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Matlab Simulink as Simulation Tool for Wind Generation Systems Based on Doubly Fed Induction Machines

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Additional information is available at the end of the chapter

1. Introduction

In the last years, Matlab-Simulink has become the most used software for modeling and simulation of dynamic systems. It provides a powerful graphical interface for building and verifying new mathematical models as well as new control strategies particularly for non linear systems. Then, using a dSPACE prototype, these new control strategies can be easily implemented and tested.

The study of wind turbine systems generators are an example of such dynamic systems, containing subsystems with different ranges of the time constants: wind, turbine, generator, power electronics, transformer and grid.

There are two principle-connections of wind energy conversion. The first one is connecting the wind-generator to grid at grid frequency. While connected to grid, grid supplies the reactive VAR required for the induction machines. Often, a DC-link is required to interface the wind-generator system with a certain control technique to the utility grid. The second is connecting the wind-generator system to isolated load in remote areas.

A wound rotor induction machine, used as a Doubly Fed Induction Generator (DFIG) wind turbines are nowadays becoming more widely used in wind power generation. The DFIG connected with back to back converter at the rotor terminals provide a very economic solution for variable speed application. Three-phase alternative supply is fed directly to the stator in order to reduce the cost instead of feeding through converter and inverter. For the control of these converters different techniques will be adopted.

The network side converter control has been achieved using Field Oriented Control (FOC). This method involves the transformation of the currents into a synchronously rotating dq reference frame that is aligned with one of the fluxes.

The Direct Torque Control (DTC) is used for the rotor side converter. The DTC is mostly used in the objective to improve the reduction of the undulations or the flux's distortion, and to have good dynamic performances. It's essentially based on a localization table which allows selecting the vector tension to apply to the inverter according to the position of the stator flux vector and of the direct control of the stator flux and the electromagnetic torque.

Also, we have chosen to develop the case where a conventional neural controller associated with a reference model, represented by a Fuzzy logic corrector, for the learning phase is used to control the generator speed.

The main structure of this control scheme, as used in the Matlab/Simulink environment, is shown by the following figure.
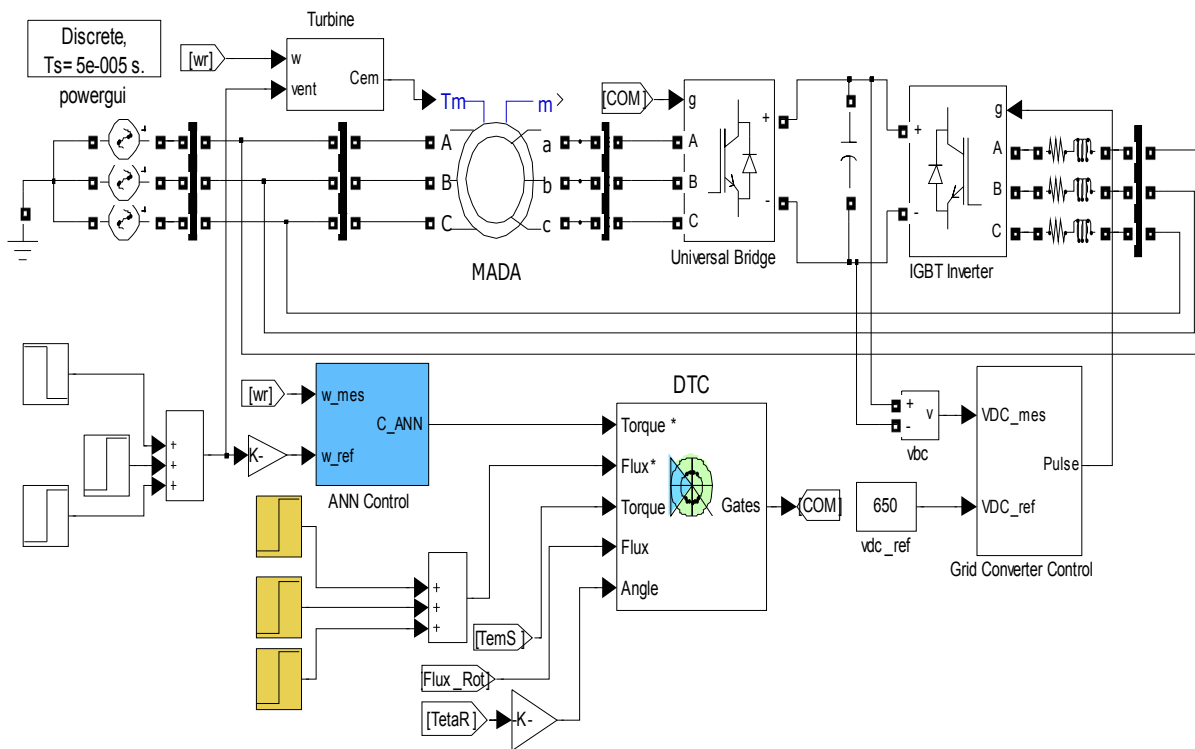

Figure 1. General structure of the DFIG with DTC control

An overview of Matlab Simulink, particularly the blocks concerned by the study of wind turbine generators based on DFIG will be presented.

In order to analyze the dynamic and/or steady state behaviour of the control of DFIG for wind generation, the basic components of a wind turbine structured in these libraries: Mechanical Components, Electrical Machinery, Power Converters, Common Models, Transformations, Measurements and Control, will be developed

SimPowerSystems DEMOS present good support and examples for the study of power systems and particularly the components of the wind generation energy systems. These tools can help for modeling and simulating basic electrical circuits and detailed electrical power systems. These tools let you model the generation, transmission, distribution, and

consumption of electrical power, as well as its conversion into mechanical power. SimPower Systems is well suited to the development of complex, self-contained power systems, such as those in automobiles, aircraft, manufacturing plants, and power utility applications.

In this chapter, we will be focalized on the following sections to show how we can use these libraries to develop a model of electrical generation based wind systems in step by step.

The different sections on the analysis and the development of such a system will concern:

- Dynamic model of DFIG in terms of dq windings
- Wind turbine simulator
- Control of rotor side converter based DTC:
    - Switching table elaboration
    - Rotor flux and torque control
    - Reference value of the torque given by a PI controller which parameters are adapted by a fuzzy logic inference system
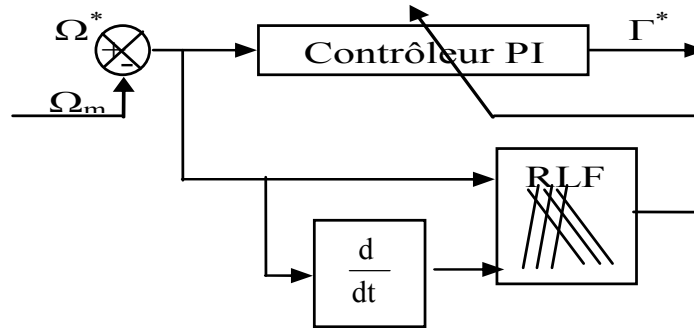

Figure 2. Speed control bused a PI adapted by a Fuzzy logic inference system

- Control of grid side converter based voltage oriented control
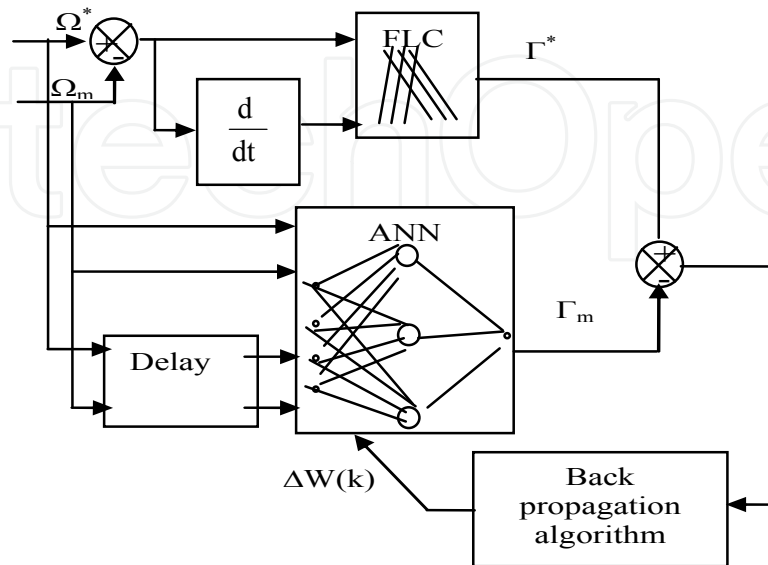- Control of DFIG speed based on a fuzzy neural corrector

Figure 3. Control of DFIG speed based on a fuzzy neural corrector

2. An overview of wind turbine control blocksets in Matlab Simulink

In order to analyze the dynamic behaviour of a wind turbine generation systems, different blocksets exist in the Matlab Simulink environment. The power scheme of the wind generation system can be divided into many blocs:

- The wind turbine or a simulator based on electrical machines for the comportment of this turbine. The principal object is to convert the aerodynamic variables (particularly wind power under variable wind speeds) to the mechanical power;
- The electrical generator witch permits to convert this energy to electrical power;
- The power converters used to connect this system and permits its control;
- The connection to the grid with filter structure constitutes the last bloc.

