

ADVANCED DEVELOPMENT OF THE RESEARCH OF THE DOUBLY FED INDUCTION MACHINE IN WIND TURBINE ENERGY

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Abstract— The details used to model any system should be enough so as to allow accurate simulation of the phenomenon of interest while not be computationally more expensive than required. The time scale of events studied is important. For example, the effects of a change in wind speed represent a slow transient as compared to a voltage dip at the generator terminals, detailed Matlab-Simulink model of the aerodynamic system is described and analysis of the steady state operational characteristics of the doubly fed induction generator is included. A specific control strategy is implemented according to the vector control strategy. The basic operational characteristics of a variable speed wind turbine with doubly fed induction generator are investigated using the software Matlab/Simulink, which leads to a brief discussion on the details necessary in modelling the system components to study the phenomenon of interest [1]. Models of the components used are then presented and controller design is discussed. The performance of the PI controller is designed for rates conditions at different wind speeds, for a 3, 5 MW DFIG based WTGS. Several control strategies are used here and among others, the power control one. The performance of the PI controller for the strategy is then used for the power controller at different wind speeds. Matlab/Simulink has been used for this purpose [2].

Keywords: Simulation; Wind Speed; DFIG; Matlab/Simulink

I. INTRODUCTION

Wind turbines (WTs) can either operate at fixed speed or variable speed. For a fixed speed wind turbine, the generator is directly connected to the electrical grid. For a variable speed wind turbine, the generator is controlled by power electronic equipment. There are several reasons for using variable-speed operation of wind turbines; among those are possibilities to reduce stresses of the mechanical structure, acoustic noise reduction and the possibility to control active and reactive power. Most of the major wind turbine farms are developing new larger wind turbines in the 3-to-5 MW range[3]. These large wind turbines are all based on variable-speed operation with pitch control using a direct driven synchronous generator (without gearbox) or a doubly-fed induction generator (DFIG). Fixed-speed induction generators with stall control are regarded as unfeasible. Today, doubly-fed induction generators are commonly used by the wind turbine industry (year 2005) for larger wind turbines[4]. The major advantage of the doubly-fed induction generator, which has made it popular, is that the power electronic equipment only has to handle a fraction (20–30%) of the total system power[5]. This means that the losses in the power electronic equipment can be reduced in comparison to power electronic equipment that has to handle the total system power as for a direct-driven synchronous generator, apart from the cost saving of using a smaller converter[6-7-8].

