Doubly Fed Induction Generator, With Crow-Bar System, under Micro-Interruptions Fault

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Abstract: The work presented in this paper focuses on studying the application of doubly fed induction generators in wind energy production under micro-interruption fault. In this context, the presented work set out to improve the performance of a wind turbine either from an energetic efficiency, or from the arrangement with behavioral of grid disturbances. To reach the maximum wind power extraction, wind turbine has to reduce their disconnection. For this reason grid operators impose, by theirs grid connection requirements, to wind turbine producer to support some grid disturbance. This paper deals with the behavior of wind turbine equipped with a Doubly Fed Induction Generator (DFIG) under micro-interruption. A scheme tolerant micro-interruption, by using a crow bar system, is proposed. A control strategy of the Unified Power Flow Control (UPFC) using PI controller is presented. And finally fuzzy logic controller is illustrated and compared to PI controller.
Keywords: wind energy, Doubly Fed Induction Generator, micro-interruption, fault, crowbar, fuzzy logic controller.

1. Introduction

The increasing integration of wind energy in the production of electrical energy restructures the way that wind farm is operated. In Denmark an annual average of 15% of the total power is developed by wind farms. During certain periods of high wind and low consumption the main part of electrical energy is developed by wind farm. The increasing number of wind farms causes that more other countries can face a similar situation in the next few times. However the increase on part of wind energy compared to the capacity of the electrical grid can cause problems for the operators such as the variation of the tension, the imbalance and the instability of the network.[1] [2]

The disconnection of a wind turbine causes important losses in possible electrical energy. To reach the objective of reducing the rate of disconnection the operators on the electrical grid impose, in their wind grid connection requirements, a variety of tolerance to the network disturbances such as the micro-interruptions, voltage dips and frequency variation. For that, wind farms are called to support some grid disturbances.

The behavior of wind turbine under grid disturbances depend on type of generator (induction generator or synchronous generator), and scheme of connection to the electric grid. In this work, a wind turbine using the Doubly Fed Induction Generator (DFIG) is studied.
This paper deals with the micro-interruptions faults. Thus it is necessary to study the behavior of DFIG under micro-interruptions faults, present a solution allowing to the DFIG to support micro-interruption and design fuzzy logic controllers to improve the performance of DFIG under such category of fault.

2. Studied System

The studied system is composed by a wound rotor induction generator connected to the electric grid within rotor and stator. The stator is directly connected to the grid and the rotor is

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connected to the grid by the unified power flow control (UPFC). Such system has the capacity to deliver the electric power with voltage and frequency constants for a variation of the speed of ±20 to 40% around the synchronous speed. [3]

Figure 1 shows the schematic configuration of the DFIG. The UPFC is a power electronics device composed by two converters C_{rot} and C_{grid}. Coordinated control of the UPFC is proposed in section III.

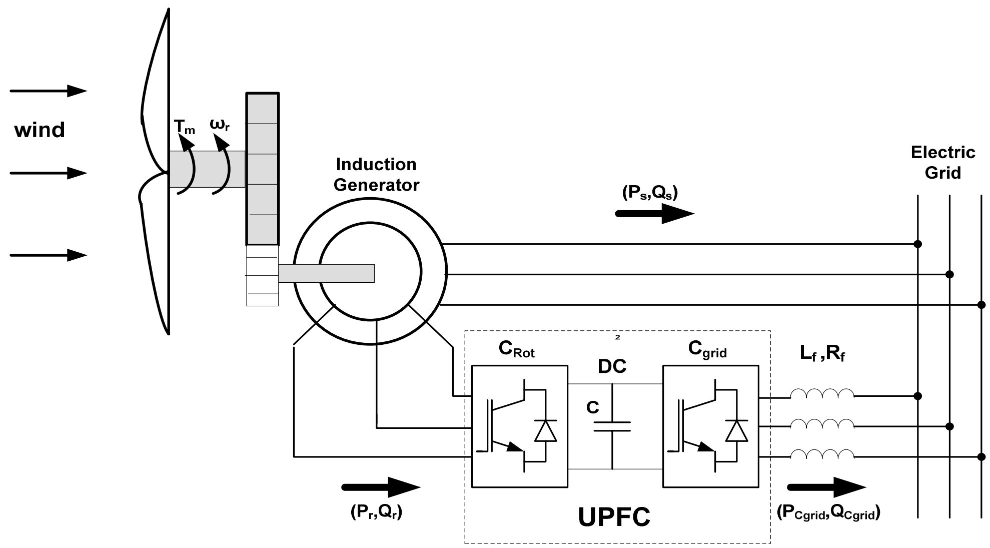

Figure 1. Configuration of a Doubly Fed Induction Generator (DFIG).

For this study it is assumed that the DFIG is subjected to a grid micro-interruption fault. Behaviors of DFIG wind turbine under micro-interruption fault are studied in section IV. Scheme tolerant such fault is provided in section V and finally fuzzy logic controllers are illustrated in section VI.

A. Wind Turbine

A simplified aerodynamic model is normally used when the electrical behavior of the wind turbine is the main interest of the study.