Different control blocs of this structure complete the general scheme.

In this chapter, we have chosen to show the simulation of wind turbine associated with a doubly fed induction generator.
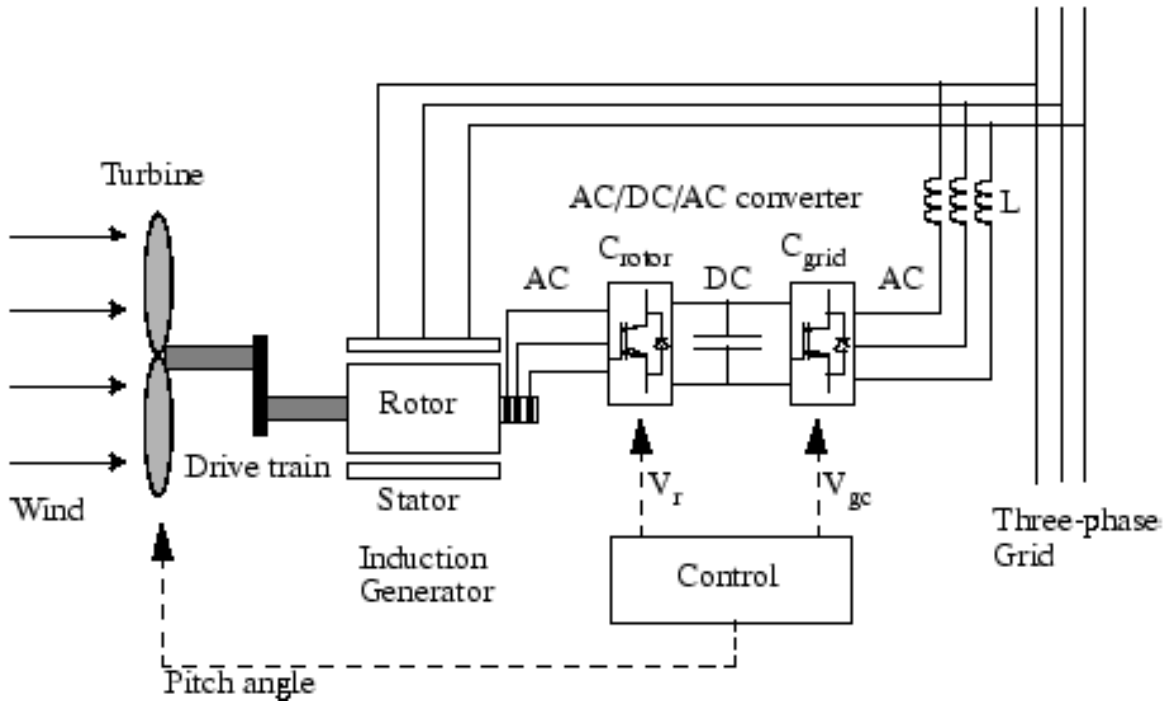

Figure 4. Structure of wind turbine coupled to DFIG

In this structure, two converters; the rotor-side converter and the grid-side converter, are Voltage-Sourced Converters that use forced-commutated power electronic devices (IGBTs).

A coupling inductor L is used to connect the inverter to the grid. The three-phase rotor winding is connected to the rectifier by slip rings and brushes and the three-phase stator winding is directly connected to the grid.

The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings.

The control system generates the pitch angle command and the voltage command signals for the rectifier and the inverter respectively in order to control the power of the wind turbine, the DC bus voltage and the reactive power or the voltage at the grid terminals.

2.1. Wind turbine model

This model is based on the steady-state power characteristics of the turbine. In fact, to simulate the behavior of the wind turbine, the torque that it exerts on the mechanical shaft must verify the relation:

$$T_{turbine} = T_{em_{mcc}} = \frac{P_m}{\Omega_t} \tag{1}$$

where Pm is the output power of the turbine (mechanical power extracted from the wind) given by the following:

$$P_m = \frac{1}{2} \rho \, S \, C_p(\lambda \, , \, \beta) \, v_{wind}^3 \tag{2}$$

where:

ϱ	Air density (kg/m)
S	Turbine swept area (m)
Cp	Performance coefficient of the turbine

Vwind   Wind speed (m/s)

λ	Tip speed ratio of the rotor blade tip speed to wind speed
β	Blade pitch angle (deg)

Ω_t (rad/s) is the mechanical speed of the turbine

$$\Omega_t = \frac{\lambda \, v_{wind}}{R_t} \tag{3}$$

By introducing another parameter, coefficient of torque, $C_m = \dfrac{C_p}{\lambda}$, the mechanical shaft is defined as

$$T_{em_{mcc}} = \frac{1}{2}.\rho.\pi.R_t^{\,3}.C_m.v_{wind}^2 \tag{4}$$

The Cp(λ) characteristics, for different values of the pitch angle β, are illustrated below.

We can note that the maximum value of the performance coefficient Cp (Cpmax = 0.48) is achieved for β = 0 degree and for λ = 8.1. This particular value of λ is defined as the nominal value (λ_nom).
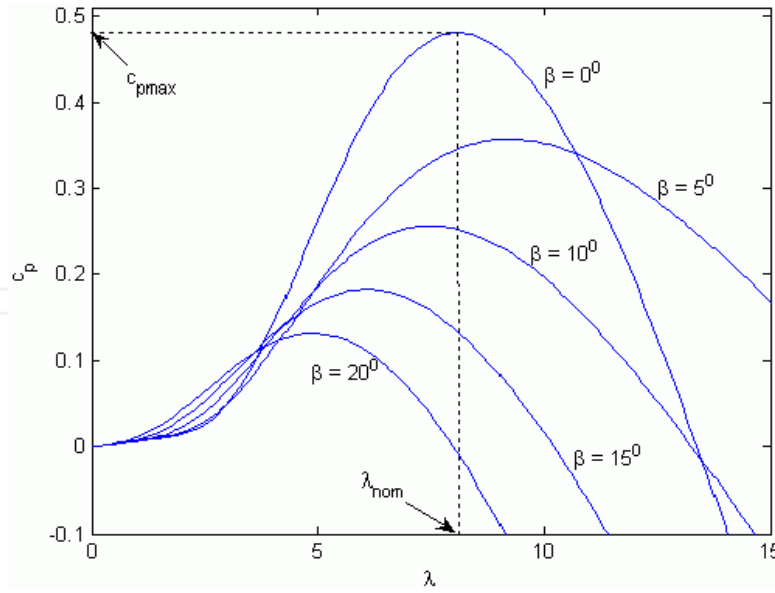
Figure 5. Cp(λ) characteristics

A generic equation can be used to model cp(λ,β). This equation, based on the modeling turbine characteristics, is represented as:

$$c_p(\lambda,\beta) = c_1(\frac{c_2}{\lambda_i} - c_3\beta - c_4)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{5}$$

where:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{6}$$

The coefficients c1 to c6 are respectively: c1 = 0.5176, c2 = 116, c3 = 0.4, c4 = 5, c5 = 21 and c6 = 0.0068.

In our simulation case, we have adopted the following relation for the evaluation of coefficient C_m as a parameter of λ.

$$C_p = (0.44 - 0.0167.\beta).\sin\left[\frac{\pi.(\lambda-3)}{(15-0.3.\beta)}\right] - 0.00184.(\lambda-3.\beta) \tag{7}$$

The torque reference corresponding to a level of wind turbine speed and generator speed is evaluated as represented by the following scheme.

A second model of wind turbine behavior could be the use of a DC machine to generate the reference mechanical torque corresponding to the wind speed plan.

