permanent magnet synchronous motor used as charge. The obtained results demonstrate a good performances of regulation for the DC voltage as input of the permanent magnet synchronous motor and the speed, torque and fluxes as its outputs.**

Key words-- **Wind energy system, Induction generator, Saturation, Sliding Mode.**

I. INTRODUCTION

As a result of increasing environmental concern, more and more electricity is generated from renewable energy. The main advantage of electricity generation from renewable sources is the absence of harmful emission and the infinite availability of the prime mover that is converted to electricity [1, 2]. One of the best ways of generating electricity from renewable energy is to use wind turbines. A tendency to erect more and more wind turbines can be observed in power industry. Wind energy technology has developed extremely rapidly and many commercial wind turbines in the market have capacity of 2MW or more. Also the cost of wind-generation electricity has fallen steadily. Wind turbines in USA produce about 1% of total generation [2]. Also, wind power meets 3% of the total electricity demand in Europe [3], and this development will continue to grow in coming years. It seems that in the near future wind turbines may start to influence the behavior of electrical power systems. As a result of such developments, extensive research is being carried out on the subject of wind generation.

Self-excited induction generators are good candidates for wind powered electricity generation, especially in remote areas, because they do not need an external supply to produce the excitation magnetic field (emf). It is well known that when capacitors are connected across the stator terminals of an induction machine, driven by an external prime mover, voltage will be induced across its terminals. The induced emf and current in the stator will continue to grow until steady-state condition is reached [2, 3]. However, self excitation has its own problems and can cause over-voltages, torque and machine speed fluctuations, etc. [4]. The impact of magnetizing inductance, minimum speed and capacitance requirement on self excitation has been examined by Seyoum [4]. The transient and steady state performance of self-excited isolated induction generators for different loading scenarios have been investigated and critical factors identified through various studies [2, 5].

In this paper, we present a study of the oriented vector control of an autonomous induction generator taking the saturation effects into account. The output voltage of the induction generator passes by the association rectifier – filter- inverter for feeding a three phase permanent magnet synchronous motor. To use the induction machine in a reliable manner as an autonomous generator that converts wind energy, the machine has to be connected to a rectifier and all the system controlled. The control system is required to keep the DC voltage at a constant value whatever the rotor speed and the load as long as the available power of the wind is sufficient.

We show that the use of the sliding mode control presented in this paper leads us to feed the load with voltage of effective value and frequency fixed whatever the speed of turbine in a given speed range.

In section II, we propose a wind- turbine model. For the induction generator, it’s a diphase model obtained by application of the Park transform. Assuming some simplifying hypotheses, the saturation effects is formulataed by a variable magnetizing inductance function of the current that we approximated by a polynomial function of 12th degree. This approach is simple and sufficiently accurate.

The third section concerns the control of the system. To control the flux in the induction machine and the DC voltage at the rectifier output, we use a sliding mode control. The sliding mode control algorithm consists of two parallel loops. The first one control the flux and leads to the d axis current reference and, by the same way, the reactive power flow in the system. The second loop control the DC voltage at the rectifier output and leads to the q-axis current reference. This permits the active power to flow from the generator to the DC circuit. In this system control, an additional level of complexity is introduced by the generator saturation. The permanent magnet synchronous motor (considered as a load of the rectifier) is controlled by a sliding mode control.

The fourth section presents simulation results of the overall system, using the MATLAB -SIMULINK package.

II. THE TURBINE -GENERATOR SYSTEM MODEL

Fig. 1 shows the wind turbine induction generator system configuration considered in this study. The wind energy generation system consists of a horizontal axis turbine connected to a cage-machine rotor through a gear system. The induction machine is driven at super-synchronous speed and it feeds a constant impedance load at a terminal voltage, V_s. The models for the different components of the wind turbine-generator system are given in the following subsections.

