

# Vector Control of wind conversion system based on a squirrel cage Induction generator (SCIG)

H. Abouobaida, M. Cherkaoui

Department of Electrical Engineering,  
Ecole Mohammadia d'ingénieurs, Mohammed V University, Rabat, Morocco  
Hassanabouobaida@gmail.com, cherkaoui@emi.ac.ma

**Abstract** - This paper presents a control strategy for a grid connected squirrel cage Induction generator (SCIG)-based wind energy conversion system. Control strategies of the grid side and stator side converters are presented along with the mathematical modeling of the employed configuration. The maximum power point extraction of the wind turbine, unity power factor operation are also addressed along with the proposed strategy. The developed approach control is then simulated in MATLAB-SIMULINK and the developed model is used to illustrate the behavior of the system. The simulation results are presented and discussed at the end of this paper.

**Index Terms** - Squirrel cage Induction generator (SCIG), grid power, unity power factor, wind energy conversion system, inverter, maximum power point extraction.

## 1. Introduction

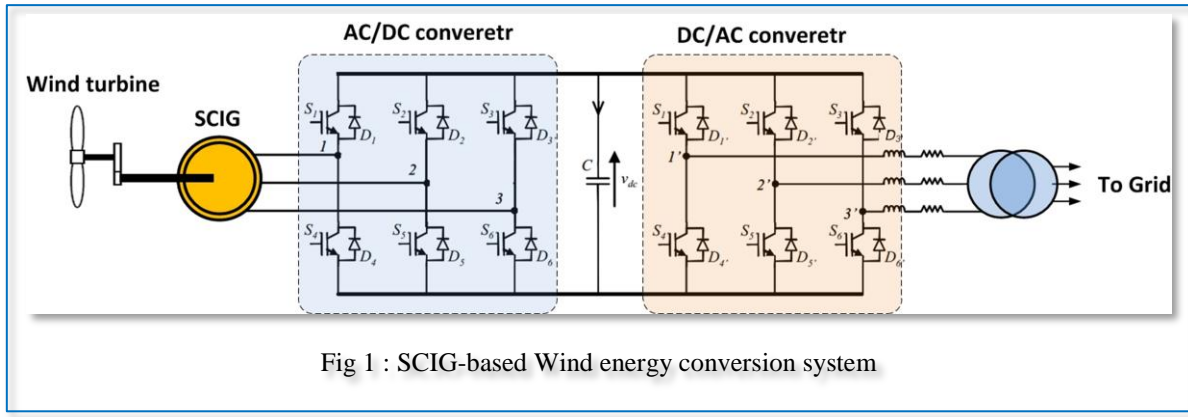
The growing need for electrical energy and the will to preserve the nature justifies the use of renewable energy sources. The use of renewable sources for electric power generation has been a huge increase since the past decade. Increased economical and ecological woes have driven researchers to discover newer and better means of generating electrical energy. In this race, the production of electricity by wind turbine is actually the best method in comparison with the energy produced by the solar source conversion and this is due to the price per a

of wind turbine based on a electric conversion generator. Different types of electric generators are used for the generation of electric energy from wind. These include the squirrel cage induction generators (SCIG), the doubly fed induction generator (DFIG) and the synchronous generator (SG) [1].

The squirrel cage induction generator (SCIG) is suitable for alternative energy source applications because it is cheap, has simple construction, good power/weight ratio, low maintenance levels, and it is robust and easily replaceable. For these reasons, the SCIG is being strongly considered as a good option in conjunction with the variable speed wind turbines [2].

Variable-speed wind turbines are advantageous for their potential capability of extracting more energy from wind resources. Thus, an MPPT control strategy is necessary to adjust the turbine rotor speed according to the variation of wind speeds so that the tip speed ratio can be maintained at its optimal value.

Several MPPT control algorithms have been proposed in the technical literature. The search control such as perturb and observe (P&O), anemometer-based method, and the fuzzy-logic based algorithms are easily implemented and are independent of wind turbine characteristics. In the P&O algorithm, the turbine speed is varied in small steps and the corresponding change in power is observed. Step changes are effected in a direction so as to move toward MPP. This process is continued until MPP is reached. By using this algorithm, maximum power corresponding to any wind velocity can be



captured. But the time taken to reach MPP is long and a considerable amount of power loss takes place during the tracking phase. The anemometer-based MPPT algorithm, the wind velocity is measured and a reference speed for the induction generator (IG) corresponding to the MPP of the present wind velocity is set. Although this is a fast MPPT scheme, the overall cost of the system increases because anemometer is expensive. Fuzzy-control-based scheme is good, but is complex to implement. Neural networks could be an alternative approach for the MPPT control, but the requirement for offline training in order to learn the turbine characteristics might be a considerable drawback for several installations. An optimal torque controller that follows a quadratic relation between turbine torque and speed can provide faster dynamic response; however, it needs a priori knowledge of the turbine characteristics [3].