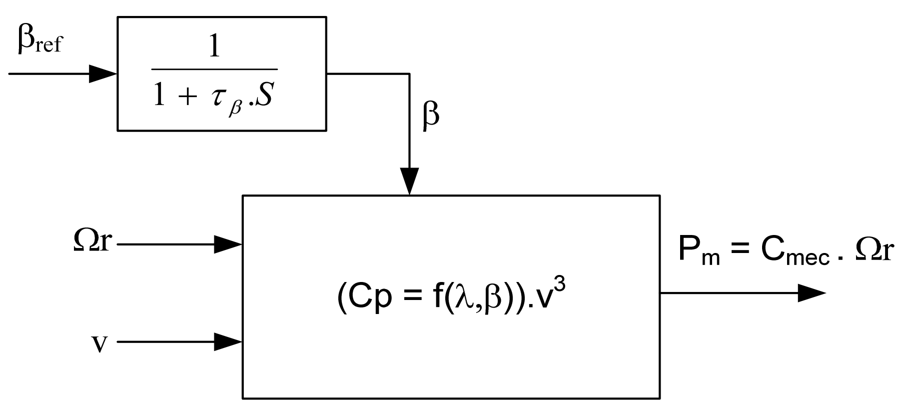

Figure 2. Schematic of a wind turbine

The relation between the wind speed and mechanic power, delivered by the wind turbine, can be described by the following equation:

$$P_m = \frac{1}{2}\pi.\rho.R^2.v^3.C_p(\lambda,\beta) \tag{1}$$

Where:
ρ: Specific mass of the air in Kg/m2.
v: wind speed (m/s).
R: Radius of turbine (m).
C_p: Power coefficient.

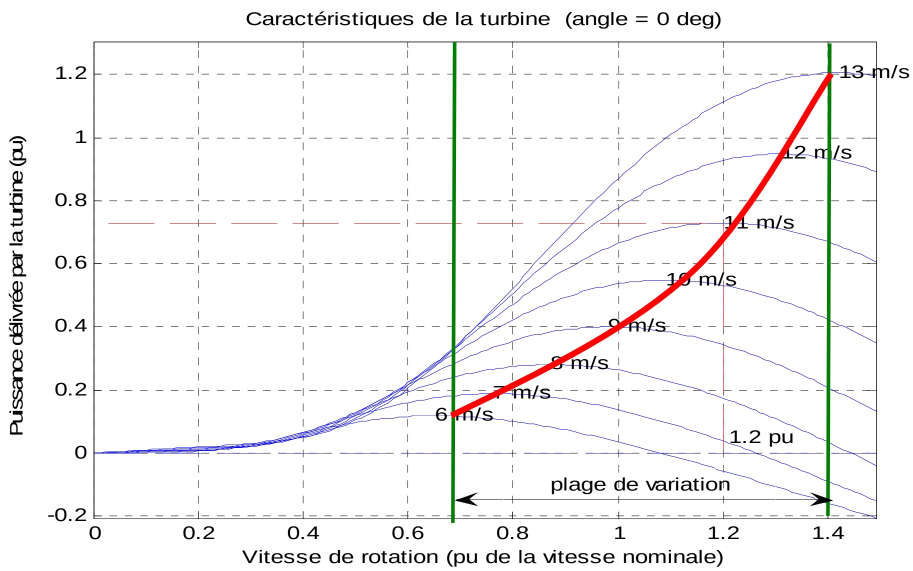

Figure 3. Turbine characteristics

Wind turbine model have two control schemes: speed control and pitch control. The speed control can be realized by adjusting the generator power or torque. The pitch control is a common control method to regulate the mechanic power from the turbine. [1]

B. Induction Generator

Using the electric equations of the wound rotor induction machine given by the following equation system [2]:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & -\omega_{dq} L_s & L_m p & -\omega_{dq} L_m \\ \omega_{dq} L_s & R_s + L_s p & \omega_{dq} L_m & L_m p \\ L_m p & -L_m(\omega_{dq}-\omega) & R_r + L_r p & -L_r(\omega_{dq}-\omega) \\ L_m(\omega_{dq}-\omega) & L_m p & L_r(\omega_{dq}-\omega) & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{2}$$

The mechanical equation of the generator is:

$$J\frac{d\omega_r}{dt} = np(T_m - T_e) \tag{3}$$

The electromagnetic torque is:

$$T_m = n_p \, L_m (i_{dr} \, i_{qs} - i_{qr} \, i_{ds}) \tag{4}$$

With:
T_m: Mechanical torque
T_e: Electromagnetic Torque
n_p: number of poles pairs
J: Effective inertia of the revolving part

C. The UPFC

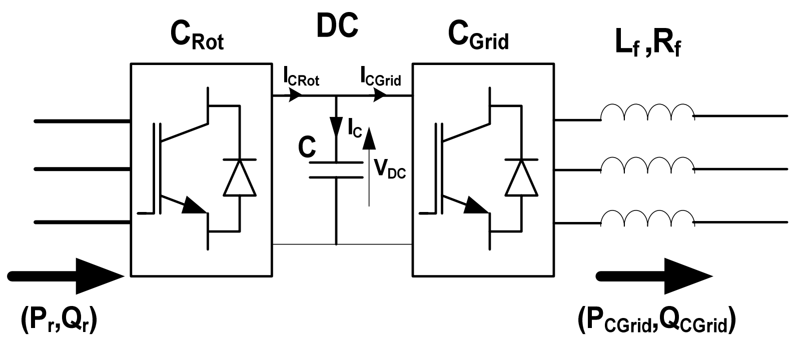

Figure 4. Unified Power Flow Controllers (UPFC)

$$P_m = T_m \, \Omega_r \tag{5}$$

$$P_s = T_e \, \Omega_s \tag{6}$$

In steady state and at fixed speed;