A separately excited DC machine is used, in this case, with the control of the field terminals and the armature circuit connected to converters. The inputs are respectively the rotor speed and electromagnetic torque of the generator.
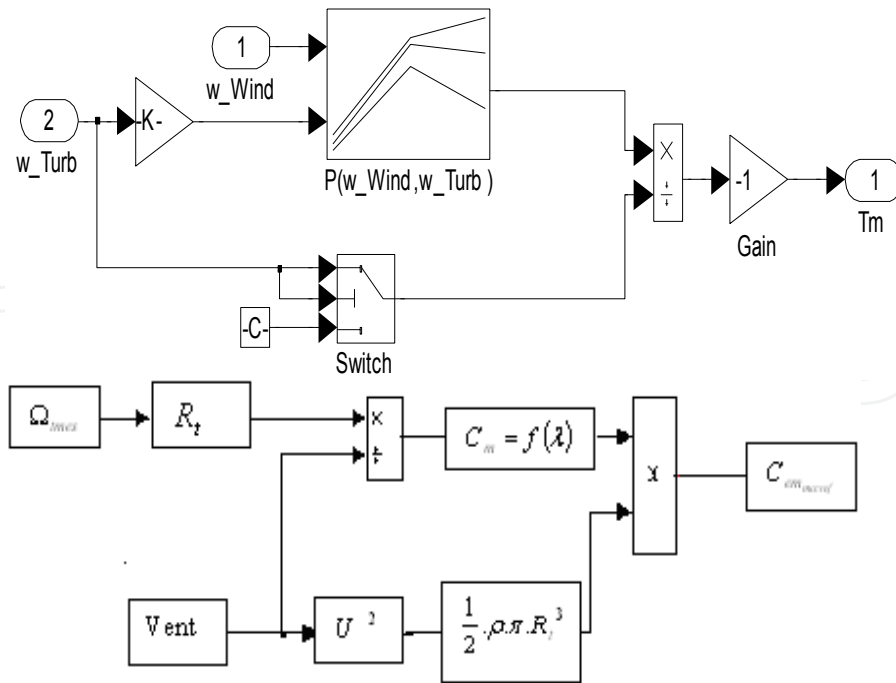
Figure 6. Estimation of reference torque (general and detailed schemes)

The mechanical power / speed characteristic, obtained at different wind speeds, is represented by the following figure.
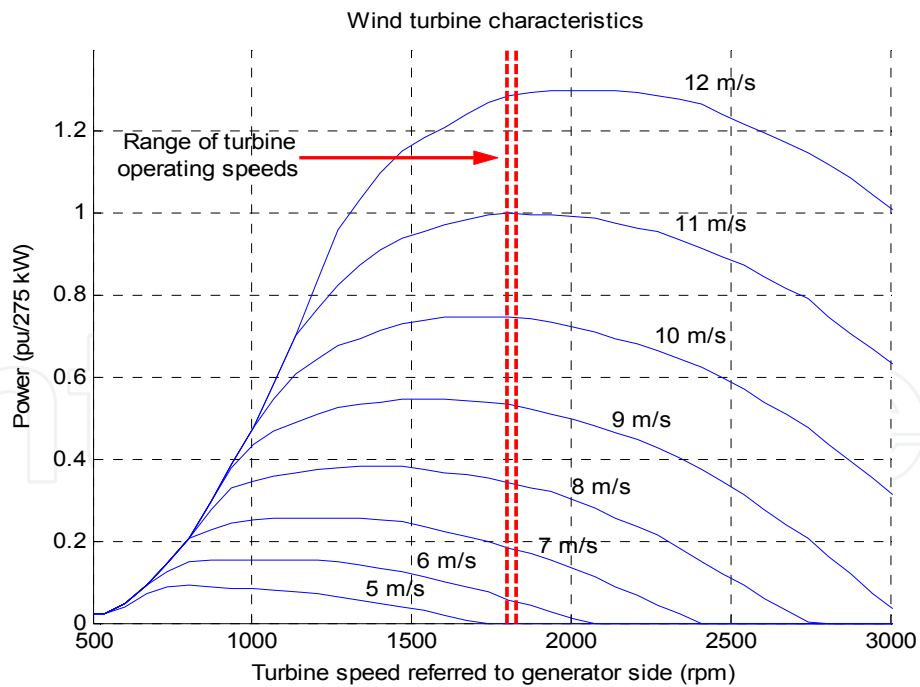

Figure 7. Mechanical power / speed characteristic

The reference field current is deduced from a lockup table with rotor speed as entry. The mechanical torque deduced form a wind and rotor speeds permits to impose the armature current.
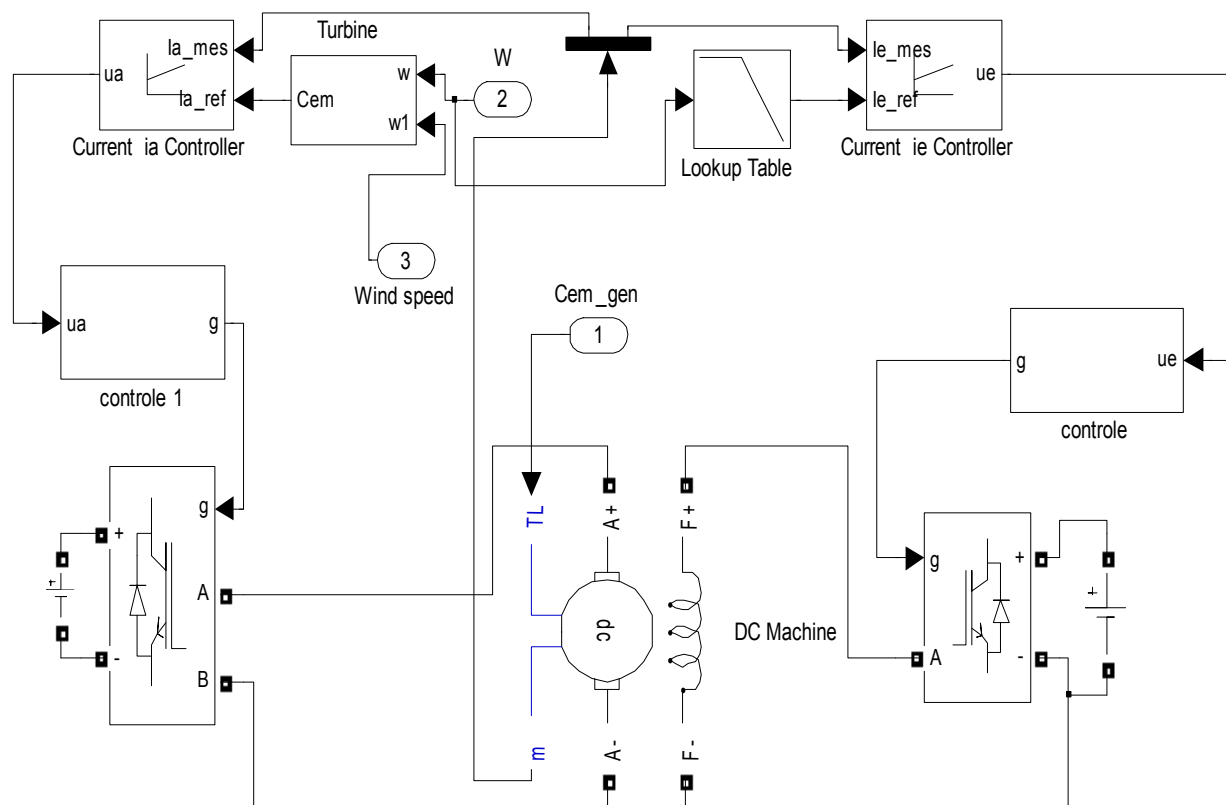
Figure 8. Second model of turbine based DC machine

2.2. Wind turbine control

For example, the wind turbine doubly fed induction generator is studied. The operating principle of the power flow is described as follows:

The mechanical power and the stator electric power output are defined by:

$$P_m = T_m \, \omega_r \quad ; \quad P_s = T_{em} \, \omega_s \tag{8}$$

For a loss less generator, the mechanical equation is:

$$J \frac{d\omega_r}{dt} = T_m - T_{em} \tag{9}$$

For a loss less generator and in steady-state at fixed speed, we have: $T_m = T_{em}$; $P_m = P_s + P_r$

It follows that: $P_r = -s \, P_s$, where $s = \dfrac{\omega_s - \omega_r}{\omega_s}$ is defined as the slip of the generator

Generally, Pr is only a fraction of Ps (the absolute value of slip is much lower than 1) and the sign of Pr is opposite to the slip sign. Pr is transmitted to or is taken out of DC bus capacitor. The control of grid converter permits to generate or absorb the power Pgc in order to keep the DC voltage constant. In steady-state for a loss less converters, Pgc is equal to Pr.

