Supervision of a Grid-Connected Wind Farm by the Electric Production Distribution Method

Walid Ouled Amor*‡, Moez Ghariani*, Soltana Guesmi*

*Department of Electrical Engineering, National School of Engineering, Laboratory of electronics and information technology, University of Sfax, 3038 Sfax,Tunisia

(oa.walid3@gmail.com, moez.ghariani@gmail.com, soltanaguesmi@gmail.com)

‡ Corresponding Author; Walid Ouled Amor, National School of Engineering 3038 Sfax, Tunisia, oa.walid3@gmail.com

Received: 06.06.2015 Accepted:15.07.2015

Abstract- Face to the growing demand in electricity, and to avoid the use of polluting fossil energies (oil and gas), several countries turned to renewable energies including wind turbine. The integration rate of wind farms into the electrical network has become increasingly significant. Consequently, several instability problems arise because, so far, they do not take part in the system services. Our study is focused on the control and management of the production of active and reactive powers of a wind farm. Indeed, this power management is guaranteed by a supervision algorithm based on proportional distribution. An analysis of the transferred powers by the wind system and an estimation of the maximum production capacity of the powers are carried out to provide the necessary information to this algorithm and to guarantee its accurate operation. A supervision algorithm was proposed for our system in order to coordinate the reactive power references distribution between the DFIG stator and the grid converter. This algorithm added reactive compensation flexibility for the wind farm by considering three operating modes. The presented simulation results validate the algorithm developed for the powers supervision of the wind farm connected to the grid during different operating modes.

Keywords—Wind farm, Supervision, distribution method, Control Strategies, DFIG and Grid.

1. Introduction

During the last years, the connection of average and great power wind farms to the electrical network has evoked many problems for the management of the electric network because of the inconsistency of the wind resources. A few years ago, the wind turbines have been controlled by the MPPT strategy to transfer the maximum power to the grid. However, these wind turbines are disconnected from the grid when a fault occurs since they do not have the capacity to adjust their production and provide services for the electric system [1]. In order to overcome these problems and to ensure the safety of the grid, the wind farms should conform to the requirements imposed by the network operation center. Several wind farm supervision and monitoring techniques are currently investigated: the control of active and reactive powers, the control of voltage, the control of the frequency and the tolerance with respect to the faults of the grid [1,2]. In order to allow a wind farm to connect to the grid without affecting its safety and its stability, the researchers orient their investigation towards the design of a centralized supervision for this farm [1,3]. The strategy investigated here consists in exploiting the effect of expansion within the farm to design an adequate distribution of the active and reactive powers on the wind turbine by guaranteeing a better support for the electrical network.

In this article, we present a supervision of the active and reactive powers in a wind farm which at the present time represents one of the major needs for the network operation center. Indeed, this article comprises four parts: the first part describes the system studied. The second part consists in the supervision of the active and reactive powers in a wind farm connected to the network. An analysis of the maximum active and reactive power exchanges of DFIG is presented in the third part. In order to better contribute to the management of reactive power within a wind turbine, a local management of the powers of each turbine is developed thus allowing a distribution of the powers between the stator of the machine and the grid converter by considering several operating modes of the wind system [1]. Finally, results of simulations are presented in the fourth part.

2. System Overview

In order to control the grid, the network operation center must manage the wind farm as a conventional turbine. The wind farm is connected to the HTA 20 Kv Bus via a 20kV/690V transformer. Different fixed or variable loads are connected to the same bus through another transformer. A central supervision unit of the wind farm is installed in order to control the powers P_{WF}, Q_{WF} exchanged with the electrical network. According to the current state of the network and the control mode requested by the manager of network (balance control, delta control, automatic frequency control, reactive power control…) an analysis of the powers exchanged between the grid and the wind farm, presents in the **Fig.1**, was carried out to consider the maximum production capacity of active and reactive powers of each wind turbine and, consequently, of the wind farm [1]. This estimation allows a correct operation of the implemented algorithm. Indeed, a local reactive management algorithm was proposed for each wind turbine of the farm in order to coordinate the distribution of the references of the reactive power between the DFIG stator and the network converter. This procedure added a compensation flexibility of the reactive power for the wind turbine by considering three operating modes: MPPT, delta and fault modes.