In the grid-connected system, however, any amount of power generated by the wind energy based (SCIG) can be injected into the grid. Hence, at any wind velocity, the system can be operated at MPP to maximize the generation and utilization of power. The block diagram of a typical grid-connected wind energy conversion system is shown in Fig. 1. The transfer of the power produced by this system is made by two cascaded converters. The first is linked to the network

operates as a rectifier and the second operates as an inverter is connected to the grid [4].

This paper is structured as follows. Section II presents the modeling of the SCIG system. The detailed control strategy is discussed in Section III. Section IV presents and discusses simulation and results followed by conclusions in Section V.

## 2. Wind energy conversion system modeling

The wind turbine modeling is inspired from [4]. In the following, the wind turbine components models are briefly described.

### a) The Turbine Model

The aerodynamic power  $P$  captured by the wind turbine is given by

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

Where the tip speed ratio  $\lambda$  is given by :

$$\lambda = \frac{R\omega}{v} \quad (2)$$

and  $v$  is the wind,  $\rho$  is the air density,  $R$  is the rotor radius, and  $C_p$  is the power coefficient.  $\lambda$  is the ratio of turbine blades tip speed to wind speed and  $\beta$  is the turbine blades rotational speed.  $C_p$  can be represented by a nonlinear curve in terms of  $\lambda$  in place of different value of  $\beta$  as illustrated in Fig 2:

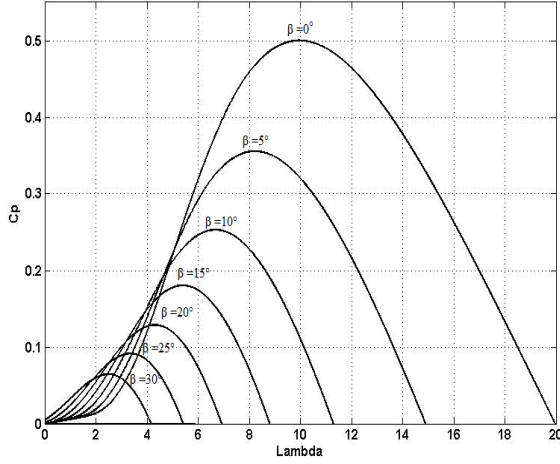


Fig 2 : Curve of  $C_p$  in function of  $\lambda$  for different value of the Pitch angle  $\beta$

The rotor power (aerodynamic power) is also defined by

$$P = T_m \cdot \omega \quad (3)$$

where  $T_m$  is the aerodynamic torque and  $\omega$  is the wind turbine rotor speed.

The following simplified model is adopted for the turbine

$$J \frac{d\omega}{dt} = T_m - T_{em} - K \cdot \omega \quad (4)$$

where  $T_{em}$  is the generator electromagnetic torque,  $J$  is the turbine total inertia, and  $K$  is the turbine total external damping.

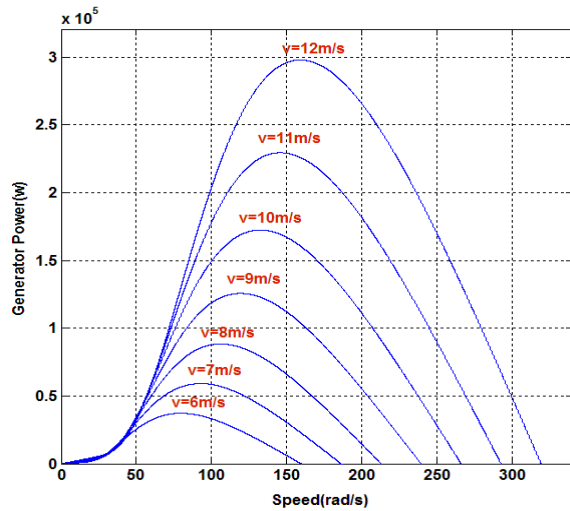


Fig 3 : Generator power as a function of generator speed for different wind speeds.

### b) The SCIG Model

The control system is usually defined in the synchronous  $d$ - $q$  frame fixed to either the stator voltage or the stator flux. For the proposed control strategy, the generator dynamic model written in a synchronously rotating frame  $d$ - $q$ .