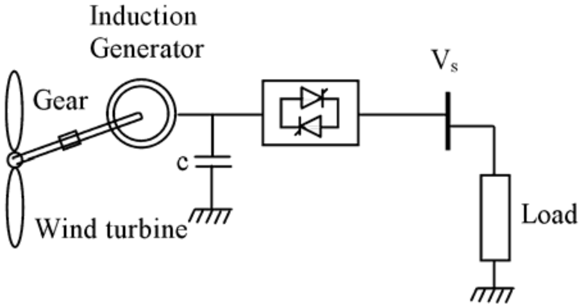

Fig.1. Wind turbine-generator system

A. *Wind turbine model*

The output power of a wind turbine is a complex relationship involving the wind speed (Vw), expressed as [6, 7]:

$$P_m = \frac{1}{2}\rho A.C_p.V_w^3 \tag{1}$$

ρ is the air density, A is the swept area by the blades. The power coefficient Cp is a function of the tip speed ratio, λ, which is the ratio of linear speed at the tip of blades to the speed of wind, expressed as

$$\lambda = \frac{\Omega R}{V_w} \tag{2}$$

R is the radius, Ω is the mechanical angular velocity, respectively, of the wind turbine rotor. Expressions of Cp as a function of λ employed in [8, 9] are:

$$\begin{aligned} C_p(\lambda) = {} & 7.9563.10^{-5}\lambda^{+5} - 17.375.10^{-4}\lambda^{+4} - 9.86.10^{-3}\lambda^{+3} \\ & - 9.41.10^{-3}\lambda^{+2} + 6.38.10^{-2}\lambda + 0.001 \end{aligned} \tag{3}$$

Typical Cp—λ curves for the pitch angle equal zero as shown in Fig. 2.

Fig. 3 shows the power-speed characteristics curves of a typical wind turbine for various wind velocities.

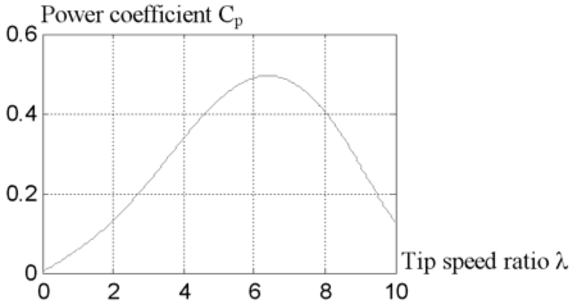

Fig.2. Typical power coefficient – tip speed ratio plot.

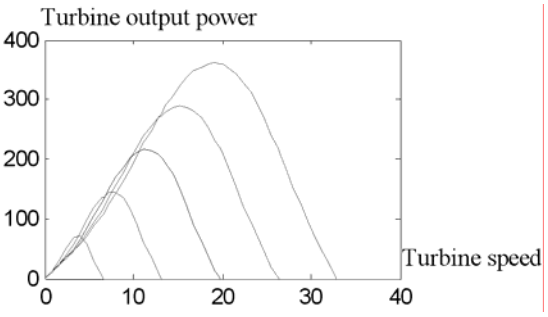

Fig.3. Speed V_s. power output characteristics of a wind turbine.

B. *Induction machine model*

The linear model of the induction machine is widely known and used. It leads to relative accurate results when the operating point studied is close to the conditions of the model parameter identification. It's offen the case when studying the motor, operating at rated voltage. As the air gap of induction machines is generally narrow, the saturation effect is not negligible in this structure. So, to improve the accuracy of simulation studies, especially when the voltage is variable, the non-linearity of the iron has to be taken into account in the machine model.

This becomes a necessary condition to study an autonomous induction generator because the linear model is not able to describe the behaviour of the system. Thus, only approaches that take account the saturation effect can be utilised. This effect is not easy to simulate using three phase classical models. So, we adopt diphase approaches to take account globally of the magnetic non-linearity. This needs some simplifying hypotheses. Indeed, the induction is considered homogenous in the whole structure. Moreover, the use of the diphase model supposes that the saturation effect is considered only on the first harmonics and does not affect the sinusoidal behaviour of the variables. In our approach, we adopt the diphase model of the induction machine expressed in the stator frame. The classical electrical equations are written, in the synchronous frame, as follows [10, 11]:

$$\begin{aligned} \begin{bmatrix} V_{sd} \\ V_{sq} \\ 0 \\ 0 \end{bmatrix} = {} & \begin{bmatrix} R_s & -\omega_s.l_s & 0 & -\omega_s.l_m \\ \omega_s.l_s & R_s & \omega_s.l_m & 0 \\ -R_r & \omega_r.l_r & R_r & -\omega_r.(l_r + l_m) \\ -\omega_r.l_r & R_r & \omega_r.(l_r + l_m) & R_r \end{bmatrix} . \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{md} \\ i_{mq} \end{bmatrix} \\ & + \begin{bmatrix} l_s & 0 & l_m + l'_m \dfrac{i_{md}^2}{|i_m|} & l'_m \dfrac{i_{md}.i_{mq}}{|i_m|} \\ 0 & l_s & l'_m \dfrac{i_{md}.i_{mq}}{|i_m|} & l_m + l'_m \dfrac{i_{md}^2}{|i_m|} \\ -l_r & 0 & l_r + L_m + L'_m \dfrac{i_{md}^2}{|i_m|} & l'_m \dfrac{i_{md}.i_{mq}}{|i_m|} \\ 0 & -l_r & l'_m \dfrac{i_{md}.i_{mq}}{|i_m|} & l_r + L_m + L'_m \dfrac{i_{md}^2}{|i_m|} \end{bmatrix} . \begin{bmatrix} \dfrac{di_{sd}}{dt} \\ \dfrac{di_{sq}}{dt} \\ \dfrac{di_{md}}{dt} \\ \dfrac{di_{mq}}{dt} \end{bmatrix} \end{aligned} \tag{4}$$

Where R_s, l_s, R_r and l_r are the stator and rotor phase resistances and leakage inductances, respectively, L_m is the magnetizing inductance and ω_s and ω_r are the stator and rotor pulsations, respectively. Besides, V_{sd}, i_{sd},V_{sq} and i_{sq} are the d–q stator voltages and currents, respectively. i_{md} and i_{mq} are the magnetizing currents, along the d- and q-axis, respectively, given by

$$\begin{cases} i_{md} = i_{sd} + i_{rd} \\ i_{mq} = i_{sq} + i_{rq} \end{cases} \tag{5}$$

ird and irq represent the d–q rotor currents.

The saturation effect is taken into account by the expression of the magnetizing inductance Lm with respect to the magnetizing current im defined as

$$i_m = \sqrt{i_{md}^2 + i_{mq}^2} \tag{6}$$

To express Lm with respect to im, we use a polynomial approximation of degree 12 [12, 13].

$$\begin{cases} l_m = f(|i_m|) = \sum_{j=0}^{n} a_j.|i_m|^j \\ l'_m = \dfrac{dL_m}{d|i_m|} = \dfrac{d}{d|i_m|} f(|i_m|) = \sum_{j=0}^{n} a_j.|i_m|^{j-1} \end{cases} \tag{7}$$

Fig 4, presents magnetizing inductance function of the magnetizing current. This figure demonstrates the non linearity nature of the induction generator.

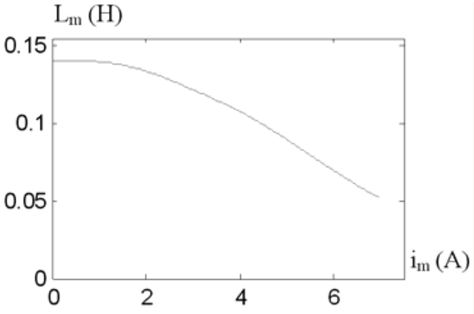

Fig.4. L_m - magnetising current.

C. Study of an induction generator connected to a capacitance bank

The stator windings of the induction machine are linked to a capacitance bank connected in parallel to a resistive load (Fig. 1).