$$T_m = T_e \text{ and } P_m = P_s + P_r \tag{7}$$

$$\begin{aligned} P_r &= P_m - P_s = T_m . \, \Omega_r - T_e . \Omega_s \\ &= - \, T_m . (\Omega_r - \Omega_s) = - \, s . P_s \end{aligned} \tag{8}$$

$$C . V_{DC} . \frac{dV_{DC}}{dt} = P_{Crot} - P_{Cgrid} \tag{9}$$

$$i_C = C . \frac{dV_{DC}}{dt} = i_{Crot} - i_{Cgrid} \tag{10}$$

With: $P_{Crot} = s.P_S$

3. Control Algorithm

In this part, it is necessary to establish the control strategy of the two converters C_{rot} and C_{grid} (respectively converter side rotor and grid side converter) as well as the angle of orientation of pale (pitch angle). The two converters (C_{grid} and C_{rot}) can control the active power of the turbine, the voltage of the continuous bus and the reactive power.

A. Control of the side rotor converter Crot

We choose a synchronously rotating reference frame so that the d-axis thus coincides with the desired direction of stator flux; hence, the flux expression will be:

$$\psi_{ds} = \psi_s = L_s i_{ds} + L_m i_{dr} \tag{11}$$

$$\psi_{qs} = L_s \cdot i_{qs} + L_m \cdot i_{qr} = 0 \tag{12}$$

The electromagnetic Torque will be reduced to:

$$T_e = n_p \frac{L_m}{L_s}\left(\psi_{ds} i_{qr}\right) \tag{13}$$

By neglecting resistances of the stator phases the stator voltage will be expressed by:

$$v_s \approx \frac{d\psi_s}{dt} \tag{14}$$

We can also deduce

$$v_{ds} = 0$$

And

$$v_{qs} = v_s = \omega_s \psi_{ds}$$

The equations [13] and [14] give these next expressions of the “d” and “q” stator currents:

$$i_{ds} = \frac{\psi_{ds}}{L_s} - \frac{L_m}{L_s} i_{dr} \tag{15}$$

$$i_{qs} = -\frac{L_m}{L_s} i_{qr} \tag{16}$$

We lead to an uncoupled power control; where, the transversal component i_{qr} of the rotor current controls the active power. The reactive power is imposed by the direct component i_{dr}.

$$P = -v_s \frac{L_m}{L_s} i_{qr} \tag{17}$$

$$Q = \frac{v_s \psi_{ds}}{L_s} - \frac{v_s L_m}{L_s} i_{dr} \tag{18}$$

The arrangement of the equations gives the expressions of flux and the voltages according to the rotor currents:

$$\begin{cases} \psi_{dr} = \left(L_r - \frac{L_m^2}{L_s}\right) i_{dr} + \frac{L_m v_s}{\omega_s L_s} \\ \psi_{qr} = \left(L_r - \frac{L_m^2}{L_s}\right) i_{qr} \end{cases} \tag{19}$$

$$\begin{cases} v_{dr} = R_r i_{dr} + \left(L_r - \frac{L_m^2}{L_s}\right)\frac{di_{dr}}{dt} - g\omega_s\left(L_r - \frac{L_m^2}{L_s}\right)i_{qr} \\ v_{qr} = R_r i_{qr+}\left(L_r - \frac{L_m^2}{L_s}\right)\frac{di_{qr}}{dt} - g\omega_s\left(L_r - \frac{L_m^2}{L_s}\right)i_{dr} + g\omega_s\frac{L_m^2 v_s}{\omega_s L_s} \end{cases} \tag{20}$$

Note by:

$$\sigma = 1 - \frac{L_m^2}{L_s.L_r}$$

$e1 = -g.\omega_s.\sigma.L_r.i_{qr}$

$e2 = g.L^2_m v_s/L_s - g.\omega_s.\sigma.L_r.i_{dr}$

ω_0 and ξ denote natural frequency and damping ratio, respectively.

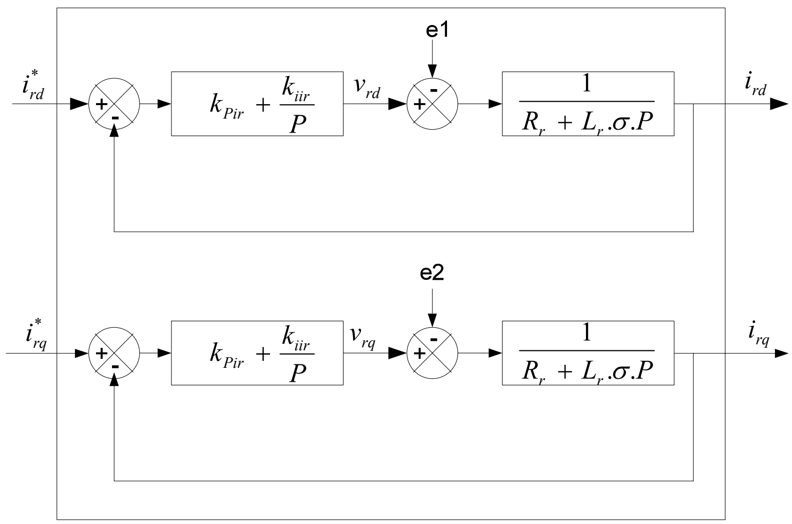

Figure 5. Rotor current regulator diagram block

The PI constants (Kiir, Piir) are obtained by using identification of the closed loop transfer function which is a second order transfer function. The optimal response is obtained for ξ =0,7 $\Rightarrow$ ω0.tr = 3. By choosing a system response time (tr), K_{iir} and K_{pir} (PI regulator coefficients) can been deduced.