The voltages of the windings of the stator and the rotor according to the  $d$ - $q$  axes are given by the following relations [5]

$$\begin{cases} v_{sd} = R_s i_{sd} + \frac{d\Phi_{sd}}{dt} - \omega_s \cdot i_{sq} \\ v_{sq} = R_s i_{sq} + \frac{d\Phi_{sq}}{dt} + \omega_s \cdot i_{sd} \\ v_{rd} = 0 = R_r i_{rd} + \frac{d\Phi_{rd}}{dt} - \omega_r \cdot i_{rq} \\ v_{rq} = 0 = R_r i_{rq} + \frac{d\Phi_{rq}}{dt} + \omega_r \cdot i_{rd} \end{cases} \quad (5)$$

The electromagnetic torque is given by the following relation

$$T_{em} = \frac{P \cdot M}{L_s} (\Phi_{sq} \cdot i_{rd} - \Phi_{sd} \cdot i_{rq}) \quad (6)$$

The magnetic flux created by the windings of the stator and the rotor are given by the following relations

$$\begin{cases} \Phi_{sd} = L_s I_{sd} + m \cdot L_m \cdot I_{rd} \\ \Phi_{sq} = L_s I_{sq} + m \cdot L_m \cdot I_{rq} \\ \Phi_{rd} = L_r I_{rd} + m \cdot L_m \cdot I_{sd} \\ \Phi_{rq} = L_r I_{rq} + m \cdot L_m \cdot I_{sq} \end{cases} \quad (7)$$

where  $v$  is the voltage,  $i$  the current,  $\Phi$  is the flux,  $R$  is the resistance,  $L$  is inductance,  $M$  is the mutual inductance,  $T_{em}$  is the electromagnetic torque, and  $P$  is the pole pair number.  $L_m$  and  $m$  ( $M = m \cdot L_m$ ) are magnetizing inductance and turns ratio of the stator current and rotor current respectively.

The active and reactive stator powers are expressed by

$$\begin{cases} P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \\ Q_s = V_{sq} I_{sd} - V_{sd} I_{sq} \end{cases} \quad (8)$$

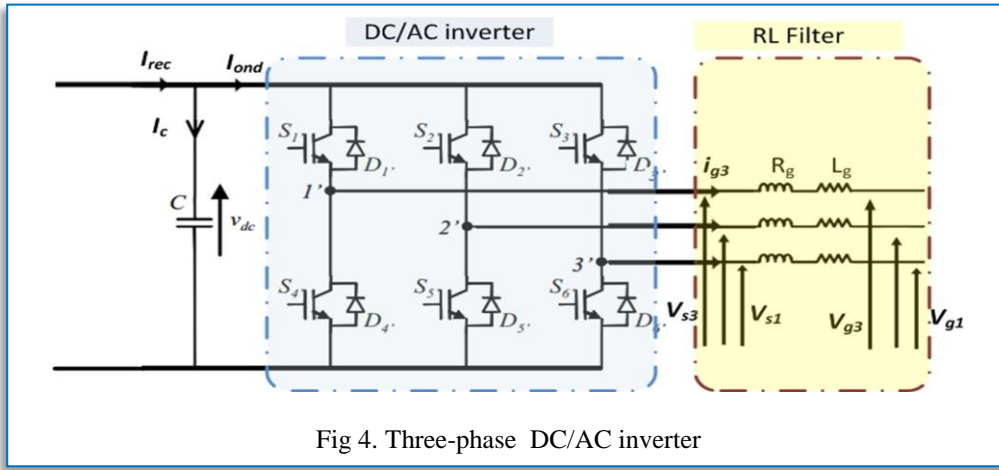


Fig 4. Three-phase DC/AC inverter

### c) Modeling three-phase inverter

In this section, we focus on the modeling of the DC/AC inverter connected to power grid via the RL filter as illustrated in Figure 4.

The model of the three-phase grid connected DC/AC converter is presented by the following equations [6]

$$\begin{cases} v_{s1} = v_{g1} + R_g \cdot i_{g1} + L_g \cdot \frac{di_{g1}}{dt} \\ v_{s2} = v_{g2} + R_g \cdot i_{g2} + L_g \cdot \frac{di_{g2}}{dt} \\ v_{s3} = v_{g3} + R_g \cdot i_{g3} + L_g \cdot \frac{di_{g3}}{dt} \end{cases} \quad (9)$$

The dynamic of the DC bus voltage is given by the following equation

$$C \cdot \frac{dV_{dc}}{dt} = i_{rec} - i_{ond} \quad (10)$$

With

$v_{gi}$  : voltages of the electrical network,

$i_{gi}$  : currents of electrical network,

$i_{rec}$ ,  $i_{ond}$ : output current of the AC/DC converter and input current of the DC/AC converter respectively,

$V_{dc}$ ,  $i_c$  : voltage and current of the DC link capacitor respectively

$v_{si}$  : output voltages of the DC/AC converter

$S_i$  : IGBT transistor

### 3. Control Strategy

The architecture of the controller is shown in Figure 5. It is based on the three-phase model of the electromechanical conversion chain of the wind system [6].