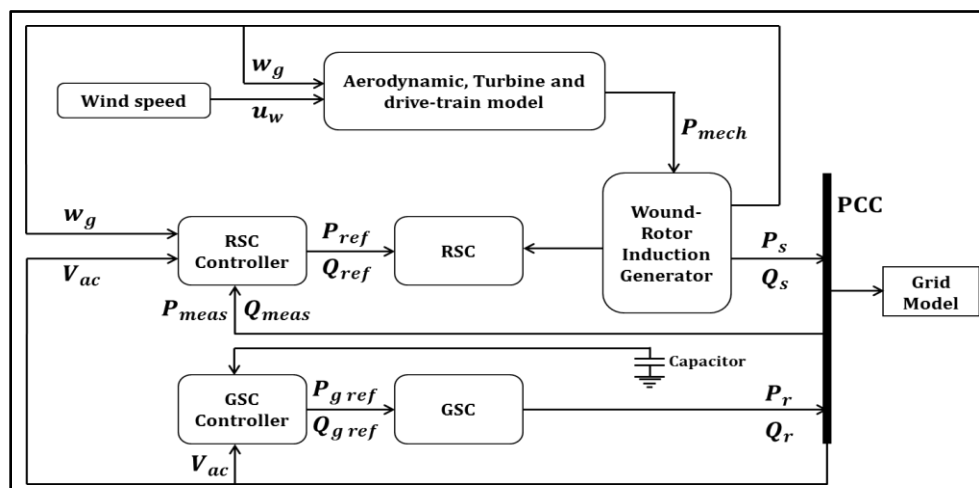


Figure 1 . DFIG control model

$P_{s\text{ref}}$: Stator active power reference (W)
 $Q_{s\text{ref}}$: Stator reactive power reference (VAR)
 $P_{s\text{mes}}$: Stator active power measured (W)
 $Q_{s\text{mes}}$: Stator reactive power measured (VAR)
 w_g : Generator shaft speed (rad/s)
 u_w : Wind speed(m/s)
 V_{ac} : AC voltage at the point of common coupling (PCC) (V)
 P_{ref} : Active power reference of RSC (W)
 Q_{ref} : Reactive power reference of RSC (VAR)
 P_{meas} : Active power measurement at PCC (W)
 Q_{meas} : Reactive power measurement at PCC(VAR)
 P_s : Active power output from stator (W)
 Q_s : Reactive power output of stator (W)
 V_{dc} : DC link voltage (V)
 P_r : Active power output from rotor (W)
 Q_r : Reactive power output of rotor (VAR)
 Φ_{ds} : The stator flux following axis d (Wb)
 Φ_{qs} : The stator flux following axis q (Wb)
 P : The number of pole pairs
 L_m : magnetizing inductance (H)
 L_s : Stator inductance (H)
 V_{ds} : The stator voltage following axis d (V)
 V_{qs} : The stator voltage following axis q (V)
 w_s : Stator pulsation(rad/s)
 I_{qr} : The rotor current following axis q (A)
 I_{dr} : The rotor current following axis d (A)
 S : Slip
 Q_{gc} : Reactive power capability of GSC (VAR)
 $Q_{g\text{ref}}$: Reactive power reference of GSC (VAR)
 P_{mech} : Mechanical power input to the generator (W)
 Q_{cc} : RSC reactive power capability (VAR)
 P_{gc} : Power transfer through the GSC (W)
 $P_{g\text{ref}}$: Active power reference of GSC (W)
 P_{mech} : Mechanical power input to the generator (W)
 PCC: The point of common coupling
 C_p : Power coefficient
 GSC: Grid side converter
 RSC: Rotor side converter
 DFIG: Doubly fed induction generator
 PWM: Pulse width modulation
 I_{ds} : Stator current following axis d (A)
 I_{qs} : Stator current following axis q (A)

A coordinated reactive power controller was designed considering the RSC as the main controller with the GSC acting as the auxiliary controller (50% converter rating). The coordinated control scheme between the GSC and RSC is shown in Figure 1. The RSC reactive power capability (Q_{cc}) is determined based on the capability while considering the total active power output (P_m) and operating slip (S) of the DFIG. Then, Q_{cc} is compared against the reactive power reference (Q_{ref}) of the DFIG system. The excess reactive power requirement becomes the reactive power reference for the GSC ($Q_{g\text{ref}}$). Therefore, the GSC is operated at unity power factor; otherwise, the reactive power requirement exceeds the RSC reactive capability. The reactive power reference is determined based on the control strategy of the DFIG [8]. In the presented study Q_{ref} is determined based on the multi-objective control schemes presented. The reactive power reference (Q_{ref}) is used as the reactive power reference for the RSC ($Q_{r\text{ref}}$), since the RSC displays higher reactive power capability over the GSC, and is selected as the main reactive power controller for the proposed control scheme [9]. Furthermore, the RSC reactive power capability is highly dependent on the operating slip of the machine. Hence, it can provide much enhanced reactive power performance during variable speed operation (i.e. variable slip) compared to the GSC. This section evaluates various multi-objective reactive power control strategies under different system conditions. The reactive power reference (Q_{ref}) was derived for each multi-objective strategy considering the reactive power requirement for the main control scheme (i.e. power factor control, voltage control and reactive power dispatch) and the flicker mitigation [10]. The flicker control strategy is

required since the main control doesn't mitigate flicker emission due to the variable active power output of the wind generator during variable wind conditions [11].