The converters have the capability of generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

The rotor-side converter is used to control the wind turbine output power and the voltage (or reactive power) measured at the grid terminals.

The grid-side converter is used to regulate the voltage of the DC bus capacitor. It's also used to generate or absorb reactive power.

2.2.1. Power control

The power is controlled in order to follow a pre-defined power-speed characteristic. An example of such a characteristic showing also tracking characteristic represented by the ABCD curve, is illustrated in the following figure.
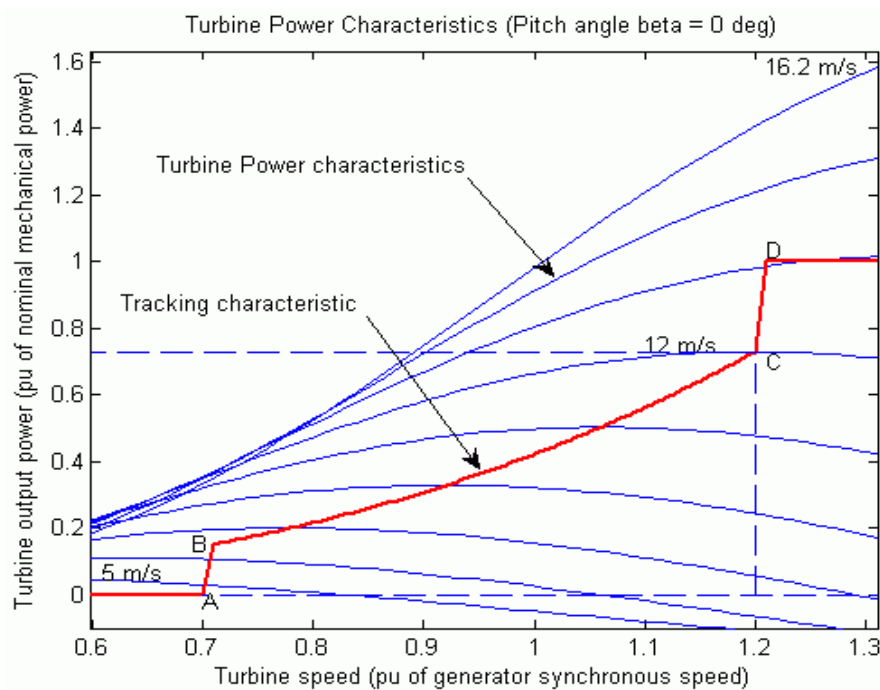

Figure 9. Power / speed characteristic and tracking characteristic

The actual speed of the turbine ωr is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. We can note that between points B and C, the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine power versus turbine speed curves).

For the power control loop, the actual electrical output power, measured at the grid terminals of the wind turbine, is added to the total power losses (mechanical and electrical) and is compared with the reference power obtained from the tracking characteristic. A Proportional-Integral regulator is used and its output is the reference rotor current that must be injected in the rotor by the rotor converter. This is the current component that produces the electromagnetic torque Tem.

2.2.2. Reactive power control

The reactive power at grid terminals or the voltage is controlled by the reactive current flowing in the rotor converter. When the wind turbine is operated in var regulation mode the reactive power at grid terminals is kept constant by a var regulator.

The output of the voltage regulator or the var regulator is the reference d-axis current that must be injected in the rotor by the rotor converter. The same current regulator as for the power control is used to regulate the actual direct rotor current of positive-sequence current to its reference value.
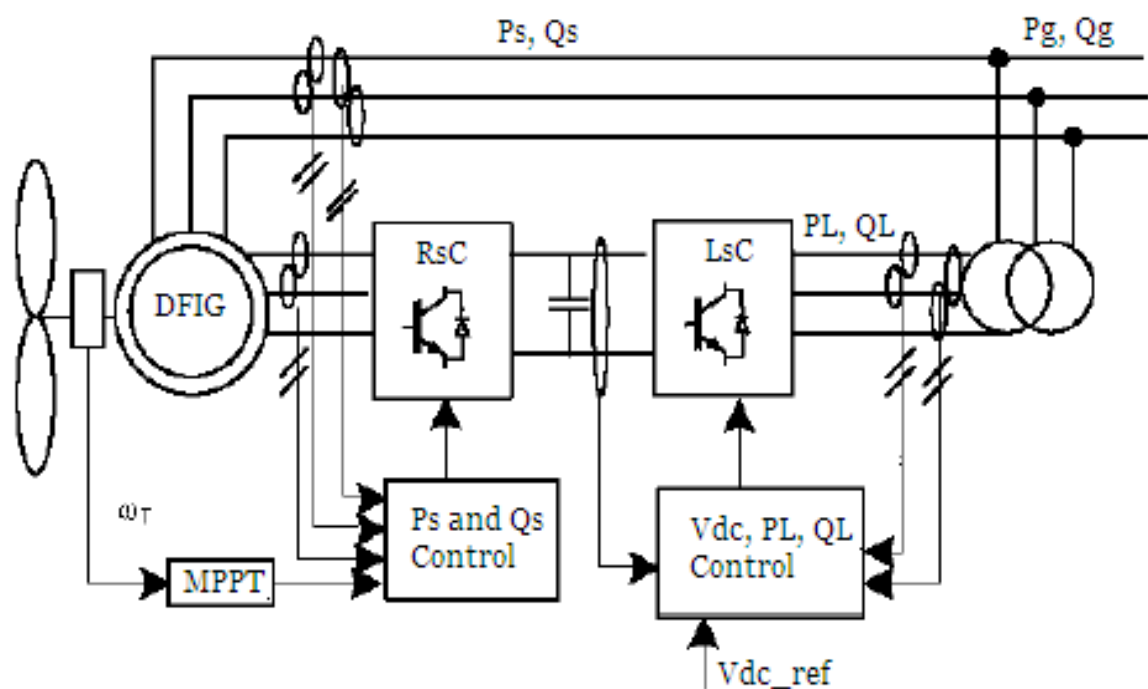

Figure 10. Powers exchange between DFIG, Converters and Grid

The rotor side converter ensures a decoupled active and reactive stator power control, Ps and Qs, according to the reference torque delivered by the Maximum Power Point Tracking control (MPPT). The grid side converter control the power flow exchange with the grid via the rotor, by maintaining the dc bus at a constant voltage level and by imposing the reactive power QL at zero.

2.2.3. Pitch angle control

The pitch angle is kept constant at zero degree until the speed reaches point D speed of the tracking characteristic.

Beyond point D, the pitch angle is proportional to the speed deviation from point D speed. The control system is illustrated in the following figure.
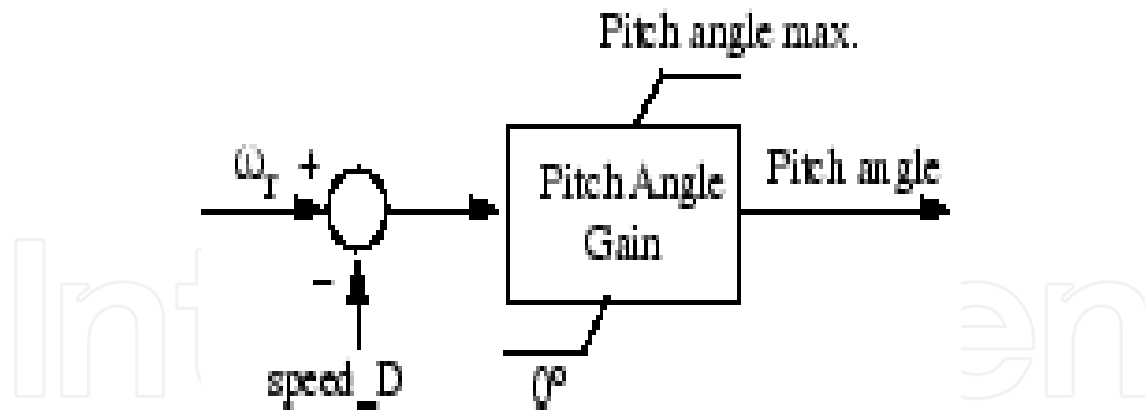
Figure 11. Pitch angle control

3. Doubly fed induction generator

3.1. Advantages of DFIG in wind turbine systems

The doubly-fed induction generator phasor model is the same as the wound rotor asynchronous machine (see the Machines library) with the following two points of difference:

- Only the positive-sequence is taken into account, the negative-sequence has been eliminated.
- A trip input has been added. When this input is high, the induction generator is disconnected from the grid and from the rotor converter.