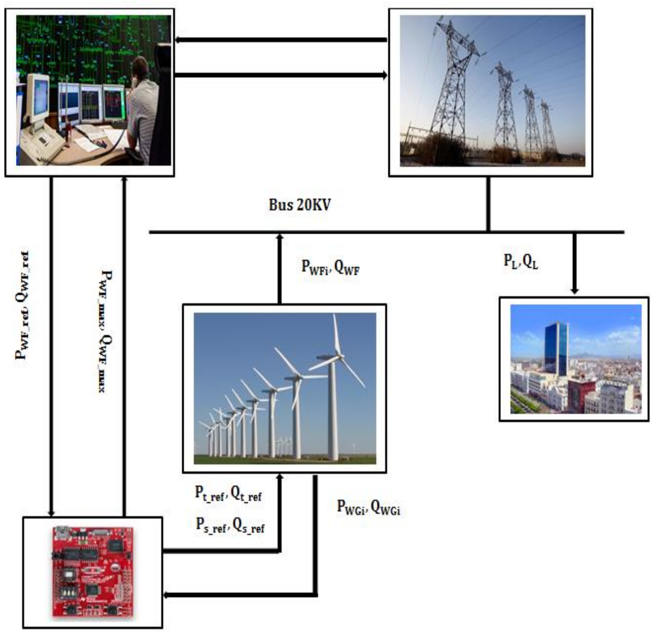

Fig.1. Diagram of power systems studied

3. Wind Turbine Modelling

3.1. Modelling of the turbine

The aero-generator is a system that converts kinetic energy of the wind into mechanical energy through a multiplier to adapt the slow speed of the turbine at the fast speed of the DFIG. Figure 2 presents a simplified diagram of the proposed control strategy for a wind turbine

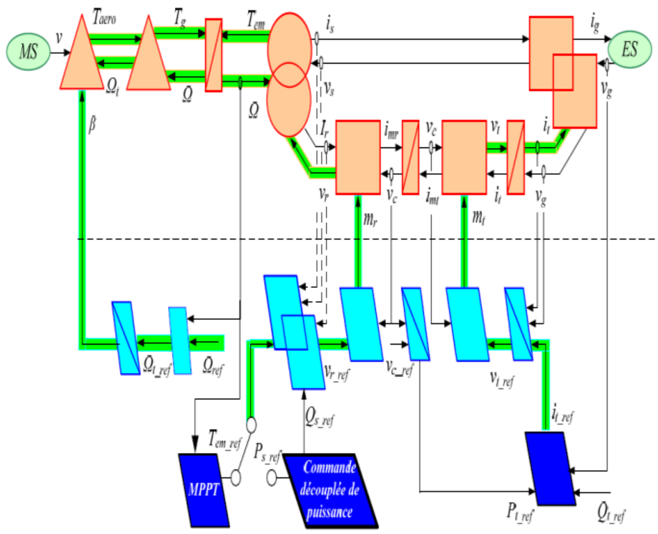

Fig.2. Wind turbine modelling and control strategy

The kinetic power collected by the blades of the wind turbine is given by the following expression:

$$P_v = \frac{\rho.S.V^3}{2} \quad (1)$$

With: $S = \pi \times R^2$

λ specific speed is written as follows:

$$ʎ = \frac{R.\Omega_t}{V} \quad (2)$$

The C_p coefficient characterizes the aerodynamic output of the turbine and defines the power which can be extracted during the kinetic energy transformation to the mechanical energy. It depends primarily on two parameters i.e. the speed ratio λ and the blades orientation angle β [4].