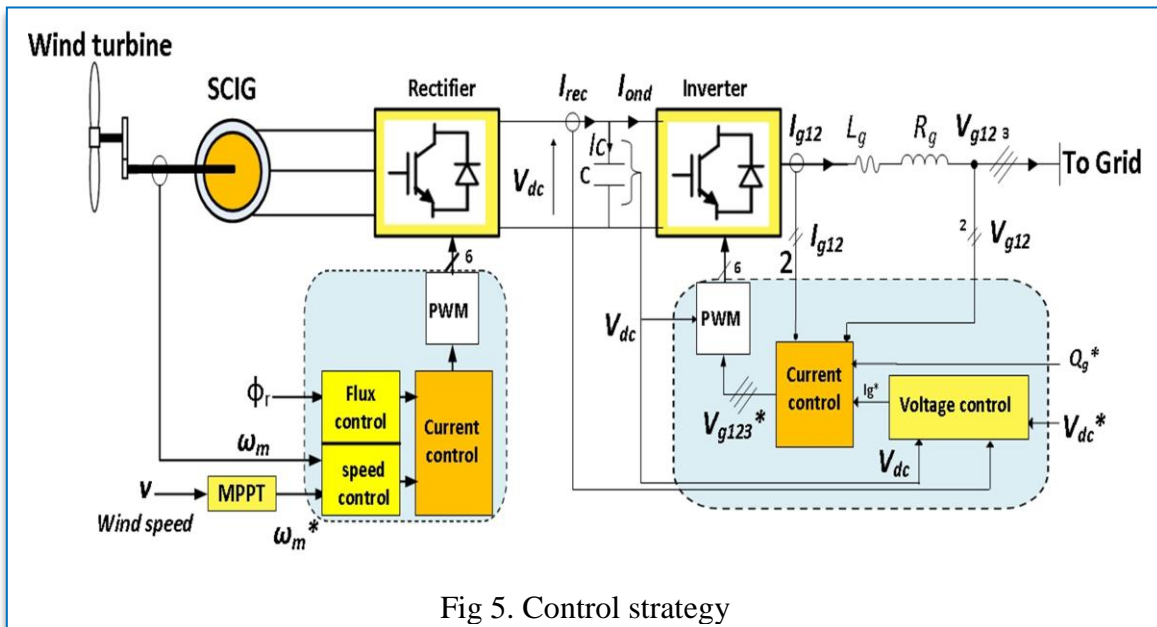


Fig 5. Control strategy

The control strategy has three objectives:

- Control of AC/DC converter to extract maximum wind power by controlling the electromagnetic torque and d-axis flux of rotor of SCIG,
- Control of the DC/AC by controlling the DC bus voltage, active and reactive power exchanged with the network.

a) *MPPT strategy :*

The control objective is to optimize the capture wind energy by tracking the optimal generator speed  $\omega_m^*$ .

The optimum speed which corresponds to operation at maximum power is approximated according to the wind speed:

$$\omega_m^* = a0 + a1 \cdot v + a2 \cdot v^2 \quad (11)$$

With

$$a0 = 16; a1 = 9.33; a2 = 0.2222$$

b) *Control of the AC/DC converter*

Controls the electromagnetic torque and rotor direct flux will be obtained by controlling the dq-axes stator currents of the SCIG.

By choosing the two-phase dq related to rotating rotor field, and placing the rotor flux vector on the d-axis, we can write

$$\begin{cases} \Phi_{rd} = \Phi_r \\ \Phi_{rq} = 0 \end{cases} \quad (12)$$

Taking into account equation (6), (7) and (12), the electromagnetic torque can be expressed as a function of the quadrature component of the stator current

$$T_{em} = P \cdot \frac{M}{L_r} \cdot \Phi_r \cdot i_{sq} \quad (13)$$

Taking into account equation (6), (7) and (12), the d-axis stator current can be expressed as a function of the rotor flux

$$\frac{d\Phi_r}{dt} + \frac{R_r}{L_r} \Phi_r = \frac{R_r}{L_r} \cdot M \cdot i_{sd} \quad (14)$$

This means that the rotor flux depends only on the d-axis stator current. This natural decoupling between the electromagnetic torque and rotor flux interprets the choice of vector control.

The rotor flux is estimated from the equation (14) as

$$\Phi_{rd\_est} = \frac{M}{1+\tau \cdot p} \cdot i_{sd} \quad (15)$$

With  $\tau = \frac{L_r}{R_r}$  the rotor time constant

The dq axis stator flux can be expressed according equation (5) and (7) as

$$\begin{cases} \Phi_{sd} = \sigma \cdot L_s \cdot i_{sd} + \frac{M}{L_r} \Phi_r \\ \Phi_{sq} = \sigma \cdot L_s \cdot i_{sq} \end{cases} \quad (16)$$

Where  $\sigma = 1 - \frac{M^2}{L_r \cdot L_s}$  is the dispersion coefficient.