$\omega_0 = 3/t_r$ [2]

$$\boxed{K_{iir} = \frac{\omega_0^2.\tau}{K}} \tag{21}$$

$$\boxed{K_{pir} = \frac{\xi.2\omega_0\tau - 1}{K}} \tag{22}$$

B. Control of the grid side converter C_{Grid}

$$i_C = C.\frac{dV_{DC}}{dt} = i_{CRot} - i_{CGrid} \quad (23)$$

$$C.V_{DC}.\frac{dV_{DC}}{dt} = P_{CRot} - P_{CGrid} \quad (24)$$

With: $P_{CRot} = g.P_S$ (25)

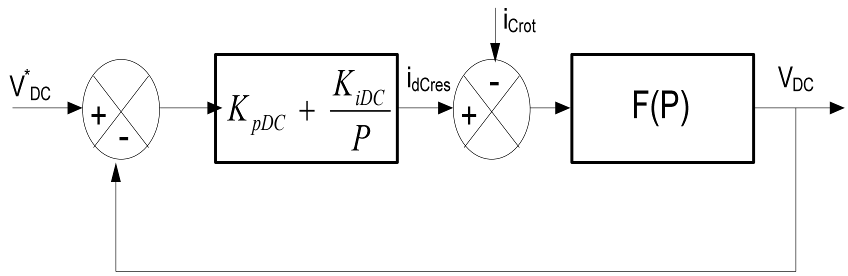

Figure 6. Continuous bus voltage Regulation block diagram

Where K_{pDC} and K_{iDC} denote proportional and integral gains of the, continuous bus, (PI) controller.
So the regulator parameter can been deduced:

$$\boxed{K_{iDC} = \omega_0^2.C}$$

$$\boxed{K_{pDC} = 2\omega_0.\xi.C}$$

Where ω_0 and ξ denote natural frequency and damping ratio, respectively.

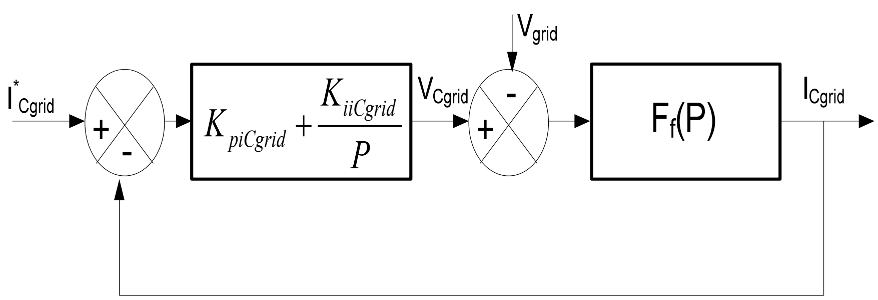

Figure 7. Cgrid Converter current Regulation block diagram

Then the PI regulator coefficient ($K_{piCgrid}$, $K_{iiCgrid}$) can been found :

$K_{piCgrid} = 2.L_f.\xi.\omega_0 - R_f$ (26)

$K_{iiCgrid} = L_f.\omega_0^2$ (27)

Where:
V_{DC}: voltage of the continuous Bus
I_{Cgrid}: Current delivered by the grid side converter
V_{CGrid}: Voltage of the grid side converter
V_{grid}: Stator voltage (Grid voltage)
L_f: Smoothing bobbin self inductance
R_f: Smoothing bobbin resistance
ω_s: Stator pulsation
*: reference value

4. DFIG Wind Turbine under Micro-Interruption

In this section behaviors of DFIG wind turbine under micro-interruption fault are studied. The micro-interruption is a disconnection of the electric grid for a short moment. For the case of the generating operation of an asynchronous machine the electric grid interruption makes the system similar to a standalone induction generator. In this case the amplitude and the frequency of the generator will not be assisted any more by the electric grid. That makes the generators terminal voltage values depending on magnetizing and speed of the generator. On this fact the influence of a micro-interruption on a wind turbine depends on the used structure of generator (DFIG or asynchronous generator directly connected to the grid).

Using the equivalent circuit, in transitory mode, of the induction machine given by the figure 8 the electric equations can been established.

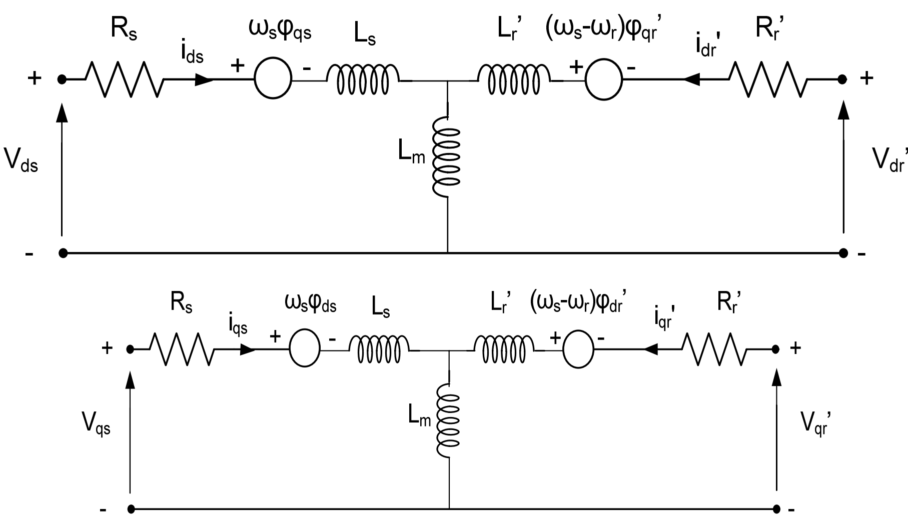

Figure 8: Schéma équivalent de la machine asynchrone selon l’axe "d" et l’axe "q"