II. REPRESENTATION DEVELOPED BY MATLAB-SIMULINK

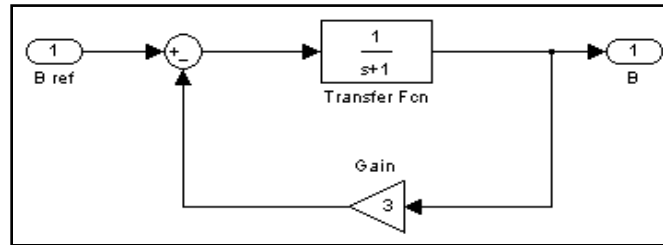


Figure 2. Regulation of the pitch angle developed in Matlab-Simulink

Variable pitch control can be used to shed the aerodynamic power generated by the wind turbine. Thus, the aerodynamic power produced by the wind turbine can be controlled by adjusting the pitch angle of the wind turbine. Figure 3 shows the effect of pitch control on power flow in wind turbine generation. With pitch control, the power captured from the wind power can be controlled by a pitch actuator. The acceleration and deceleration is the result of the difference between the input power to the generator and the aerodynamic power captured by the wind turbine. Theoretically, at constant electric load, the acceleration and deceleration can be made zero if the pitch can be controlled fast enough to react to the wind speed so that the power captured from the wind is equal to the electric power. For example, in the high wind speed region when the rotor speed limit is reached, the pitch can be controlled to keep the rotor speed from exceeding its limit.

III. Application of the command of the DFIG

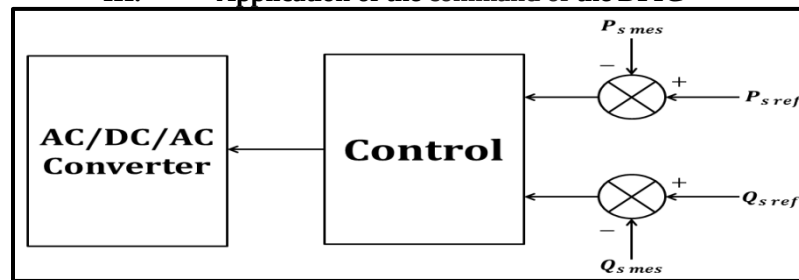


Figure 3. Power control of DFIG

When the DFIG is connected to an existing grid, this connection must be done in three steps. The first step is the regulation of the stator voltages with the network voltages as referenced. The second step is the stator connection to this grid. As the voltages of the two devices are synchronized, this connection can be done without problem. Once this connection is achieved, the third step is the transit power regulation between the stator and the grid (Fig.5)[12-13]. To achieve a stator active and reactive power vector control as shown on Fig.5, we choose a d-q reference-frame synchronized with the stator flux by setting null the quadratic component of the stator flux:

$$\Phi_{ds} = \Phi_s \text{ and } \Phi_{qs} = 0 \quad (1)$$

Then the couple is simplified into:

$$C_{em} = -p \frac{L_m}{L_s} I_{qr} \Phi_s \quad (2)$$

The electromagnetic couple and then the active powers will only depend on the q-axis rotor current. By neglecting the stator resistance R_s , we can write:

$$V_{qs} = 0 \text{ and } V_{ds} = V_s$$

In order to calculate angles from the Park transformation for stator and rotor variables, the stator pulsation and the mechanical speed must be determined. By choosing this reference frame, stator voltages and fluxes can be rewritten as follows:

$$V_{ds} = 0 \quad (3)$$

$$V_{qs} = V_s = \omega_s \phi_s \quad (4)$$

$$\phi_{ds} = \phi_s = L_s I_{ds} + L_m I_{dr} \quad (5)$$

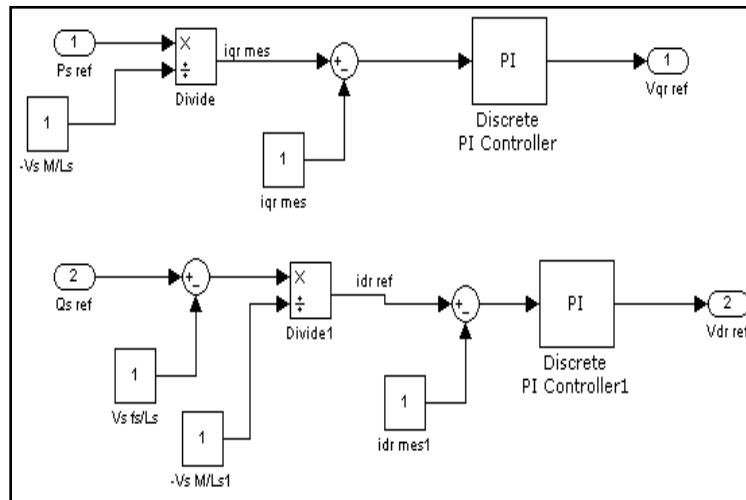


Figure 4. Power control of DFIG

The vector control orientation of the flow has an attractive solution to achieve better performance in variable speed applications in case the DFIG is either under operation generator or motor [14-15-16]. In this context, we proposed a control law for DFIG based on the orientation of the stator flux used to run a generator. The latter highlights the relationship between the stator and rotor ingredients. These relationships will help to act on the rotor signals to control the exchange of active and reactive powers between the stator of the machine and the grid with a constant and directed stator flux $\varphi_{sd} = \varphi_s$ and $\varphi_{sq} = 0$ if we neglect the resistance of the stator windings, the equations of the tensions of the machine are reduced to the following form [17-18]. The wind turbine is connected to the DFIG through a mechanical shaft system, which consists of a low and a high-speed shaft with a gearbox in between. The wound rotor induction machine in this configuration is fed from both stator and rotor sides. The stator is directly connected to the grid while the rotor is connected to the grid through power converters. In order to produce electrical power at constant voltage and frequency to the utility grid for a wide operating range from sub synchronous to super synchronous speeds, the power flow between the rotor circuit and the grid must be controlled both in magnitude and in direction. Therefore, the power converters consists of two four-quadrant insulated-gate bipolar transistor (IGBT) pulse width modulation (PWM) converters connected back-to-back by a dc-link capacitor. The crowbar is used to short circuit the rotor side converter in order to protect it from over current in the rotor circuit during transient grid disturbances. The Control of the DFIG is achieved by control of the converters, which includes control of the RSC and control of the GSC. The objective of the RSC is to independently regulate the stator active and reactive powers, which are represented by P_s and Q_s respectively. The reactive powers control using the RSC can be applied to keep the stator voltage V_s within the desired range when the DFIG feeds into a weak power system without any local reactive compensation. When the DFIG feeds into a strong power system, the command of Q_s shows the overall vector control scheme of the RSC in order to achieve independent control of the stator active powers P_s and Q_s .

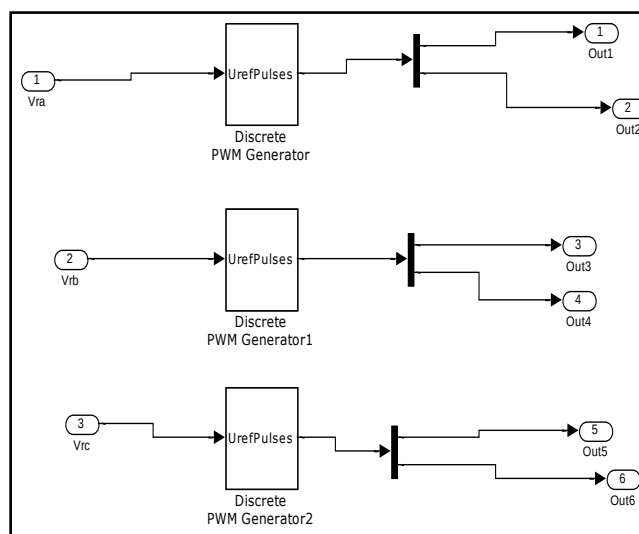


Figure 5. PWM control of injected reference rotor tensions in converters

This figure shows the three-phase voltage regulation by pulse width modulation to extract the maximum from the stator active power and the minimum reactive stator power injected into the grid developed by Matlab/ Simulink.

Table 1. Parameters of the machine

Parameters	Values
Nominal Power	3,5 MW
Nominal Voltage	660 kV
Nominal Frequency	50 Hz
Stator Inductance	0.0067 H
Rotor Inductance	0.0065 H

IV. Results of the simulation and discussions

The functioning of the complete device was simulated under the environment Matlab-simulink in the time of simulation of 5s. The strategy of the command introduced previously was tested in the case of variations of the rotor speed. In what follows we shall detail the relative aspects of this strategy and we shall interpret results of simulation. The strategy of command is based on the indirect command without locking up of power of the DFIG.