The DFIG, in the wind turbine system, presents the following attractive advantages:

- The active and reactive power can be controlled independently via the current of the rotor;
- The magnetization of the generator can be achieved via the rotor circuit and not necessarily via the grid.
- The DFIG is capable of producing reactive power that it is delivered through the grid-side converter. Usually, this converter operates under constant unity power factor and it is not involved in reactive power trading with the grid. Also, the DFIG can be regulated in order to produce or consume a certain amount of reactive power. This way, the voltage control is achieved in cases of weak distribution grids.
- The converter size is not determined according to the total power of the generator but according to the decided speed range of the machine and therefore the slip range. For example, if the speed range is controlled between ±30% of the nominal speed, the nominal power of the converter is equal to the 30% of the nominal power of the generator. The selected speed range is decided according to the economical optimization and the increased performance of the system.

In this part, the dynamic model of DFIG in the dq frame is succinctly presented.

3.2. Dynamic model of DFIG in terms of dq windings

The general model for wound rotor induction machine is resumed as follows.

- Stator and rotor voltage equations :

$$\underline{V}_s = R_s \, \underline{i}_s \; + \; \frac{d\underline{\varphi}_s}{dt} \; + \; j \, \omega_s \underline{\varphi}_s \tag{10}$$

$$\underline{V}_r = R_r \, \underline{i}_r \; + \; \frac{d\underline{\varphi}_r}{dt} \; - \; j \, \omega \underline{\varphi}_r \tag{11}$$

where Rs, Rr, φs and φr are the stator and rotor resistances and flux
ωs is the synchronously frequency and ω = ωs - ωr is the slip frequency.

- Stator and rotor flux equations :

$$\underline{\varphi}_s = L_s \, \underline{i}_s \; + \; L_m \, \underline{i}_r \tag{12}$$

$$\underline{\varphi}_r = L_r \, \underline{i}_r \; + \; L_m \, \underline{i}_i \tag{13}$$

where Ls = Lsλ + Lm and Lr = Lrλ + Lm
Lsλ and Lrλ are stator and rotor leakage inductances
Lm is the mutual inductance

- Power and torque equations :

The electromechanical torque and the electrical power will be:

$$T_e \; = \; Im\left[\varphi_s \, i_s^*\right] \qquad P_e \; = \; Im\left[\varphi_r \, i_r^*\right] \tag{14}$$

Referring to the model developed in Matlab Simulink and defining the different parameters of the induction machines (DFIG in particularly), the DFIG equations can be resumed as follows:

$$v_{sd} \; = \; R_s \, i_{sd} \; + \; \frac{d\varphi_{sd}}{dt} -\omega_s \, \varphi_{sq} \quad v_{sq} \; = \; R_s \, i_{sq} \; + \; \frac{d\varphi_{sq}}{dt} +\omega_s \, \varphi_{sd} \tag{15}$$

$$v_{rd} \; = \; R_r \, i_{rd} \; + \; \frac{d\varphi_{rd}}{dt} -\omega_r \, \varphi_{rq} \quad v_{rq} \; = \; R_r \, i_{rq} \; + \; \frac{d\varphi_{rq}}{dt} +\omega_r \, \varphi_{rd} \tag{16}$$

$$\varphi_{sd} \; = \; (L_{is} \; + \; L_m) \, i_{sd} \; + \; L_m \, i_{rd} \quad \varphi_{sq} \; = \; (L_{is} \; + \; L_m) \, i_{sq} \; + \; L_m \, i_{rq} \tag{17}$$

$$\varphi_{rd} \; = \; (L_{ir} \; + \; L_m) \, i_{rd} \; + \; L_m \, i_{sd} \quad \varphi_{rq} \; = \; (L_{ir} \; + \; L_m) \, i_{rq} \; + \; L_m \, i_{sq} \tag{18}$$

In most practical work, the DFIG will have a non-unity turns ratio, n witch must be included in the flux linkage equations. Also, it will be useful to define the d- and q-axis magnetizing current.

Including magnetizing currents and turns ratio, the flux linkage equations must be rewritten and finally the electrical model of the machine is schematised as follow (case of d-axis seen from stator):
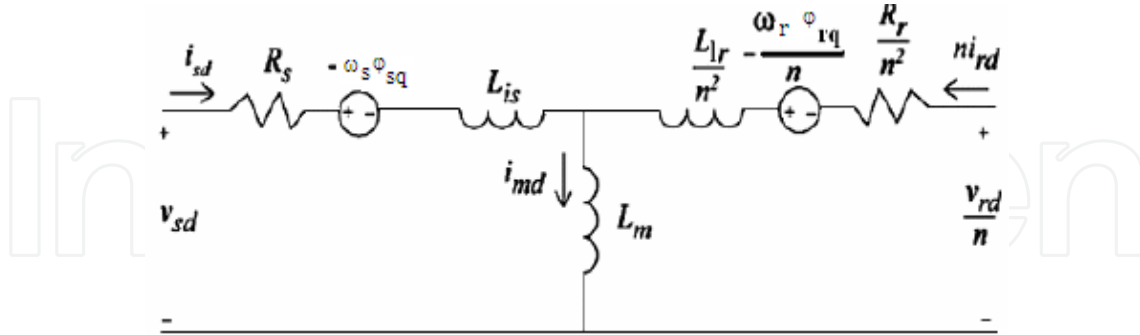

Figure 12. Electrical model in d-axis seen from stator

4. Control of rotor side converter based DTC

To control the torque and power factor of a doubly fed machine used in wind power generation system, a Direct Torque Control (DTC) method is adopted. As well known, a DTC technique is based on switching table which permits to choose an adequate inverter voltage vector to be applied to the converter according to flux and torque errors. These ones are deduced by a comparison between the references and estimated or measured values of flux and torque.

The DTC technique has the following steps:

- calculating the estimated torque and rotor flux of the DFIG;
- determining the reference torque from the wind and a rotor speed;
- evaluating the desired rotor flux ;
- selecting an inverter voltage vector from the torque error, the flux error and the rotor angle.

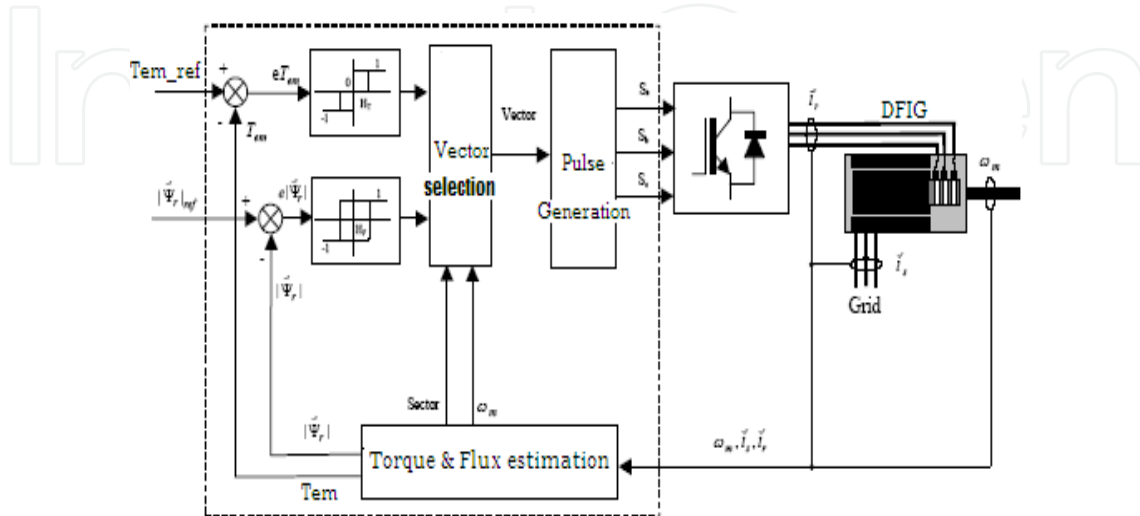The control bloc of this strategy is shown by the following figure:

Figure 13. DTC principle of DFIG

4.1. Rotor flux and torque control

For the control of the electromagnetic torque, we can use a three level hysteresis comparator which permits to have the two senses of motor rotation. The output of this corrector is represented by a Boolean variable *Ccpl* indicating directly if the amplitude of the torque must be increased, decreased or maintained constant $(ccpl = 1, -1, 0)$.
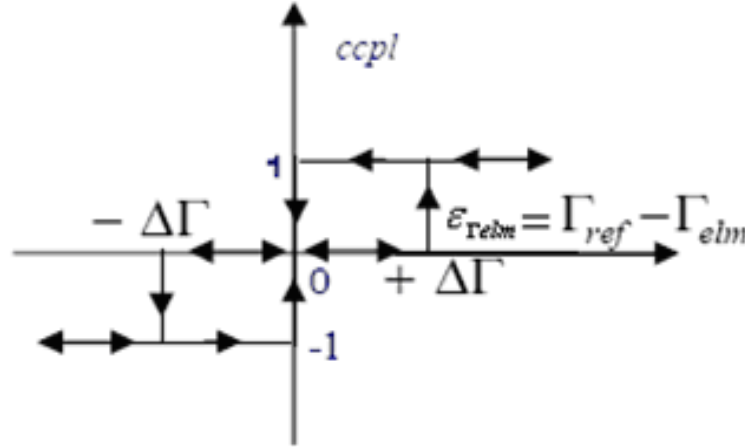

Figure 14. Three level hysteresis comparator

The control of the flux is carried out by selecting a suitable voltage vector with the inverter.