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \quad (3)$$

With:

$$\frac{1}{\lambda_i} = \left(\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\lambda + \beta^3}\right) \quad (4)$$

C_1=0.5176; C_2=116; C_3=0.4; C_4=5; C_5=21; C_6=0.0068;

The aerodynamic power is given by the following expression:

$$P_{aero} = \frac{C_p\,(ʎ).\rho.S.V^3}{2} \quad (5)$$

In the same way, the expression of the aerodynamic torque C_{aero} is presented as follows:

$$C_{aero} = \frac{C_p(\lambda).\rho.S.V^3}{2.\Omega_t} \quad (6)$$

The mechanical speed of the DFIG is given by the following expression:

$$\Omega_t = \frac{\Omega}{G} \quad (7)$$

Thus, we deduce the mechanical torque transmitted to the DFIG tree:

$$C_{mec} = C_g - C_{em} - C_{vis} \quad (8)$$

According to the fundamental equation of our system dynamics, we can determine the mechanical rotation speed of the DFIG tree. It depends on the torque applied to the rotor (C_{mec}) of the generator.

$$J.\frac{d\Omega}{dt} = C_g - C_{em} - f.\Omega \quad (9)$$

With :

$$C_{mec} = J.\frac{d\Omega}{dt} \quad (10)$$

$$C_g = \frac{C_{aero}}{G} \quad (11)$$

The viscous friction couple is presented as follows:

$$C_{vis} = f.\Omega \quad (12)$$

3.2. Modelling of the DFIG

The DFIG modelling, presents in the **Fig.3**, is described in the PARK referential. Our work is based on the following simplifying assumptions [4]:

- The air-gap is constant and the notch effect is negligible
- The flow distribution is sinusoidal
- The magnetic circuit saturation is negligible
- The heating influence and the skin effect on the DFIG characteristics are not taken into account.

The following equation system makes a global modelling of the generator:

Stator:

$$V_{sd} = R_s.i_{sd} + \frac{d}{dt}\phi_{sd} - \phi_{sq}.W_s \quad (13)$$

$$V_{sq} = R_s.i_{sq} + \frac{d}{dt}\phi_{sq} + \phi_{sd}.W_s \quad (14)$$

Rotor:

$$V_{rd} = R_r.i_{rd} + \frac{d}{dt}\phi_{rd} - \phi_{rq}.W_r \quad (15)$$

$$V_{rq} = R_r.i_{rq} + \frac{d}{dt}\phi_{rq} + \phi_{rd}.W_r \quad (16)$$

The rotor pulse is deduced according to the stator pulse and the rotation speed:

$$W_r = W_s - p.W_m \quad (17)$$

The flow equations are written as follows:

$$\phi_{sd} = L_s.i_{sd} + M.i_{rd} \quad (18)$$

$$\phi_{sq} = L_s.i_{sq} + M.i_{rq} \quad (19)$$

$$\phi_{rd} = L_r.i_{rd} + M.i_{sd} \quad (20)$$

$$\phi_{rq} = L_r.i_{rq} + M.i_{sq} \quad (21)$$

The Electromagnetic Couple is presented as follows:

$$C_{em} = p.(\phi_{rq}.i_{rd} - \phi_{rd}.i_{rq}) \quad (22)$$

From the magnetic equation linking the flows with the currents, we obtain [4]:

$$\begin{pmatrix} i_{sq} \\ i_{rq} \end{pmatrix} = \begin{pmatrix} L_s & M \\ M & L_r \end{pmatrix}^{-1} . \begin{pmatrix} \phi_{sq} \\ \phi_{rq} \end{pmatrix} = \frac{1}{L_s.L_r - M^2} . \begin{pmatrix} L_s & -M \\ -M & L_r \end{pmatrix} . \begin{pmatrix} \phi_{sq} \\ \phi_{rq} \end{pmatrix}$$

$$\begin{pmatrix} i_{sd} \\ i_{rd} \end{pmatrix} = \begin{pmatrix} L_s & M \\ M & L_r \end{pmatrix}^{-1} . \begin{pmatrix} \phi_{sd} \\ \phi_{rd} \end{pmatrix} = \frac{1}{L_s.L_r - M^2} . \begin{pmatrix} L_s & -M \\ -M & L_r \end{pmatrix} . \begin{pmatrix} \phi_{sd} \\ \phi_{rd} \end{pmatrix}$$