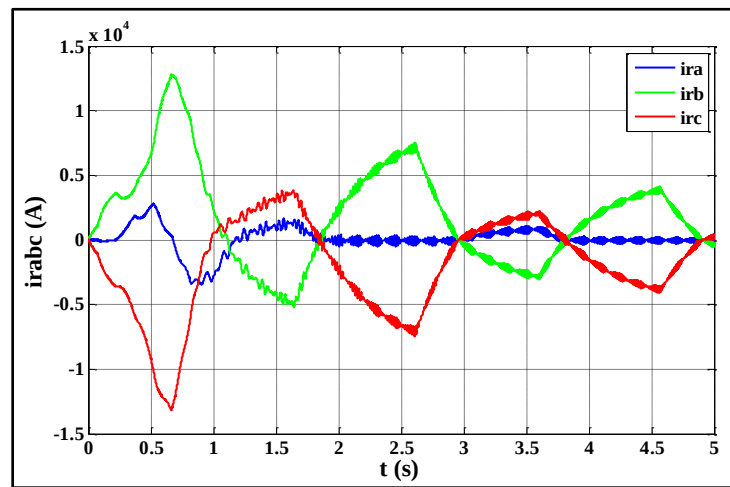


Figure 6. Rotor currents $ira(A)$, $irb(A)$, $irc(A)$ according to time (s)

The rotor currents is influenced by the variation of the reactive stator power absorbed by the DFIG we can remark that these currents $ira(A)$, $irb(A)$, $irc(A)$, which vary between $(-1.2 \times 10^4 A)$ and $(1.2 \times 10^4 A)$, are independent from the profile of wind speed. The rotor currents depend on the variation of the speed of asynchronous machine with double feeding, and on the variation of the slip.

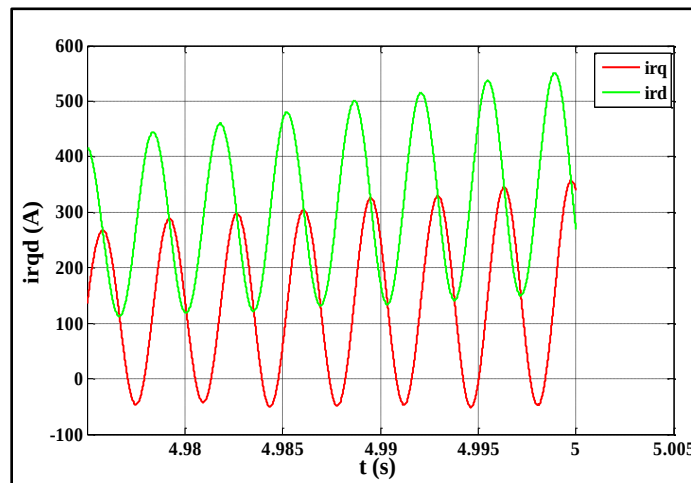


Figure 7. Rotor currents $irq(A)$, $ird(A)$ according to time (s)

The currents $irq(A)$ and $ird(A)$ vary from $(-60A)$ to $(550A)$. These values show that the systems are adapted to high power wind turbine. These currents depend on the active and reactive powers.

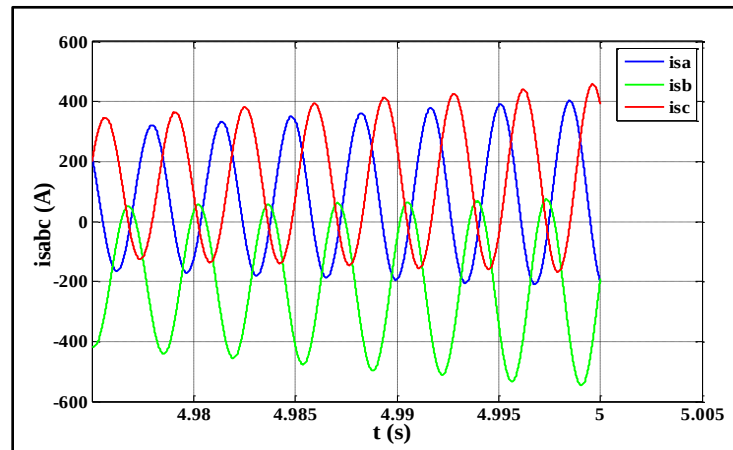


Figure 8. Stator currents $is_a(A)$, $is_b(A)$, $is_c(A)$ according to time (s)

The stator currents is influenced by the variation of the reactive stator power absorbed by the DFIG, we can remark that these currents $is_a(A)$, $is_b(A)$, $is_c(A)$ which vary between (-500A) and (450A), are independent from the profile of wind speed.