A two level hysteresis comparator could be used for the control of the flux. So, we can easily control and maintain the flux vector Φ_r in hysteresis bound as shown in the following Figure.

The output of this corrector is represented by a Boolean variable *cflx* which indicates directly if the amplitude of flux must be increased $(cflx = 1)$ or decreased $(cflx = 0)$ so as to maintain: $\left|(\Phi_r)_{réf} - \Phi_r\right| \leq \Delta\Phi_r$, with $(\Phi_r)_{réf}$ the flux reference value and $\Delta\Phi_r$ the width of the hysteresis corrector.
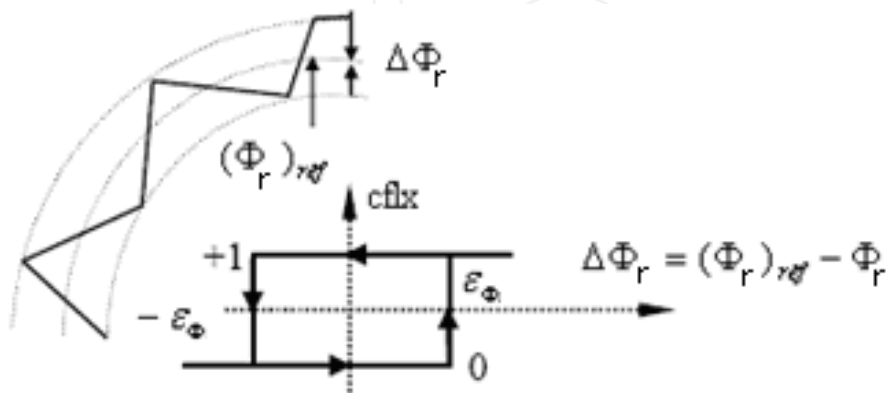

Figure 15. Flux hysteresis corrector

The reference value of the torque is given by a PI controller which is able to reach the reference speed. The PI parameters are adapted by a fuzzy logic inference system.
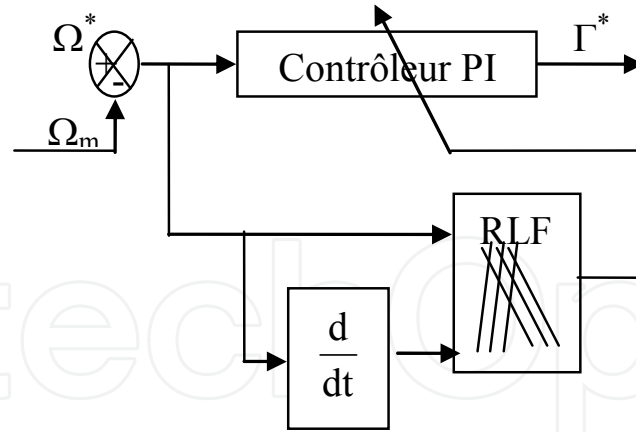
Figure 16. Torque reference estimation

The rotor flux amplitude is controlled in order to keep the unity power factor of the rotor current and rotor voltage. This is obtained if the rotor flux amplitude has to be the orthogonal projection of the stator vector. So, the reference value of the rotor flux is defined by:

$$|\varphi_r| = \frac{L_m}{L_s} |\varphi_s| \cos(\theta) \tag{19}$$

θ is the angle between the rotor and the stator flux.

Another issue for calculating the rotor flux reference, tested in our case, is defined as:

$$\varphi_r^* = \sqrt{\left(\frac{\sigma L_s L_r}{L_m} \frac{T_e^*}{|\hat{\psi}_g|} \right)^2 + \left(\frac{L_r}{L_m}|\hat{\psi}_g| + \frac{\sigma L_s L_r Q^*}{\omega_e L_m |\hat{\psi}_g|} \right)^2} \tag{20}$$

4.2. Switching table

As mentioned below, the Direct Torque Control of DFIG is directly established through the selection of the appropriate stator vector to be applied by the inverter. To do that, in first state, the estimated values of stator flux and torque are compared to the respective references, and the errors are used through hysteresis controller.

The phase plane is divided, when the DFIG is fed by two-level voltage inverter with eight sequences of the output voltage vector, into six sectors.

When the flux is in a sector (i), the control of flux and torque can be ensured by the appropriate vector tension, which depends on the flux position in the reference frame, the variation desired for the module of flux and torque and the direction of flux rotation:

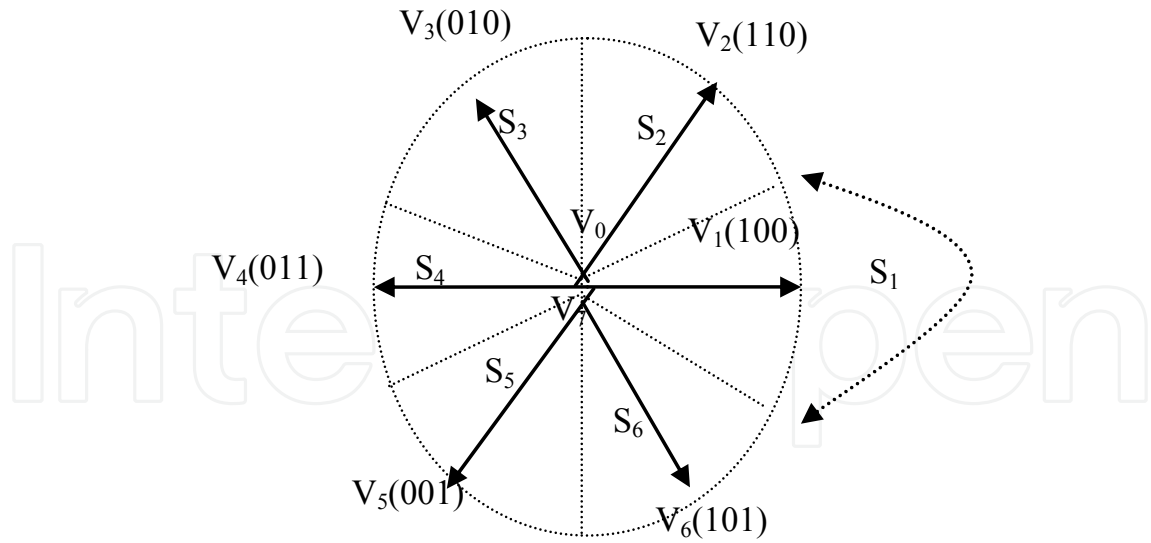|	Φs increase, Γ_{elm} increase	Φs increase, Γ_{elm} decrease	Φs decrease, Γ_{elm} increase	Φs decrease, Γ_{elm} decrease
Vector tension selected	V_{i+1}	V_{i-1}	V_{i+2}	V_{i-2}