$$V_{ds} = R_s\, i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega\varphi_{qs} \tag{28}$$

$$V_{qs} = R_s\, i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega\varphi_{ds} \tag{29}$$

$$V_{dr}^{'} = R_r^{'}\, i_{dr}^{'} + \frac{d\varphi_{dr}^{'}}{dt} - (\omega - \omega_r)\,\varphi_{qr} \tag{30}$$

$$V'_{qr} = R'_r i'_{qr} + \frac{d\varphi'_{qr}}{dt} - (\omega - \omega_r)\varphi_{dr} \tag{31}$$

$$T_e = n_p \frac{M}{L_r}\left(\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}\right) = n_p\left(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}\right) \tag{32}$$

Under micro-interruption between the network and the wind turbine the amount of power delivered to the electric grid will be forwarded towards the rotor. This amplifies excessively the rotor current and consequently increases the stator tensions see equation (28) and (29).

For the active and reactive powers, during a sudden increase in the rotor current caused by a micro-interruption, a peak with a positive value appears in the active power curve and a peak with negative value appears in the reactive power curve. This is confirmed by the following expressions of the active and reactive power:

$$P_S = \frac{3}{2}\omega_s \frac{M^2}{L_s} I_m \cdot I_{rq} \tag{33}$$

$$Q_S = \frac{3}{2}\omega_s \frac{M^2}{L_s} I_m (I_m - I_{rd}) \tag{34}$$

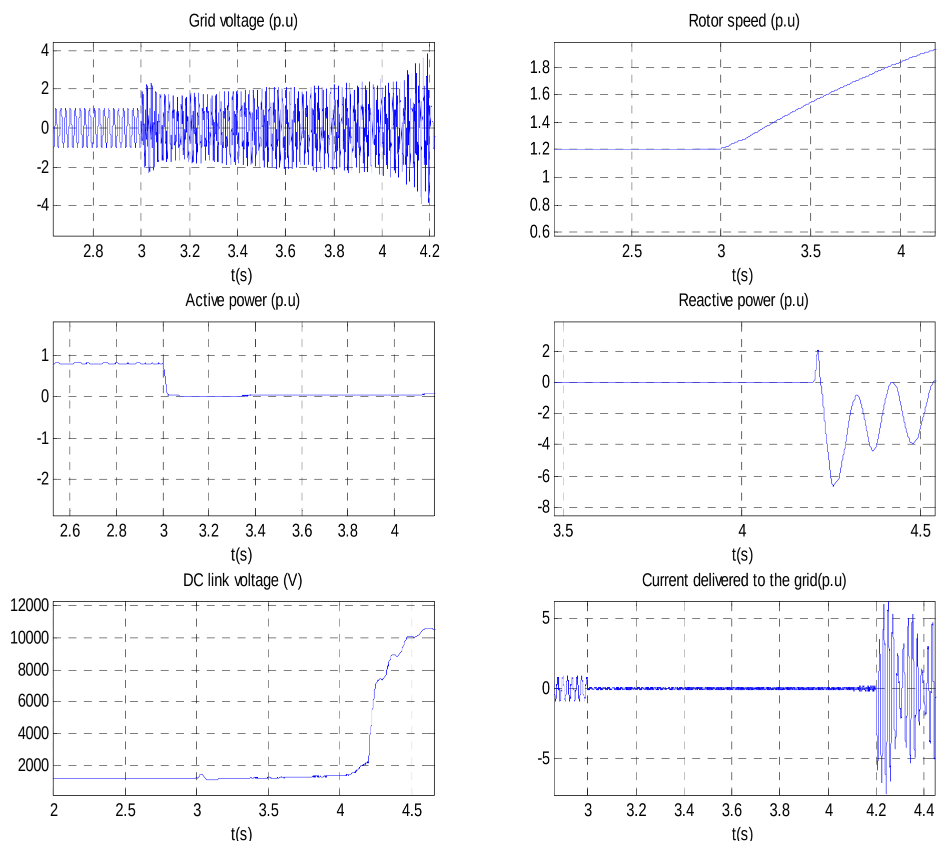

Figure 9: a- Grid voltage, b- Generator speed, c- Active power, d- reactive power, e- DC link voltage, f- Rotor active power Time of micro-interruption appearance: t=3s

Figure 9 shows that under micro-interruption wind turbine based on DFIG diverges. Note that the UPFC is dimensioned to support only 30% of the rated power. Then this device, under micro-interruption of the electric grid, will be damaged. So it is recommended to protect these converters. Some uses the Crow-Bar as a method of protection. It makes possible to short-circuit the rotor and to insulate the converters. [4] The diagram of a wind turbine based on DFIG using a crow-bar is given by the figure 10.