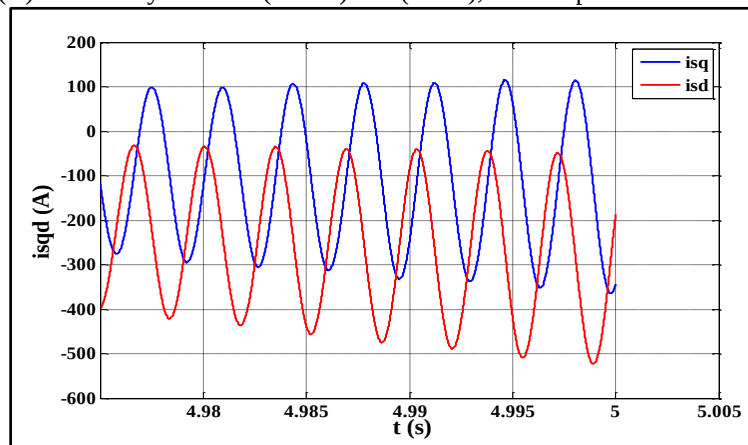


Figure 9. Stator currents $is_q(A)$, $is_d(A)$ according to time (s)

The form of the wave of stator currents is linked to that of the stator active powers and of the stator reactive powers. These currents vary in sinusoidal forms. We can remark that the currents vary in a sinusoidal manner by increasing their amplitudes. The values of these curves vary from (100A) to (-520A). These curves depend on the stator flux and stator voltage.

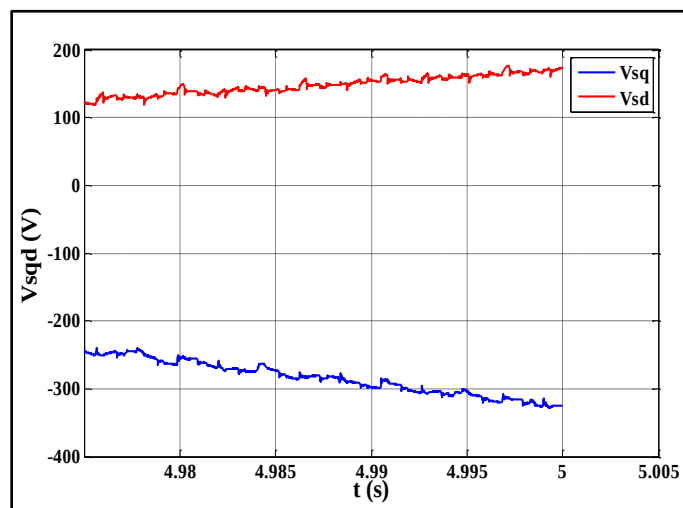


Figure 10. Stator voltages $Vs_q(V)$, $Vs_d(V)$ according to time (s)

The forms of waves of the stator tensions are independent of the speed of wind and they are equal to the tensions of the grid. The stator voltages $Vs_q(V)$, $Vs_d(V)$ vary from (180 V) to (-320V).

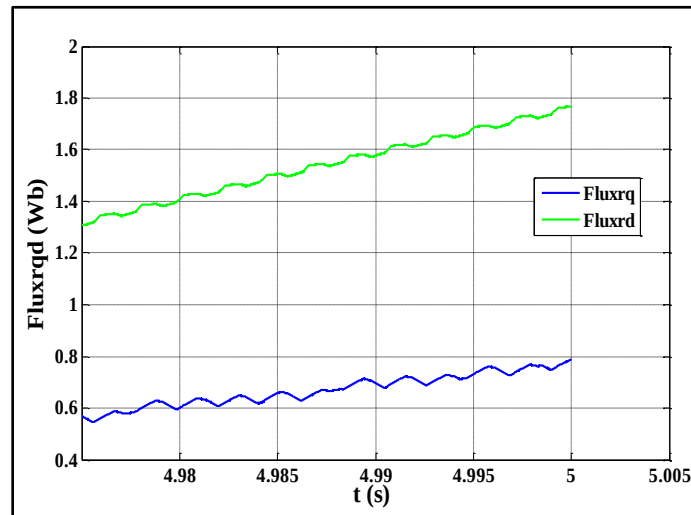


Figure 11 . Curve rotor flux (Wb) in the mark qd according to time (s)

The rotor fluxes adapt themselves according to the evolution of the rotor and stator currents. The fluxes are adapted to the evolution of the rotor currents, and they are independent from the profile of wind turbine .The values vary from (0.79Wb) to (1.7Wb). The fluxes show that our system wind turbine is adapted to the high power wind turbine.