The dynamics of the dq-axis stator currents are expressed according to the equation (5) and (16) as

$$\begin{cases} L_s \cdot \sigma \cdot \frac{di_{sd}}{dt} = v_{sd} - R_s i_{sd} + e_{sd} \\ L_s \cdot \sigma \cdot \frac{di_{sq}}{dt} = v_{sq} - R_s i_{sq} + e_{sq} \end{cases} \quad (17)$$

Where:

$$\begin{cases} e_{sd} = \omega_s \Phi_{sq} - \frac{M}{L_r} \frac{d\Phi_{rd}}{dt} \\ e_{sq} = -\omega_s \Phi_{sd} \end{cases} \quad (18)$$

$e_{sd}$  and  $e_{sq}$  are considered as disturbances that must be compensated. The controllers are determined for the following transfer function

$$\begin{cases} \frac{i_{sd}}{v_{sd}} = \frac{1}{R_s + \sigma \cdot L_s \cdot p} \\ \frac{i_{sq}}{v_{sq}} = \frac{1}{R_s + \sigma \cdot L_s \cdot p} \end{cases} \quad (19)$$

The strategy of adjustment of the rotor flux and electromagnetic torque is given in figure 6.

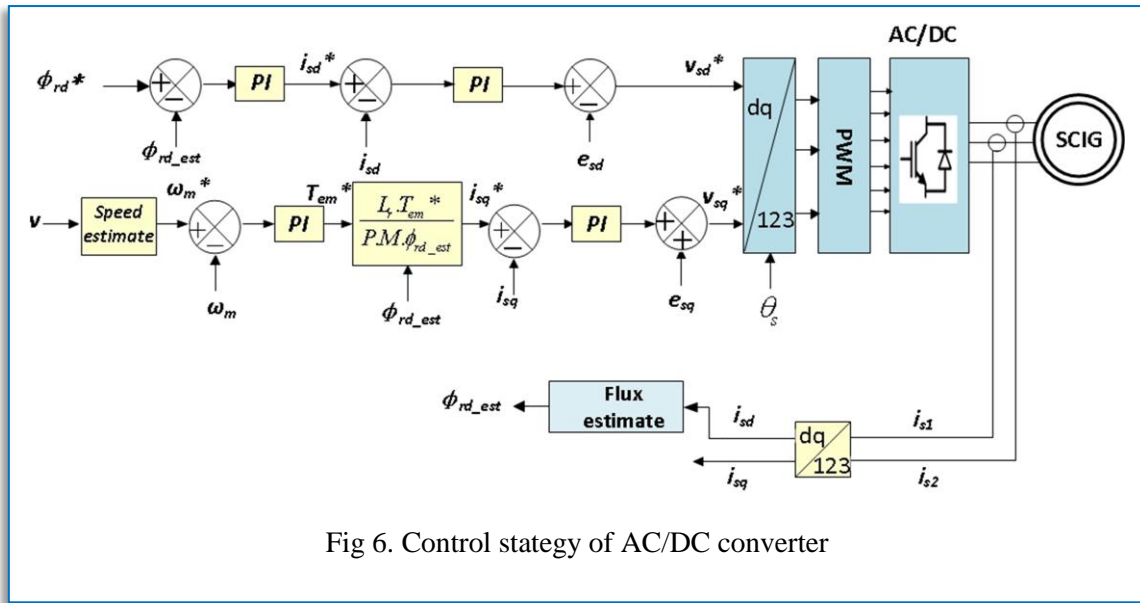


Fig 6. Control strategy of AC/DC converter

### b) DC/AC control strategy

The three-phase inverter is controled to:

- Regulating the dc bus voltage
- Provide a power factor close to unity (network current in phase with the network voltage).

The inverter modeling is relatively simple and is accomplished through  $dq$  transformation. The modeling for the current control is obtained considering the AC output. When the circuit is observed from the AC output, it is possible to make some initial considerations that result in a simplified circuit, shown in Fig. 7. The line voltages are presented in (20) considering  $L_1=L_2=L_3=L_g$ ,  $R_1=R_2=R_3=R_g$  [7]