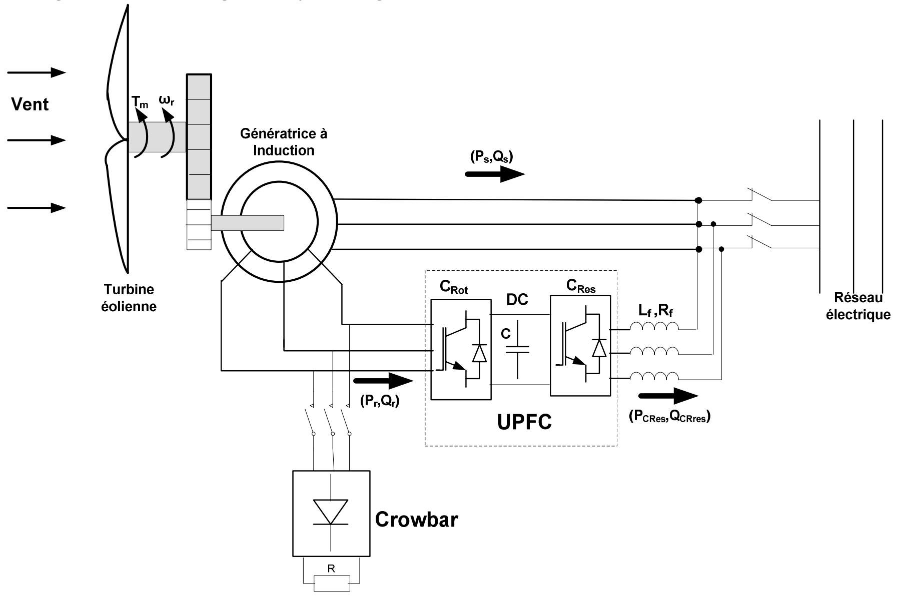

Figure 10. Diagram of A Wind Turbine Based On DFIG Using A Crow-Bar System.

The proposed solution permits the protection of the power electronics device. But it is limited since it does not allow the system to recover in energy production after departure of the micro-interruption. In fact with the appearance of a micro-interruption the system is disconnected from the electric grid and it is necessary for him a new starting launch. That causes a production loss for the duration between the disappearance of the micro-interruption and the re-establishment of the system in energy production.

5. Scheme Tolerant Micro-Interruption Fault

In this section, a method allowing a wind turbine, based on a DFIG, to tolerate the micro-interruptions will been presented. This method is based on the use of a crow-bar inserted between the wind turbine and the electric grid as presented in the figure 11.

To improve the performance of this system an evaluation of the behavior of the system, under micro-interruption, using two types of regulators (PI regulator and Fuzzy Logic regulator) is presented.

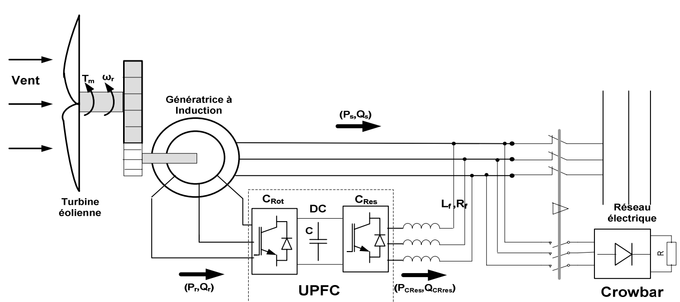

Figure 11. Doubly Fed Induction Generator (DFIG) with a crowbar system.

In safety condition the crow-bar is disconnected. When a micro-interruption appears the crow-bar is immediately activated in order to absorb the power delivered by the generator. A dimensioning of crow-bar power is necessary.

Obtained results:

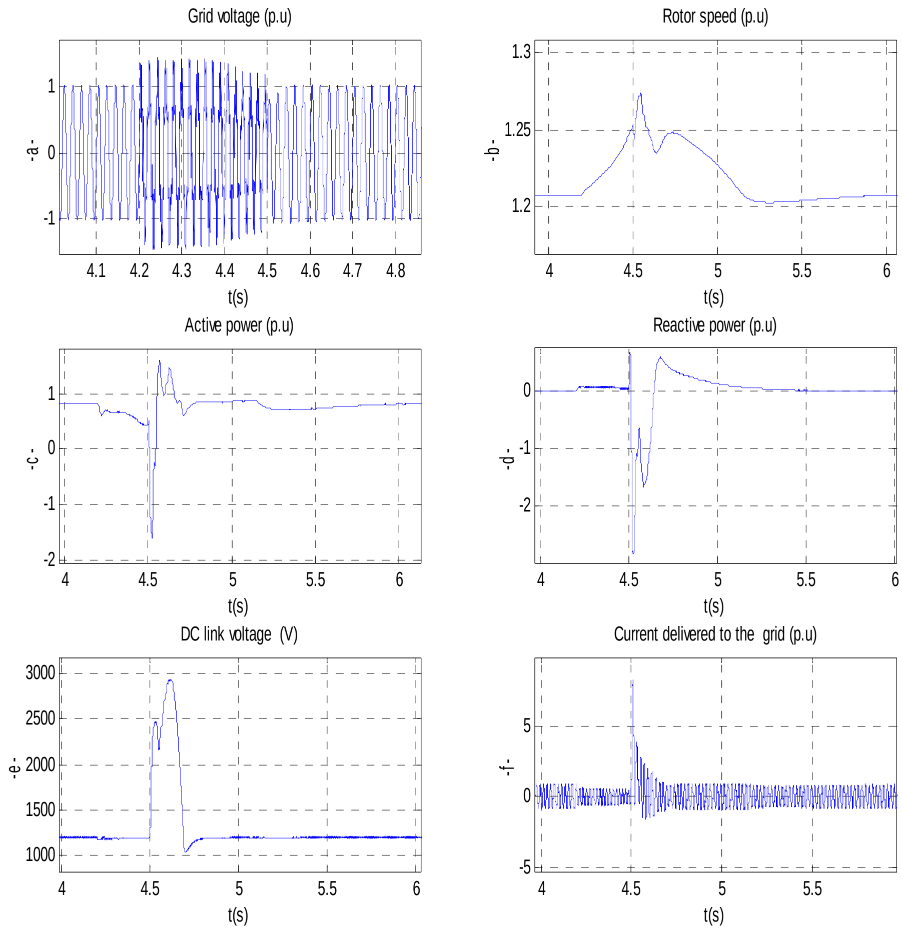

Figure 12 Results obtained with a PI regulator a- Grid voltage, b- Generator speed, c- Active power, d- reactive power, e- DC link voltage, f- Rotor active power