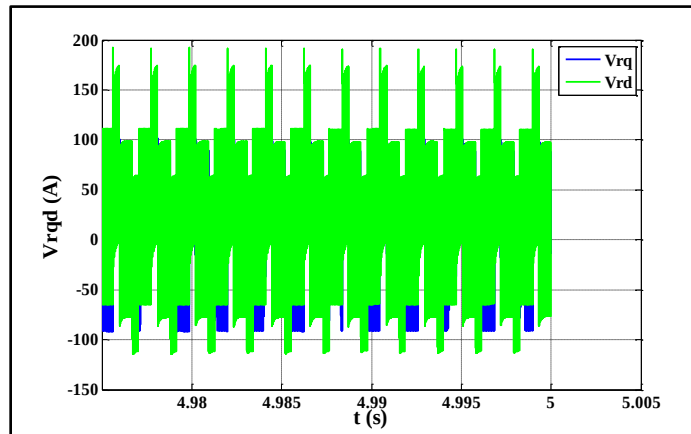


Figure 12. Rotor voltages $V_{rq}(V)$, $V_{rd}(V)$ according to time (s)

This curve shows the evolution of rotor voltages; these wave forms depend on the speed of the wind. They depend on the rotor currents $i_{rq}(A)$ and $i_{rd}(A)$.The values of these curves vary from (190V) to (-110V), in variable ways.

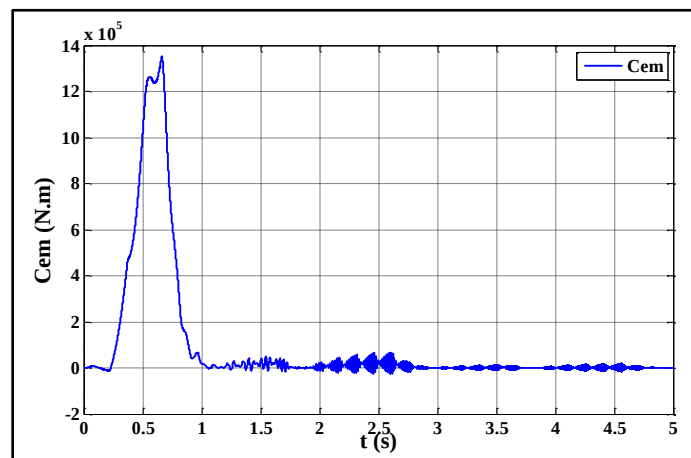


Figure 13. Electromagnetic couple C_{em} (N.m) according to time (s)

The electromagnetic couple depends on the evolution of the stator flux $\phi_s(Wb)$ and on the rotor current $i_{rq}(A)$.The value of this couple varies between (130000N.m) and (-10000N.m) in the beginning of the simulation and it becomes very adequate to the function of high power wind turbines in the end of the simulation.

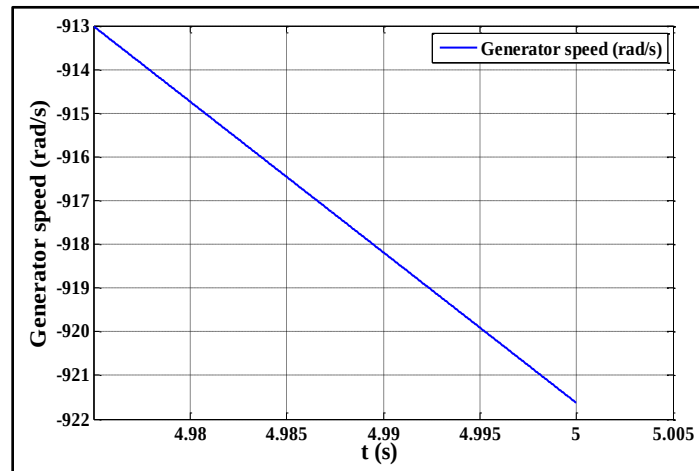


Figure 14. Generator speed (rad/s) according to time (s)

The mechanical speed on the slow tree multiplied by the coefficient of multiplying leads to a rapid mechanical couple on the asynchronous machine, and then to the increase in the speed of its rotation. It varies between (0 rad/s) and (-921.7 rad/s).