Table 1. Selection of vector tension

Figure 17. Stator vectors of tensions delivered by a two level voltage inverter

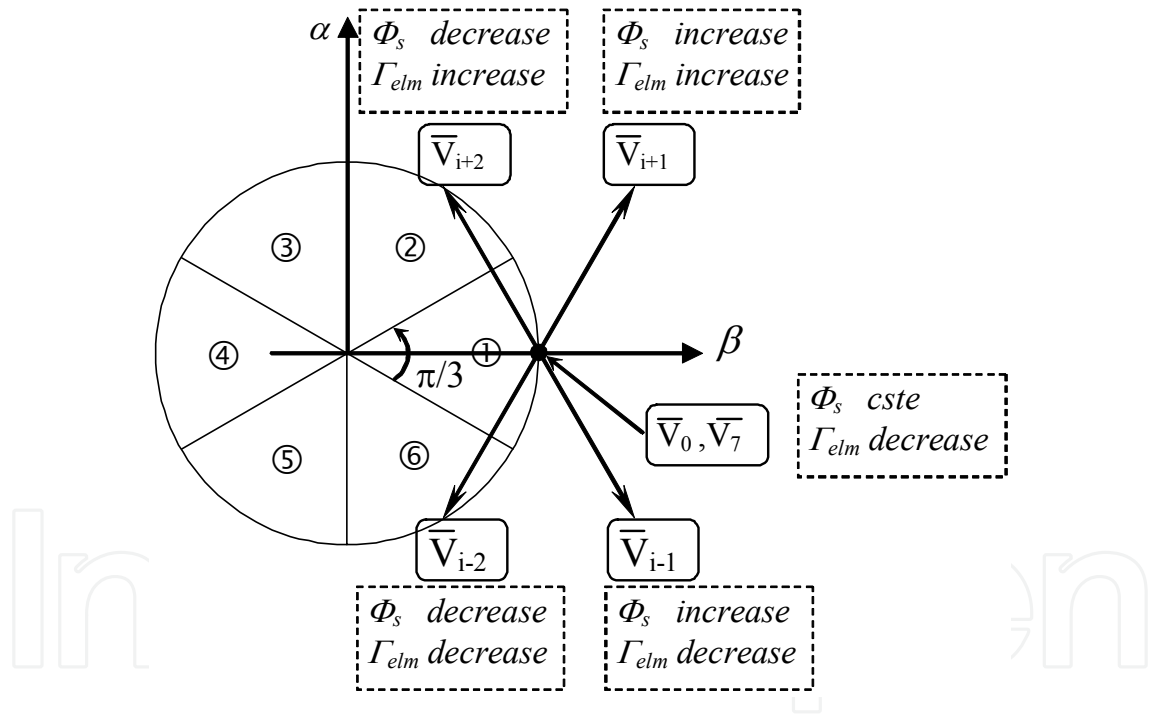This selection is schematized by the following figure:

Figure 18. Selection of vector tension

The implemented switching table consents to give the right pulses to the rotor side converter having as inputs the sector in which the rotor flux lies and the values of the hysteretic controllers.

The null vectors (V0, V7) could be selected to maintain unchanged the rotor flux.

According to the table 2, the appropriate control voltage vector (imposed by the choice of the switching state) is generated:

Cflx	ccpl	S_1	S_2	S_3	S_4	S_5	S_6
	1	V_2	V_3	V_4	V_5	V_6	V_1
1	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
	1	V_3	V_4	V_5	V_6	V_1	V_2
0	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

Table 2. Voltage vector selected (for each sector S_i)

The following figure shows the selected voltage vector for each sector to maintain the stator flux in the hysteresis bound.
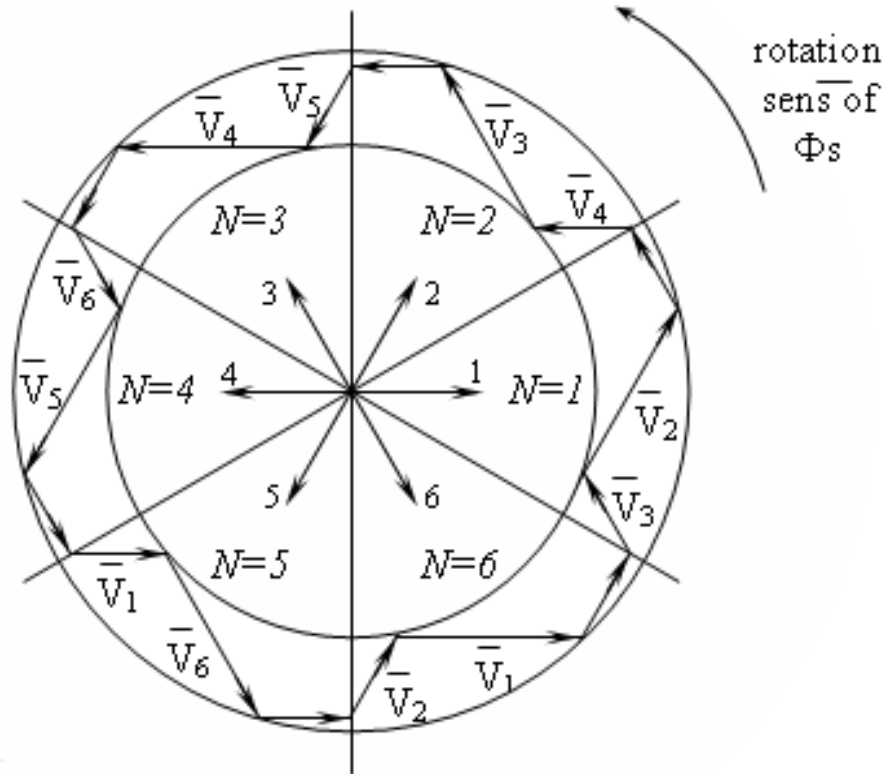

Figure 19. Selection of vector tension

5. Control of grid side converter based voltage oriented control

The applied vector control is based on a synchronously rotating, stator flux oriented d-q reference frame, which means that the d-axis is aligned with the vector of the grid voltage and the q component is zero.

For this technique of control of the inverter connected to the network, we proceed as follows:

- We establish a regulation of the DC bus voltage to its reference by a PI corrector. The output of this corrector is the direct current reference.

- The current measured at the output of the inverter connecting the MADA to the network is transformed into its dq components.
- By imposing the quadrature component of reference voltage to zero, and then, performing the regulation of the direct and quadrature components of the output voltage of the network side converter, we obtain the two components voltage to be imposed.
- After decoupling and compensation procedures, followed by transformation into Cartesian coordinates, we define the control signals of the converter with a simple modulation based on level comparators.

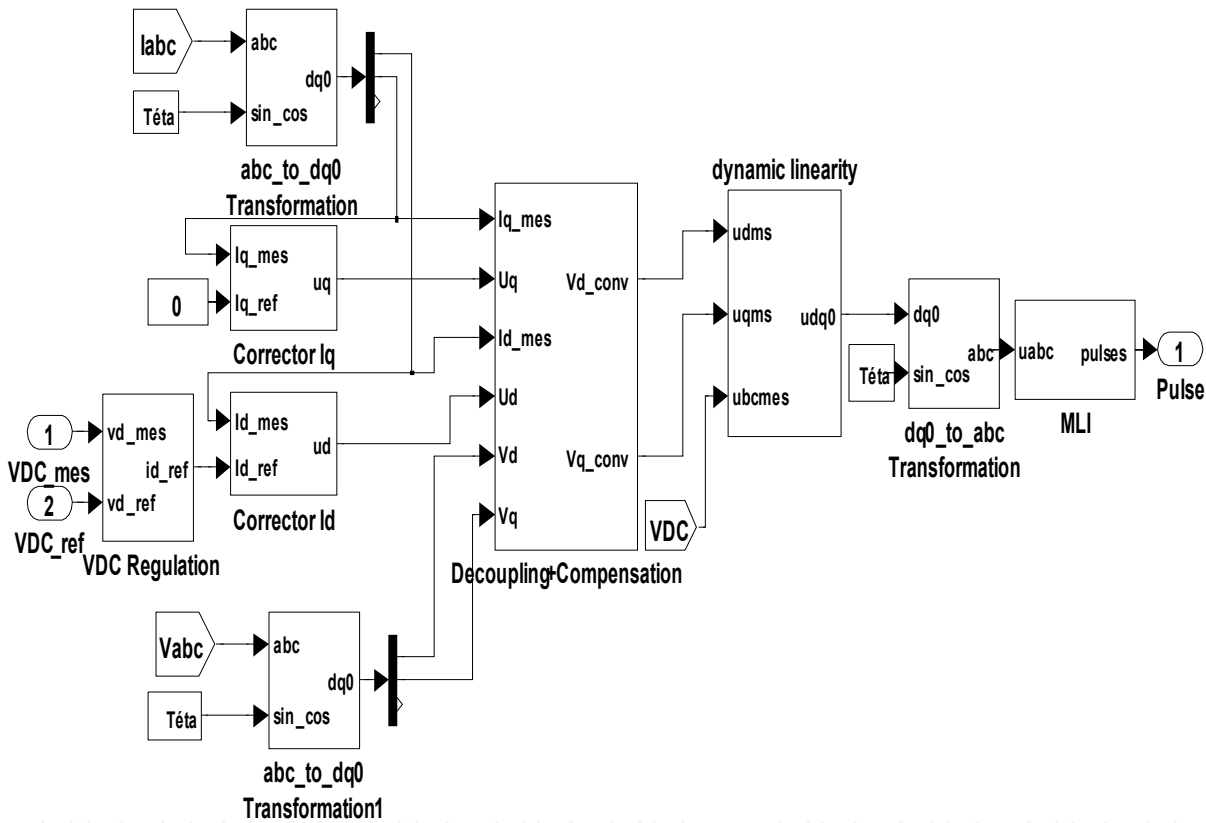A simplified diagram in Matlab Simulink environment of this control is then presented.