At the onset of a micro-interruption between the network and the wind turbine, the crow-bar connects to the generator terminals in order to absorb the provided energy. The system becomes similar to an isolated wind turbine using a DFIG. When the micro-interruption disappears and the system connects to the network again, a transient appears. This is due to the potential difference. This phenomenon is reflected by peaks on the characteristic of the system.

6. Fuzzy Logic Regulation

Previously fuzzy logic has not been used much in wind turbine control. One of the main reasons for this is that most of the wind turbine control tasks have been in the small signal range, where linear PI and PID controllers perform well. [5]

For transient mode, the case of micro-interruption and voltage dip, the system becomes difficult to describe mathematically. This is the prime area for application of fuzzy logic control.

A. Regulator conception

The structure of the current fuzzy logic controller is given by the figure 13:

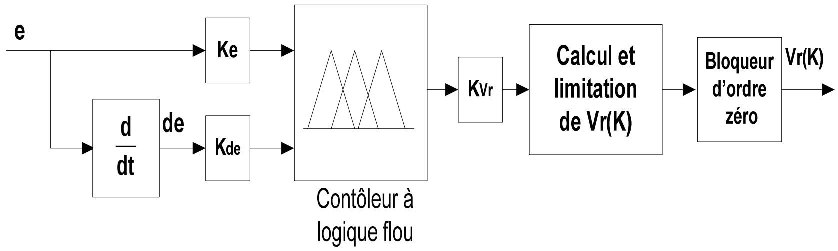

Figure 13. Diagram of fuzzy logic controller.

As the membership functions are normalized between [-1, 1], the variables are multiplied with the proportional gains.

Figure 14 illustrates membership functions of the input variables.

Note By:

NB: Negative Big
PB: Positive Big
NM: Negative Medium
PM: Positive Medium
NS: Negative Small
PS: Positive Small
ZE: Zero

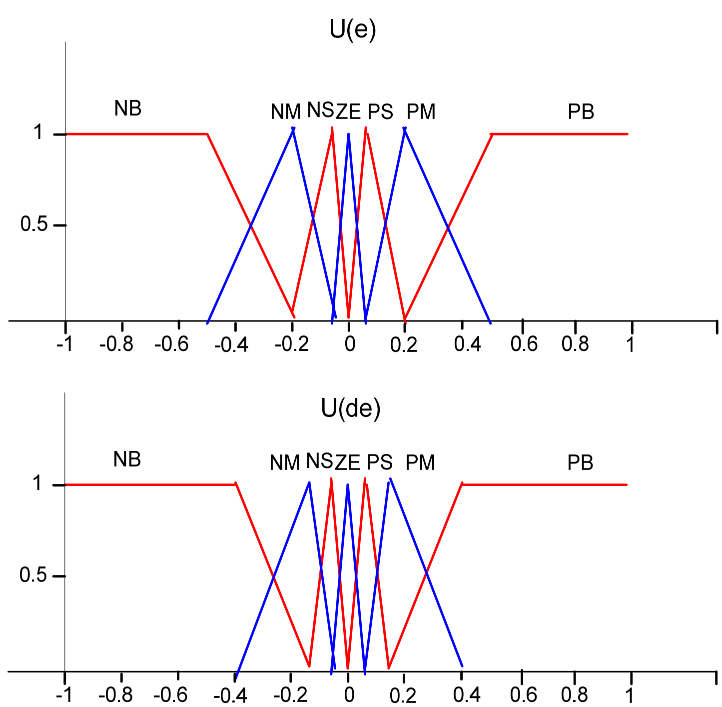

Figure 14. Inputs membership functions

We note that the membership functions of error have an asymmetric shape creating a concentration around zero, which improves the accuracy near the nominal operating point. Output membership functions are shown by the figure 15.

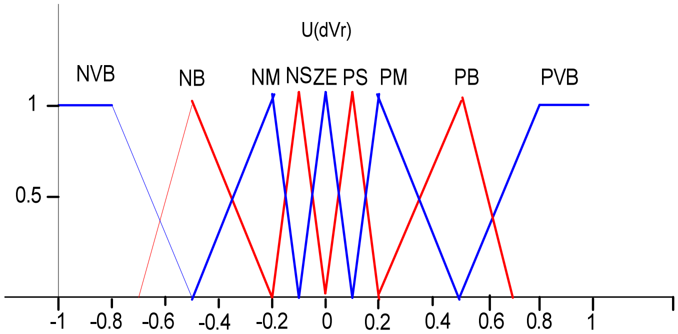

Figure 15. Output membership functions.