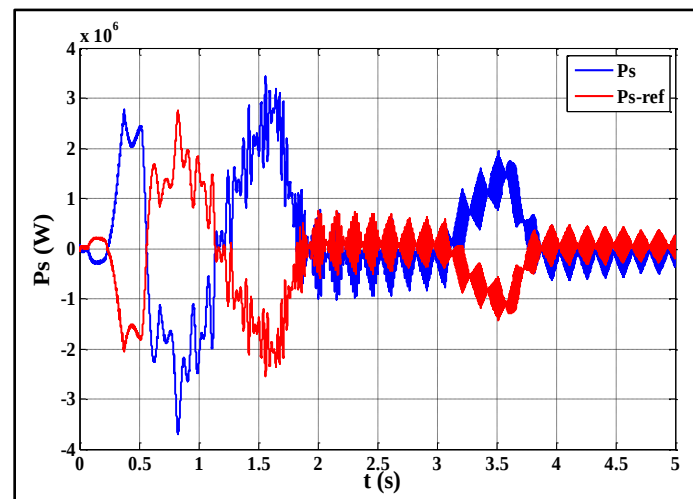


Figure 15. The active stator powers P_s (W) according to time (s)

The active stator powers depend on the variation of the stator currents of the machine and of the sliding of the machine. It varies between (-3.7MW) and (3.5MW), which is adapted to high power wind turbine; the simulation time is 5 seconds.

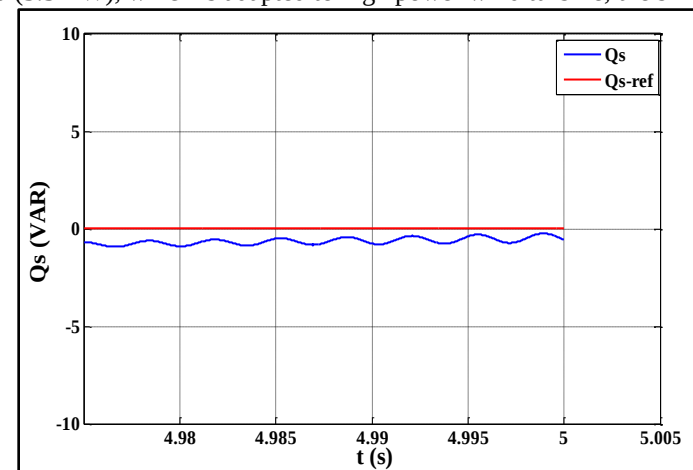


Figure 16. The reactive stator powers Q_s (VAR) according to time (s)

These curves vary between (-1 VAR) and (0 VAR), which shows the robustness of the indirect command of the DFIG used in wind energy and they depend on the rotor current $i_{dr}(A)$. They are independent from the profile of wind turbine.

V. CONCLUSION

In the first part, we presented the modelling of the wind turbine, the modelling of the DFIG by Matlab-Simulink and the power control. We presented the method of control of the powers through the rotor currents power control. Considering the results, it can be said that doubly fed induction generator proved to be a more reliable and stable system when connected to grid side with the proper converter control systems [19]. We were inspired by the modelling of the asynchronous generator with double feeding in order to apply a separate control of active and reactive powers. A review of the component modelling detail required for different study objectives has been provided and appropriate component models are selected. The control design is discussed and the controller performance for power strategies has been discussed and tested by Matlab-simulink. This method demonstrated that it can be used for a DFIG used in wind turbine energy. Thus, it would be interesting to continue analysing the real implementation of the indirect opened control. Finally, as new power regulation systems related to renewable energy sources are being applied in different countries, some researches are needed on the generated active power and its quality together with economic aspects of wind farm exploitation [20].

Format of reference

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