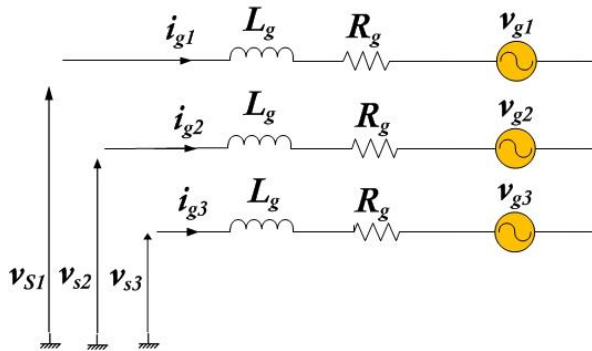


Fig. 7. Equivalent model of the grid side

$$\begin{cases} v_{s1} = R_g i_{g1} + L_g \frac{di_{g1}}{dt} + v_{g1} \\ v_{s2} = R_g i_{g2} + L_g \frac{di_{g2}}{dt} + v_{g2} \\ v_{s3} = R_g i_{g3} + L_g \frac{di_{g3}}{dt} + v_{g3} \end{cases} \quad (20)$$

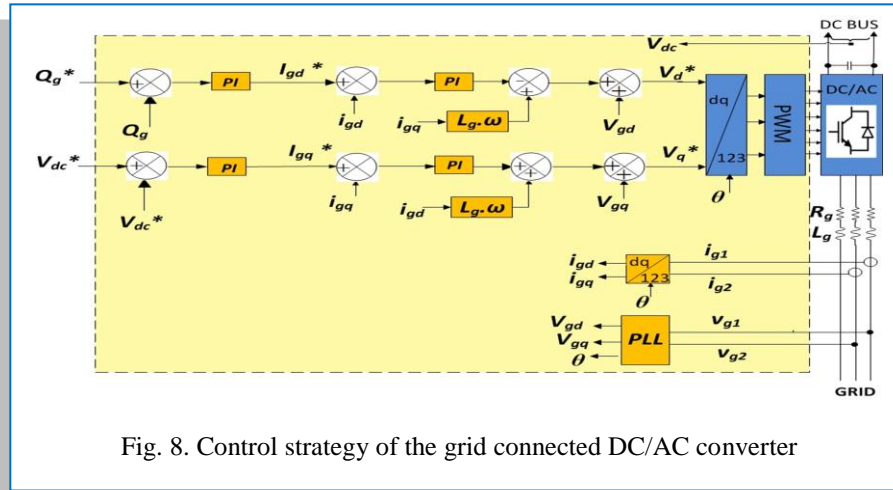
Where  $v_{s1}$ ,  $v_{s2}$  and  $v_{s3}$  are the output voltages of the invrter  $v_{g1}$ ,  $v_{g2}$  and  $v_{g3}$  are the grid voltage.

Applying  $dq$  transformation and developing the equations system (20), it is possible to find the differential equations (21):

$$\begin{cases} v_d = R_g i_d + L_g \frac{di_d}{dt} + L_g \omega i_q + v_{gd} \\ v_q = R_g i_q + L_g \frac{di_q}{dt} - L_g \omega i_d + v_{gq} \end{cases} \quad (21)$$

The expression of the active and reactive power exchanged with the grid are :

$$\begin{cases} P_g = V_d i_d + V_q i_q \\ Q_g = V_q i_d - V_d i_q \end{cases} \quad (22)$$



Where  $(v_d, v_q)$  are the direct and quadrature components of the grid voltage respectively.  $(i_d, i_q)$  are the direct and quadrature components of the grid current.

The term  $-\omega.L_g.i_q + v_{gd}$  and  $\omega.L_g.i_d + v_{gq}$  are compensated by a feed-forward action. By applying the Laplace transform to the compensated system, the transfer function of the inverter is given as:

$$G_i(p) = \frac{v_d}{i_d} = \frac{v_q}{i_q} = \frac{1}{L_g \cdot p + R_g} \quad (23)$$

Where  $v_d$  and  $v_q$  are the inputs voltages and the  $i_d$  and  $i_q$  are the outputs currents respectively.

The DC bus dynamics is given as :

$$c.\dot{\vec{V}}_{dc} = i_{rec} - i_{ond} \quad (24)$$

The application of the Laplace transform to (24) result in :

$$c.p.\bar{V}_{dc} = i_{rec} - i_{ond} \quad (25)$$

The term  $i_{rec}$  is a disturbance in the control. It is assumed in this work that the DC bus loop is sufficiently fast, as to eliminate the perturbation term. For this reason, the DC bus function will be:

$$G_u(p) = \frac{V_{dc}}{i_{ond}} = -\frac{1}{c.p} \quad (26)$$

The control loops of the inverter are shown in figure (8). Externally, there is the reactive power loop that controls the power factor and the loop to regulate the DC bus voltage. The current control loops use proportional-integral controllers. The controller gains are adjusted by the poles allocation method [8].