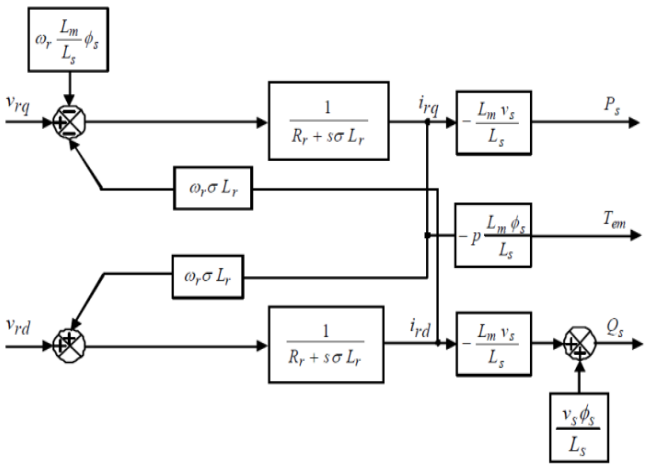

Fig.3. DFIG Modelling

3.3 DFIG converter Controls

The strategy of the DFIG converter, presents in the **Fig.4**, is to ensure the management of transfer of the active and reactive powers through the stator of the DFIG towards the grid [5]. In order to receive the active and reactive reference powers ($P_{s_{ref}}, Q_{s_{ref}}$) of the local supervision unit of each wind turbine, this control device sends the control commands to the converter. The power control strategy calculates and sends the i_{rq_ref} and i_{rd_ref} of the DFIG rotor current, that refer to the active and reactive stator reference powers [1,5].

$$i_{rq\_ref} = -\frac{Ls}{V_v.M} P_{s\_ref} \quad (25)$$

$$i_{rq\_ref} = -\frac{Ls}{V_v.M} Q_{s_{ref}} + \frac{\phi_s}{M} \quad (26)$$

The ϕ_s is estimated in accordance with the measured stator currents:

$$\breve{\phi}_{sd} = L_s.\check{i}_{sd} + M.\check{i}_{rd} \quad (27)$$

$$\breve{\Phi}_{sq} = L_s.\breve{i}_{sq} + M.\breve{i}_{rq} \quad (28)$$

$$\breve{\Phi}_s = \sqrt{\breve{\Phi}_{sd}^{\ 2} + \breve{\Phi}_{sq}^{\ 2}} \quad (29)$$

Figure 4 presents the DFIG converter Control. In order to evaluate the voltage V_{rd_ref} and V_{rq_ref} in accordance with the FEM coupling equations e_{q_ref}, $e_{d_{ref}}$ and e_{ϕ_ref} :

$$e_{q\_ref} = -W_r.L_r.\sigma.I_{rq} \quad (30)$$

$$e_{d\_ref} = W_r.L_r.\sigma.I_{rd} \quad (31)$$

$$e_{\phi\_ref} = \frac{M}{L_s}.W_r.\Phi_{sd} \quad (32)$$

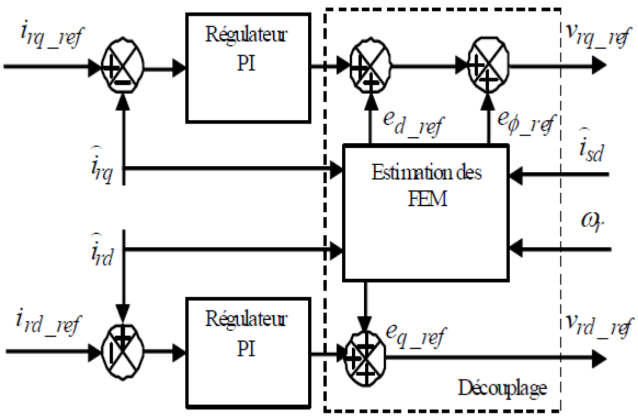

Fig.4. DFIG converter control

3.4 Grid control Strategy

The control strategy of the grid converter aims at controlling the continuous bus voltage and the direct and quadrature rotor currents from filter RL. During the connection of the wind turbine to the grid, the power-factor should be fixed at 1 by simply imposing a null reactive power. To ensure the decoupling between the control of the active and reactivate powers, a vectorial control with the orientation of the PARK reference according to the voltage of the grid is used as follows [1]:

$$V_{gd} = V_g \quad (33)$$

$$V_{gd} = 0 \quad (34)$$

The power active and reactivate powers forwarding through the grid converter is given:

$$P = V_{Gd}.I_{fd} + V_{Gq}.I_{fq} \quad (35)$$

$$Q = V_{Gq}.I_{fq} - V_{Gd}.I_{fq} \quad (36)$$

Based on the current filter losses, the following expression of the voltage is given:

$$V_{fd} = V_{Gd} = V_G \quad (37)$$

$$V_{fd} = V_{Gd} = 0 \quad (38)$$

From expressions 39 and 40 the expressions of active P_t and reactive Q_t powers can be simplified as follows:

$$P_f = V_g.i_{fd} \quad (39)$$

$$Q_f = -V_g.i_{fq} \quad (40)$$

The reference currents $(i_{fd_{ref}}, i_{fq_{ref}})$ are imposed by the reference powers $\left(P_{fd_{ref}}, P_{fq_{ref}}\right)$ given by:

$$i_{fd\_ref} = \frac{P_{f\_ref}}{\breve{V}_g} \quad (41)$$

$$i_{fq\_ref} = -\frac{Q_{f\_ref}}{\breve{V}_g} \quad (42)$$

The equations of the filter connected to the network in the PARK reference are expressed by:

$$V_{fd} = V_{fd1} - W_s.L_f.I_{fq} + V_{Rd} \quad (43)$$

$$V_{fq} = V_{fq1} + W_s.L_f.I_{fd} + V_{Rq} \quad (44)$$

With:

$$V_{fd1} = R_f.I_{fd} + L_f.\frac{d}{dt}I_{fd} \quad (45)$$

$$V_{fq1} = R_r.I_{fq} + L_f.\frac{d}{dt}I_{fq} \quad (46)$$

Figure 5 presents the PI controllers of the currents i_{fd} and i_{fq} from filter RL

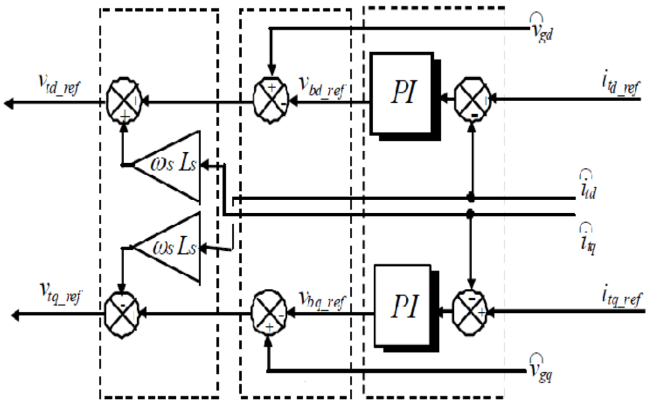

Fig.5. Diagram of Grid converter control

2. Supervision of the Active and Reactivate Powers in A Wind Farm Connected to the Network

We divided our algorithm into two units: a central supervision unit and a local supervision one. The first unit controls the total farm active and reactive powers according to an hourly production plan required by the network manager. Indeed, this unit receives a request for power (P_{WF_ref}, Q_{WF_ref}) of the network manager on the one hand and sends information to it on the maximum capacity of power production (P_{WF_max}, Q_{WF_max}) on the other hand [6,7]. By adopting the proportional distribution algorithm, the reference powers for each wind turbine of the farm ($P_{WG\_ref\_i}, Q_{WG\_ref\_i}$) are sent in real time to the local supervision units of each wind turbine. On the other hand, the local supervision unit of each wind turbine must coordinate the distribution stator ($P_{s\_ref\_i} Q_{s\_ref\_i}$) and rotor ($P_{t\_ref\_i} Q_{t\_ref\_i}$) powers deduced according to the active $P_{WG\_ref\_i}$ and reactive $Q_{WG\_ref\_i}$ powers received from the central supervision unit [6,8,9].

$$\tilde{P}_{WF\_max} = \sum_{i=1}^{n} \tilde{P}_{WG\_\max\_i} \quad (47)$$

$$\tilde{Q}_{WF\_max} = \sum_{i=1}^{n} \tilde{Q}_{WG\_\max\_i} \quad (48)$$

$$P_{WG\_ref\_i} = \frac{\tilde{P}_{WG\_\max\_i}}{\tilde{P}_{WF\_max}} \tilde{P}_{WF\_ref} \quad (49)$$

$$Q_{WG\_ref\_i} = \frac{\tilde{Q}_{WG\_\max\_i}}{\tilde{Q}_{WF\_max}} \tilde{Q}_{WF\_ref} \quad (50)$$