Figure 20. Diagram of Voltage Oriented Control of Grid side converter

6. Simulation results

Simulations were performed to show the behavior of the Doubly Fed Induction generator connected to the grid by a bi-directional converter.

The torque reference value is deduced from the regulation of the wind generator speed according to the wind speed and using a PI corrector. In this example, we have used three levels of wind speed. We have chosen to present the results corresponding to the rotation speed evolution, the electromagnetic torque, the flux evolution in the αβ subspace and the stator currents.

The obtained simulation results show that:

- trajectory of the stator flux, represented by its two components in the αβ phase plane, is in a circular reference (Figure 21)
- phase current obtained by this strategy is quasi-sinusoidal (Figure 22)
- speed track its reference with good performance (Figure 8)
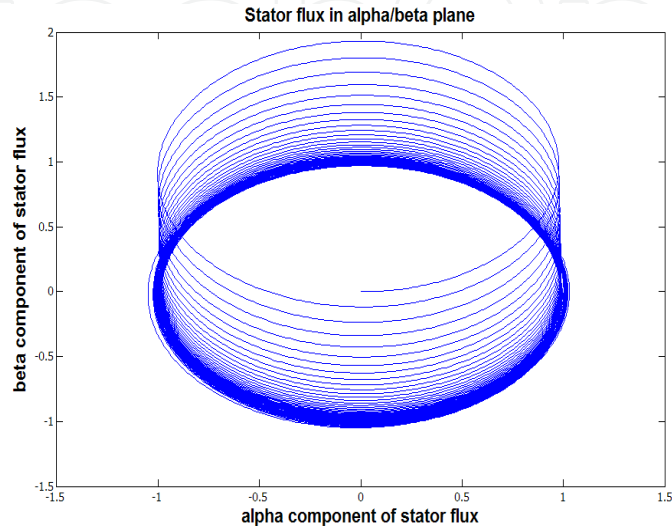- overshoot on torque is limited by saturation on the reference value (Figure 8)

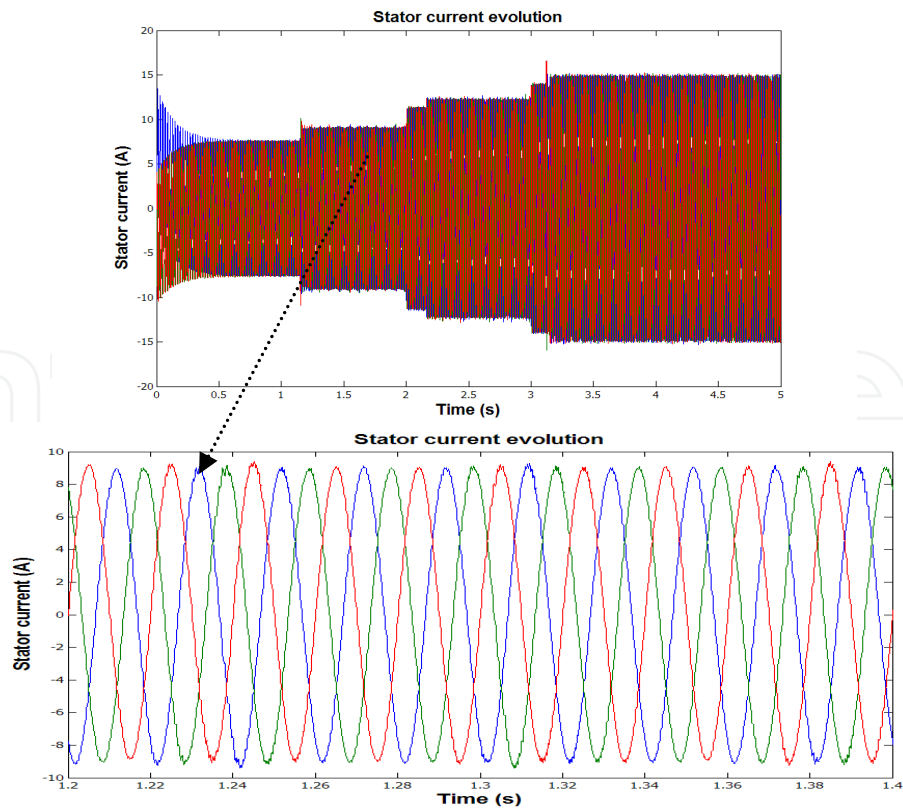**Figure 21.** Stator flux in the αβ phase plane

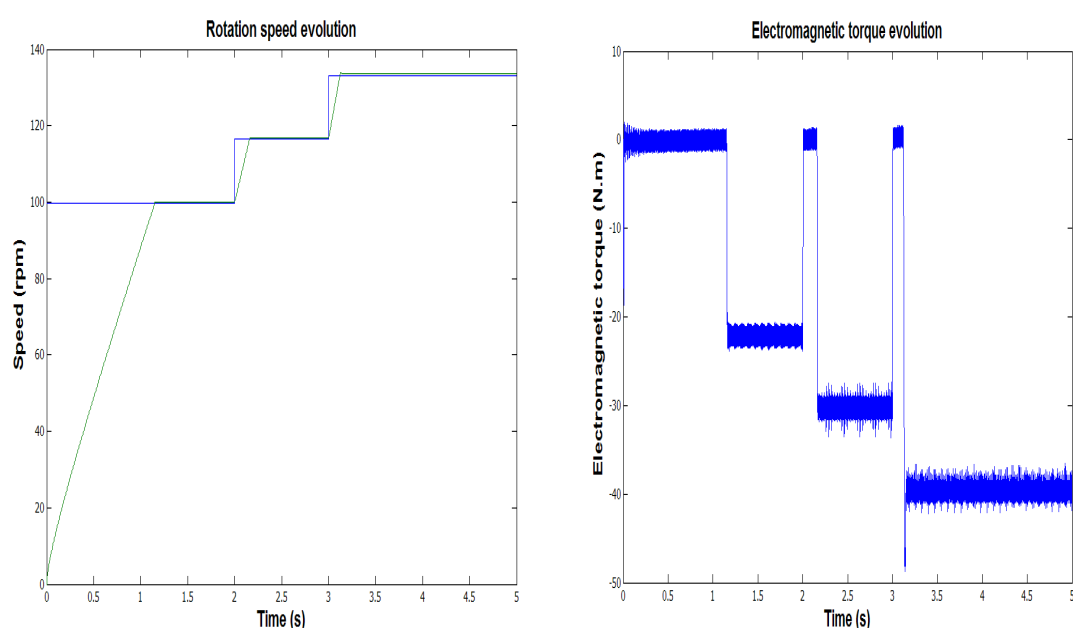**Figure 22.** Phase current time evolution

Figure 23. Time evolution of mechanical speed and electromagnetic torque

7. Conclusion

Through a concrete example of implementation of a prototype simulation of a system of wind power generation based on a doubly fed induction machine, we have highlighted some of the tools offered by Matlab / Simulink to design and to help for the complete study for such system.

The Direct Torque Control (DTC) is an important alternative method for the doubly fed induction machine drive based wind turbine, with its high performance and simplicity. The control of the DFIG connected to the grid with back to back converter, using two control techniques: DTC for the rotor side converter and Voltage Oriented Control for the grid converter present good performance and undulations reduction.

The effectiveness of the proposed scheme control is demonstrated by simulation using the blocks PSB of Matlab / Simulink and the results corresponding to the test of three levels of wind speed.

Finally, we can conclude that the control methods applied to DFIG present most interest and contribute to improvement of system response performances.

The first investigations, presented here, of the DFIG control prove its effectiveness and its high dynamics. It will be completed in a future work by considering others control techniques and particularly limiting torque undulations and resolving the problem of variable switching frequency.

Also, we conclude that Matlab / Simulink is a powerful tool in the comprehensive study of dynamical systems and particularly in what concerns us the power generation based on renewable and new energy.

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