As the stator and rotor pulsations are unknown, it is necessary to re-write the electrical equations in the rotor frame where only the mechanical pulsation, known, is considered. In this case, with no load, the diphase stator voltages and currents are linked by the following expression:

$$\frac{d}{dt}\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} \frac{1}{c} & 0 \\ 0 & \frac{1}{c} \end{bmatrix} . \begin{bmatrix} -i_{sd} \\ -i_{sq} \end{bmatrix} + \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix} . \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \tag{8}$$

which becomes, when the induction generator is loaded:

$$\frac{d}{dt}\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} \frac{1}{c} & 0 \\ 0 & \frac{1}{c} \end{bmatrix} . \begin{bmatrix} -i_{sd} & -i_{chd} \\ -i_{sq} & -i_{chq} \end{bmatrix} + \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix} . \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \tag{9}$$

III. THE PROPOSED CONTOL STRATEGY

A. Control strategy of Wind turbine-generator system

To lead to a generated voltage with a constant magnitude and frequency, the induction machine must be connected to a rectifier and an inverter. Both have to be controlled. In this part, we will study the vector control of the system consisting of a wind turbine, an induction generator, a PWM rectifier and a PWM inverter (Fig. 5). The goal of the control is to maintain the DC bus voltage at a constant value when the rotor speed is varying. To control the flux in the generator and the DC voltage at the rectifier output, we use a rotor flux oriented vector control.

The vector control algorithm consists of two loops that operate in parallel (Fig. 6). The first one allows us to control the flux and leads to the d-axis current reference. It controls, by the same way, the reactive power flow in the system. The second loop enables us to control the DC voltage at the rectifier output and then to reach the q-axis current reference. This permits the active power to flow from the generator to the DC circuit. In this system control, an additional level of complexity is introduced by the saturation of the generator. We will show that the control of the flux implies a constant saturation level of the generator and, then, leads to a model of the machine, which becomes linear at an operating point. The flux variations around this point are negligible.

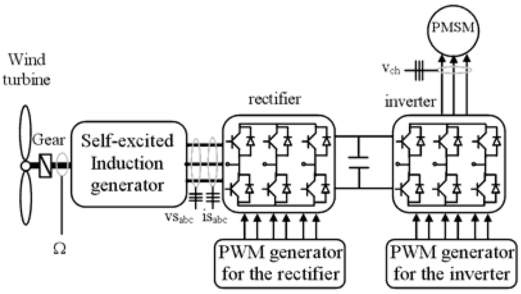

Fig.5. Scheme of the system studied.

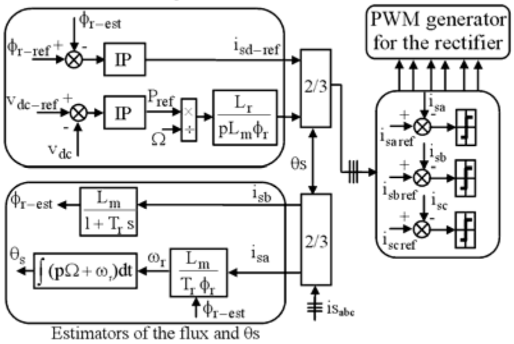

Fig.6. Structure of the vector control scheme.

B. Sliding Mode Control of the PMSM

With the simplifying assumptions relating to the PMSM, the model of the motor expressed in the Park reference frame is given in the suitable state form [14, 15]:

$$\begin{cases} \dot{X} = F(X) + G \cdot U \\ Y = H(X) \end{cases} \tag{10}$$

where:

$$Y(X) = \begin{bmatrix} y_1(X) \\ y_2(X) \end{bmatrix} = \begin{bmatrix} h_1(X) \\ h_2(X) \end{bmatrix} = \begin{bmatrix} x_1 \\ x_3 \end{bmatrix} = \begin{bmatrix} I_d \\ \Omega \end{bmatrix}$$