## 4. Simulation results

The model of the SCIG based variable speed wind turbine system is built using MATLAB\SIMULINK. The parameters of the turbine and SCIG are given in the following Table.

System	Parameter
<b>Turbine</b>	$J_t = 50 \text{ kg.m}^2$ , $V_{t_n} = 12 \text{ m/s}$ , $R = 14 \text{ m}$
<b>Multiplier</b>	$M_u = 46$
<b>DFIG</b>	$U_s = U_r = 575 \text{ V}$ , $P_n = 300 \text{ Kw}$ , $\omega_n = 400 \text{ rad/s}$ , $f = 50 \text{ Hz}$ , $R_r = 46 \text{ m}\Omega$ , $R_s = 63 \text{ m}\Omega$ , $M = 11.6 \text{ mH}$ , $L_s = 11.8 \text{ mH}$ , $L_r = 11.8 \text{ mH}$ , $P = 2$
<b>DC BUS</b>	$C = 20 \text{ mF}$ , $V_{dc} = 1000 \text{ V}$
<b>RL Filter</b>	$R_g = 0.1 \Omega$ , $L_g = 0.6 \text{ mH}$
<b>GRID</b>	$U_g = 575 \text{ V}$ , $f = 50 \text{ Hz}$



Figure (9) shows the response system for a wind change velocity. Figure 9.a shows the wind velocity profile imposed. Figure 9.b shows the power coefficient  $C_p$ . According to this figure, the power coefficient  $C_p$  is adjusted to its optimum value ( $C_p=0.5$ ).

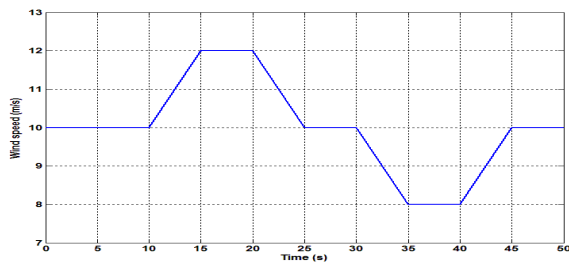
Figure 9.c shows the d-axis rotor flux. We note that the d-axis rotor flux is regulated to its reference value.

Figure 9.d shows the mechanical power extracted from the wind power generator. According to figure 3, the extracted power is maximum.

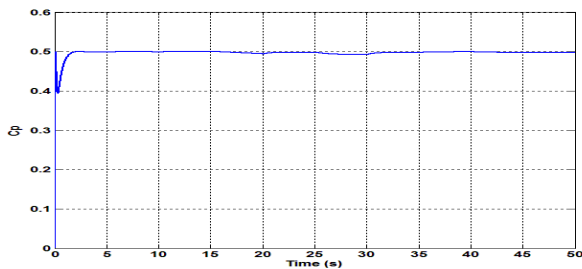
Figure 9.e shows the speed of the SCIG machine. We note that the speed is regulated at the reference provided by the MPPT.

Figure 9.f shows the DC bus voltage. The reference of the DC bus voltage denoted  $V_{dc}^*$  is set at 1000V. According to this figure, the DC bus voltage is regulated to its reference.

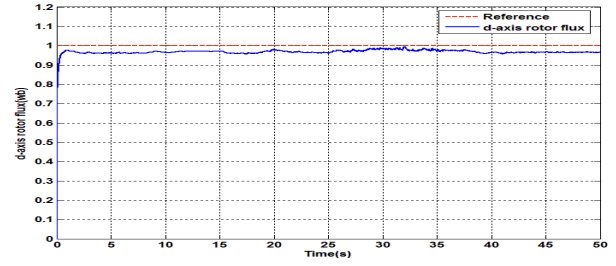
Figure 9.g shows the reactive power injected to the grid. The reference value of reactive power  $Q_g^*$  is set to 0VAR, which guarantees a power factor close to unity. The reactive power of stator  $Q_s$  is regulated to reference value.