For the same reason, the shapes of membership functions of output are asymmetric. However, it is necessary to introduce an additional subset given the sensitivity of this variable. With:

NVB: Negative Very Big

PVB: Positive Very Big

The following table illustrates the rules giving dV_r according to the states of the error “e” and the variation of the error “de”.

Table 1. Base Of Rules Relative To The Current Fuzzy Logic Regulator

		e						
		NB	NM	NS	ZE	PS	PM	PB
de	NB	NVB	NVB	NVB	NB	NM	NS	ZE
	NM	NVB	NVB	NB	NM	NS	ZE	PS
	NS	NVB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PVB
	PM	NS	ZE	PS	PM	PB	PVB	PVB
	PB	ZE	PS	PM	PB	PVB	PVB	PVB

A synthesis based on the heuristics allows the determination of the gains K_e, K_{de} and K_s corresponding respectively to the error, the variation of the error and the output.

B. Obtained results

During the appearance of a micro-interruption, between the electric grid and the wind turbine, the crow-bar is activated in order to absorb the energy provided by the DFIG. The system becomes similar to a standalone wind turbine using a DFIG. When the micro-interruption disappears and the system is connected again to the electric grid a transient mode appears. This is due to the voltage difference explained in the section IV. This phenomenon is translated by peaks in power, current and voltage of the DFIG. The use of the fuzzy logic controller for the rotor current shows a clear superiority in front of PI regulators. The results obtained show how the fuzzy logic regulators reduce well the transitory mode in amplitude and time of re-establishment of the system.

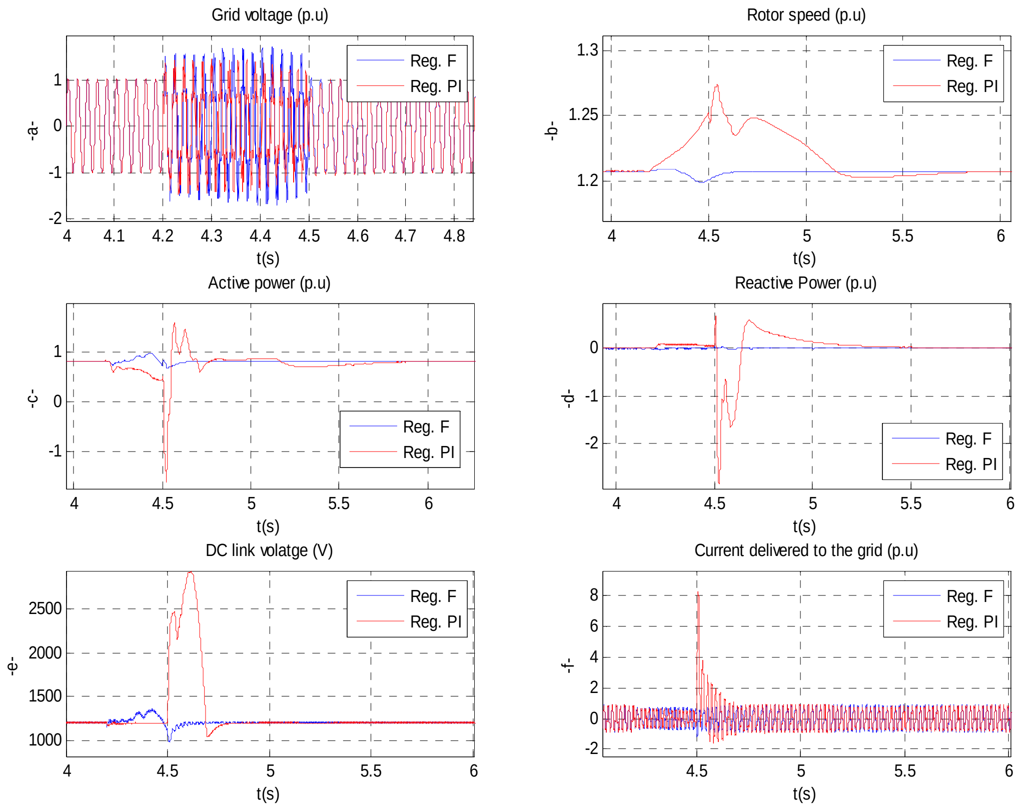

Figure 16. 300ms Micro-interruption at the moment t=4.2s
Fuzzy logic controller (blue) PI controller (Red)
a- Grid voltage, b- Generator speed, c- Active power, d- reactive power,
e- DC link voltage, f- Rotor active power

Finally it is clear that the suggested structure permits to wind turbine the toleration of micro-interruptions. So, it reduces wind turbine disconnections. The regulation of the rotor currents by using fuzzy logic controller improved the performance of the system during the appearance of the micro-interruptions fault.

7. Conclusion

To reach the maximum wind power extraction, wind turbine has to reduce their disconnection. For this reason grid operators impose, by theirs grid connection requirements, to wind turbine producer to support some grid disturbance. Doubly fed induction generators are more sensible to the grid disturbance compared to other kind of generator.

This paper has proposed a scheme allowing, a wind turbine based on DFIG, to avoid disconnection when micro-interruption appears. This involves installing a crow bar between the wind and the network.

In safe mode the crow bar is disconnected. At the onset of a micro-interruption, the crow-bar connects to GADA in order to absorb the power delivered by the generator. At the fault disappears, the crow-bar disconnects and new DFIG is connected to the network. A control strategy of the UPFC, using PI regulator, has been presented.

Finally a fuzzy logic controller was illustrated. Such controller performs well in transient mode of the DFIG. Especially for micro-interruption they reduce peak and duration of transient mode.

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