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} I_d \\ I_q \\ \Omega \end{bmatrix}; U = \begin{bmatrix} V_d \\ V_q \end{bmatrix}; G = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \end{bmatrix}$$

$$F(X) = \begin{bmatrix} f_1(X) \\ f_2(X) \\ f_3(X) \end{bmatrix} = \begin{bmatrix} a_1 \cdot x_1 + a_2 \cdot x_2 \cdot x_3 \\ b_1 \cdot x_2 + b_2 \cdot x_1 \cdot x_3 + b_3 \cdot x_3 \\ c_1 \cdot x_3 + c_2 \cdot x_1 \cdot x_2 + c_3 x_2 - \frac{T_l}{J} \end{bmatrix}$$

and:

$$a_1 = -\frac{R_s}{L_d}; \quad a_2 = \frac{p \cdot L_q}{L_d}; \quad b_1 = -\frac{R_s}{L_q}; \quad b_2 = -\frac{p \cdot L_d}{L_q}$$

$$b_3 = -\frac{p \cdot \phi_f}{L_q}; c_1 = -\frac{f}{J}; c_2 = \frac{p \cdot (L_d - L_q)}{J}; c_3 = \frac{p \cdot \phi_f}{J}$$

In $f_1(X)$ the load torque T_l is removed from the state equations and will be considered as a perturbation.

The surfaces are chosen in order to determine the behaviour of the motor in the transient period. For the speed control, we propose a switching law which depends on the difference between reference speed and real speed, presented in (11):

$$S(\Omega) = \Omega_{ref} - \Omega \tag{11}$$

The derivative of this surface is given by the expression:

$$\overset{\bullet}{S}(\Omega) = -c_1\Omega + \frac{C_r}{J} + \overset{\bullet}{\Omega}_{ref} - (c_2 I_{ds} + c_3) I_{qs} \tag{12}$$

The associated control input is given by (15):

$$I_{qsref} = \frac{-c_1\Omega + \frac{C_r}{J} + \overset{\bullet}{\Omega}_{ref} + K_\Omega \mathrm{Sing} S(\Omega)}{(c_2 I_{ds} + c_3)} \tag{13}$$

The components i_{ds} and i_{qs} are independently controlled as described by (15) and (16):

$$S(I_{ds}) = I_{dsref} - I_{ds}, \ I_{dsref} = 0 \tag{14}$$

Frequently I_{dref} is made equal to zero, because its contribution to the motor torque is almost insignificant [16, 17]. Flux and torque control are independently made through the surfaces $S(I_{ds})$ and $S(I_{qs})$ respectively.

The derivative of the surface $S(I_{ds})$ is given by the expression:

$$\overset{\bullet}{S}(I_{ds}) = I_{dsref} - a_1 I_{ds} - a_2 I_{qs}\Omega - \frac{1}{Ld} u_d \tag{15}$$

The associated control input is given by (15):

$$u_{dref} = \frac{[\overset{\bullet}{I}_{dsref} - a_1 I_{ds} - a_2 I_{qs}\Omega] + k_d \mathrm{sign} S(I_{ds})}{Ld} \tag{16}$$

and:

$$S(I_{qs}) = I_{qsref} - I_{qs} \tag{17}$$

The derivative of this surface is given by the expression:

$$\overset{\bullet}{S}(I_{qs}) = I_{qsref} - b_1 I_{qs} - b_2 I_{ds}\Omega - b_3\Omega - \frac{1}{Lq} u_q \tag{18}$$

The associated control input is given by (17):

$$u_{qref} = \frac{[\overset{\bullet}{I}_{qsref} - b_1 I_{qs} - b_2 I_{ds}\Omega + b_3\Omega + k_q \mathrm{sign} S(I_{qs})}{Ld} \tag{19}$$

The suitable choice of the parameters K_d K_q and K_Ω [18-20]:

- Ensures the rapidity of the reaching mode,
- Imposes the dynamic of the convergence and sliding mode,
- Allow to the drive to work with maximum energy during transient state.

Hence, K_d K_q and K_Ω are positives gains, given as followed:

$$\begin{aligned} K_d &< -\max_{I_{ds}, I_{qs}, \omega} \left| RI_{ds} - L_q \omega I_{qs} \right| \\ K_q &< -\max_{I_{ds}, I_{qs}, \omega} \left| RI_{qs} - L_{ds} \omega I_{ds} + \omega\phi_f \right| \\ K_\omega &< -\max_{I_{ds}, I_{qs}, \omega} \left| \frac{C_r - f\omega}{p\phi_f} \right| \end{aligned} \tag{20}$$

The block diagram of the sliding mode control of permanent magnet synchronous motor drive system is shown in fig 7.