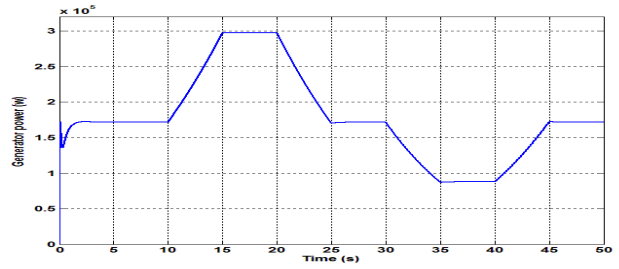
(a) Wind velocity



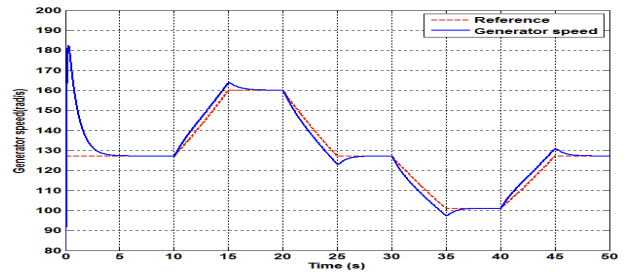
(b) Power coefficient  $C_p$



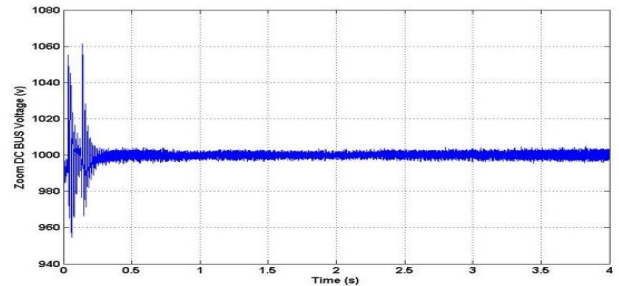
(c) d-axis rotor flux and reference



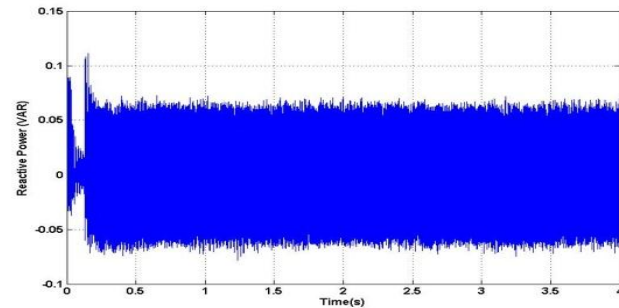
(d) Power generator



(e) Generator speed and reference



(f) DC bus Voltage



(g) Reactive power  $Q_s$

Fig 9. simulations results



## 5. Conclusion

This paper has addressed the modeling and control of a wind system with variable speed of the wind based on a SCIG. We are interested in modeling of various components of wind system. In fact, the aerodynamic and mechanical models of the turbine have been developed. In order to establish different controllers of two converters, we have developed models of SCIG and liaison of the SCIG to the network via the inverter and RL filter.

To validate the modeling and control of the global wind system, we have performed a simulation for an operating point at variable wind speed.

According to the simulation results, the control strategy allowed regulation of the generator speed to the optimal value provided from the MPPT. On the other hand a good decoupling between the adjustment of d-axis rotor flux and the generator speed. Finally, operating at a near-unity power factor at the injection of extracted of wind power into the grid system.

### **Bibliographies :**

[1] Suebkinorn, W. ; Neammanee, B. , An implementation of field oriented controlled SCIG for variable speed wind turbine, IEEE Conference on Industrial Electronics and Applications (ICIEA), pp : 39 – 44, 2011

[2] Trapp, J.G. ; Farret, F.A. ; Fernandes, F.T. ; Correa, L.C. Variable speed wind turbine using the squirrel cage induction generator with reduced converter power rating for stand-alone energy systems, IEEE International Conference on Industry Applications (INDUSCON), pp. 1 – 8, 2012

[3] A. Mesemanolis and C. Mademlis, Self-Tuning Maximum Power Point Tracking Control for Wind Generation Systems, Conference on Clean Electrical Power (ICCEP), pp.407-413, 2013

[4] Manaullah, M. ; Sharma, A.K. ; Ahuja, H. ; Bhuvaneswari, G. ; Balasubramanian, R., Control and Dynamic Analysis of Grid Connected Variable Speed SCIG Based Wind Energy Conversion System, IEEE International Conference on Computational Intelligence and Communication Networks (CICN), pp: 588 – 593, 2012

[5] Kedjar, B. ; Al-Haddad, K., Optimal control of a grid connected variable speed wind energy conversion system based on squirrel cage induction generator, IEEE Conference on Industrial Electronics Society, pp: 3560 – 3565, 2012

[6] Mehdi, A. ; Boulahia, A. ; Medouche, H. ; Benalla, H., Induction generator using AC/DC/AC PWM converters and its application to the wind energy systems, IEEE EUROCON, pp: 1038 – 1043, 2013

[7] Domínguez-García, J.L. ; Gomis-Bellmunt, O. ; Trilla-Romero, L. ; Junyent-Ferré, A., Vector control of squirrel cage induction generator for wind power, IEEE International Conference on Electrical Machines (ICEM), pp: 1 – 6, 2010

[8] Wu Dinghui ; Li Yuanlong ; Ji Zhicheng, Modeling and MPPT control of squirrel-cage induction generator wind power generation system via VisSim, IEEE Conference on Control and Decision, pp: 48 – 53, 2009