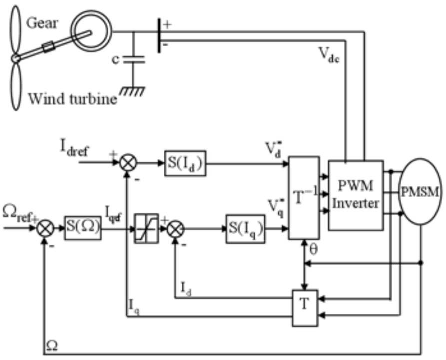

Fig.7. Speed control of *a* PMSM using the sliding mode control

IV. RESULTS AND DISCUSSIONS

A. Simulation Results of Wind turbine-generator system

The simulation conditions are given in the appendix.

Simulation results using the vector control strategy with different cases are given. Both the inverter and rectifier are modeled in the same way. The switches are considered as ideal, and their states are given by logical functions that take value 1 when the component is closed and 0 when it is open.

First, the rotor speed of the induction machine is increased till the synchronous speed. Once this last is reached, the flux and Vdc reference values are applied. These are: $\phi_{r-ref} = 0.8\mathrm{Wb}$; $v_{dc-ref} = 515\mathrm{v}$.

The DC voltage regulation is obtained using the proposed vector control algorithm. In Fig. 8, we can see the stator voltage waveform. The increase of the rotor speed implies an increase of the voltage. Fig (9) presents the a, b, c currents and the DC voltage is presented in fig (10), we can see that the generated voltage reache the reference one with high precision. The DC voltage is controlled with the torque via the current isq.

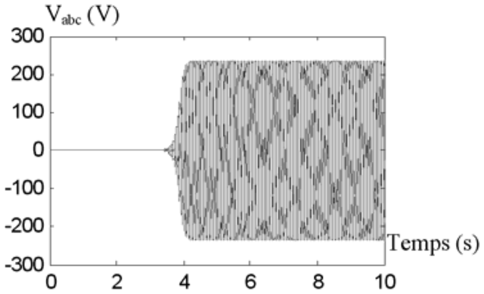

Fig.8. stator voltage V_{abc}.

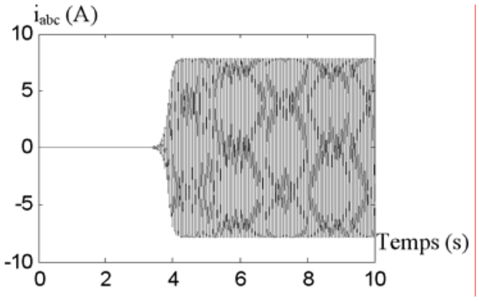

Fig.9. stator current i_{abc}..

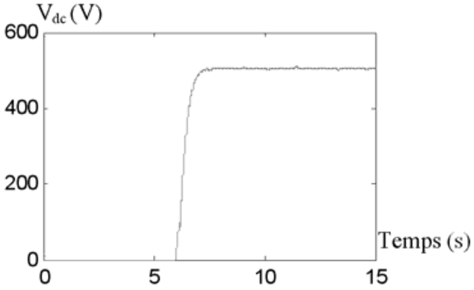

Fig.10. DC voltage V_{de}.

B. Simulation Results of Sliding Mode Control of PMSM

The performance of the proposed sliding mode control of PMSM scheme (fig 7) is assessed through simulation study. The simulation conditions are given in the appendix. The PWM inverter is considered in the simulation.

The validity of the control scheme is demonstrated through the results shown in figure 11.

To illustrate performances of control, we simulated a loadless starting up mode with the reference speed +100 rad/s at time 10 s and an application of the load torque (C_r=5 Nm)at time 12 s. We can notice the good performances of the non-linear control; the real speed converges to the reference one with a high precision. The electromagnetic torque allure is presented, it can concluded that the electromagnetic torque developed by the motor increased at t =12 s to 5 Nm for compensate the load torque.

This figure demonstrates the perfect decoupling between the d and q axis. The d stator current conserved a constant value while q stator current followed the increasing and the decreasing of electromagnetic torque. These results demonstrate the good performances of the regulation.

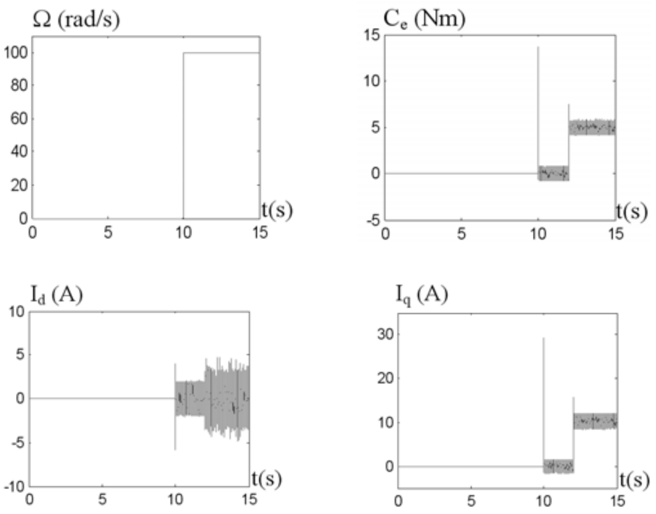

Fig.11. Drive response of permanent magnet synchronous motor under load disturbanse.

V. CONCLUSION

In this paper, the vector control of an induction generator used in an autonomous speed wind system is presented. An analytical model of the autonomous induction generator, taking the saturation effects into account by means of a variable magnetizing inductance has been presented. This magnetizing inductance is expressed, using a polynomial function of degree 12, as a function of the magnetizing current.

The diphase model of the induction machine enabled us to define a vector control for the generator operation of this machine. As the flux is maintained at a constant value, the machine model can be considered linear around an operating point. Then, the adjustment of the torque is independent of the flux. This avoids having a complex algorithm of control when taking into account saturation.

This control enables us to maintain the saturation level of the generator constant and to control the DC voltage through the torque in the same way as it was done for the motor operation. Finally, the use of the control leads us to feed the load with voltage of effective value and frequency fixed whatever the speed of the turbine.

The sliding mode control of the permanent magnet synchronous motor used as charge presents a good performance of regulation of speed. We can say that the associations of the wind turbine and induction generator permits feeding the induction motor with a sufficient voltage and frequency.

VI. APPENDIX

Parameters of the system used in simulation:

Parameters of the turbine:

$R = 3.36\text{m}$

$\rho = 1.225\text{kg}/\text{m}^3$

$V_w = 6\text{m}/\text{s}$

Parameters of the Induction generator:

$R_s = 1.2\Omega;\ R_r = 1.8\Omega;\ L_s = 0.115\text{H};\ L_r = 0.115;$

$J = 0.07\text{Kg.m}^2;\ f_r = 0.001\text{Nm.s}/\text{rad};$

$p = 1;\ \Omega = 314\text{Rad}/\text{s}.$

Parameters of the PMSM:

Rated power 1 Kw
Rated speed 3000 rpm
Stator winding resistance 0.6 Ω
Stator winding direct inductance 4 mH
Stator winding quadrate inductance 2.8 mH
Rotor flux 0.12 Wb
Viscous friction 1.4 e-3 Nm/rad/s
Inertia 1.1 e-3 kg m2
Pairs pole number 4
Nominal current, voltage line 20 A, 310 V
Machine type: Siemens 1FT6084-8SK71-1TGO

Parameters of the PWM converter:

Supply's voltage and frequency: 220 V(rms), 50 Hz
Line's inductor and resistance 0.002 H, 0.08 Ω
Output capacitors 0.0025 F
PWM carrier frequency 1 kHz

VII. REFERENCES

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