The total power generated by each wind turbine is expressed as:

$$P_{WG\_i} = P_{s\_i} + \mathrm{P_{t\_i}} \quad (51)$$

$$Q_{WG\_i\_} = Q_{s\_i} + \mathrm{Q_{t\_i}} \quad (52)$$

$$P_{s\_ref\_i} = P_{WG\_ref\_i} - P_{r\_i} \quad (53)$$

$$P_{t\_ref\_i} = P_{r\_i} - P_{c\_ref\_i} \quad (54)$$

With:

$$P_{c\_ref} = \tilde{V}_c i_{c\_ref} \quad (55)$$

$$P_r = V_{rd} i_{rd} + V_{rq} i_{rq} \quad (56)$$

We impose $\cos\varphi = 1$ on the grid converter ($Q_{t\_ref\_i} = 0$), therefore we obtain:

$$Q_{s\_ref\_i} = Q_{WG\_ref\_i} \quad (57)$$

The estimation of the maximum active and reactive powers is expressed as follows:

$$P_{WG\_\max\_i\_} = P_{aéro\_i\_} \quad (58)$$

$$Q_{WG\_\max\_i} = Q_{s\_\max\_i} + Q_{t\_\max\_i} \quad (59)$$

The maximum production capacity of the reactive power $Q_{t_\max}$is given according to its diagram (P_t, Q_t). The latter depends mainly on the continuous bus voltage, the used modulation technique, the nominal current of the switches and the converter design [7]. Similarly, in order to analyse the power exchange and the maximum DFIG reactive power estimation, the reactive power production limitation is studied in the light of the various constraints namely the stator current, the rotor current, the rotor voltage and stability in steady regime [8,9].

3. Supervision Algorithm Based on the Proportional Distribution of the Power References

In order to better distribute the production of the reference reactivate power within a wind turbine, a local supervision algorithm of the latter was proposed. It makes it possible to distribute the reactive power between the DFIG stator and the grid converter in a coordinated way. Three operating modes of the system were considered [6,10].

- Mode 1 (Delta):

For the reserve power operating mode, the wind farm functions below its maximum active power production capacity $0 < Q_{WF\_ref} < Q_{WF\_\max}$. In this case, the grid converter and the DFIG stator contribute in a coordinated way to compensate the required total reactive power $Q_{WG\_ref\_i}$. The proportional distribution strategy is used to calculate the reference reactive powers for the grid converter $Q_{t_ref_i}$and the DFIG stator $Q_{s\_ref\_i}$.

- Mode 2 (MPPT):

This mode corresponds to a weak electric production case. The wind turbine delivers its maximum active power production to the electrical network. In this case, the grid converter compensates for the totality of the required reference reactive power and the DFIG stator is used to produce only active power.

$$Q_{\mathrm{t\_ref\_i}} = Q_{WG\_ref\_i} \quad (60)$$

$$Q_{s\_ref\_i} = 0 \quad (61)$$

If:

$$Q_{t\_ref\_i} < Q_{WG\_ref} < Q_{WF\_\max} \quad (62)$$

So we obtain :

$$Q_{\mathrm{t\_ref\_i}} = Q_{t\_max\_i} \quad (63)$$

$$Q_{\mathrm{s\_ref\_i}} = Q_{WG\_ref\_i} - Q_{\mathrm{t\_max\_i}} \quad (64)$$

- Mode 3 (Fault):

This control mode is applied when the electrical network is defective (a voltage dips, a short circuit, frequency perturbation). The shorts-circuit crow bar, the DFIG rotor and the grid converter function as a STATCOM to compensate for the required reactive power, within the limit of its maximum reactive production capacity.

$$Q_{\mathrm{t\_ref\_i}} = Q_{WG\_ref\_i} - Q_{s\_mes\_i} \quad (65)$$

$$Q_{\mathrm{s\_ref\_i}} = Q_{s\_mes\_i} \quad (66)$$

Figure 6 presents the proportional distributed algorithm:

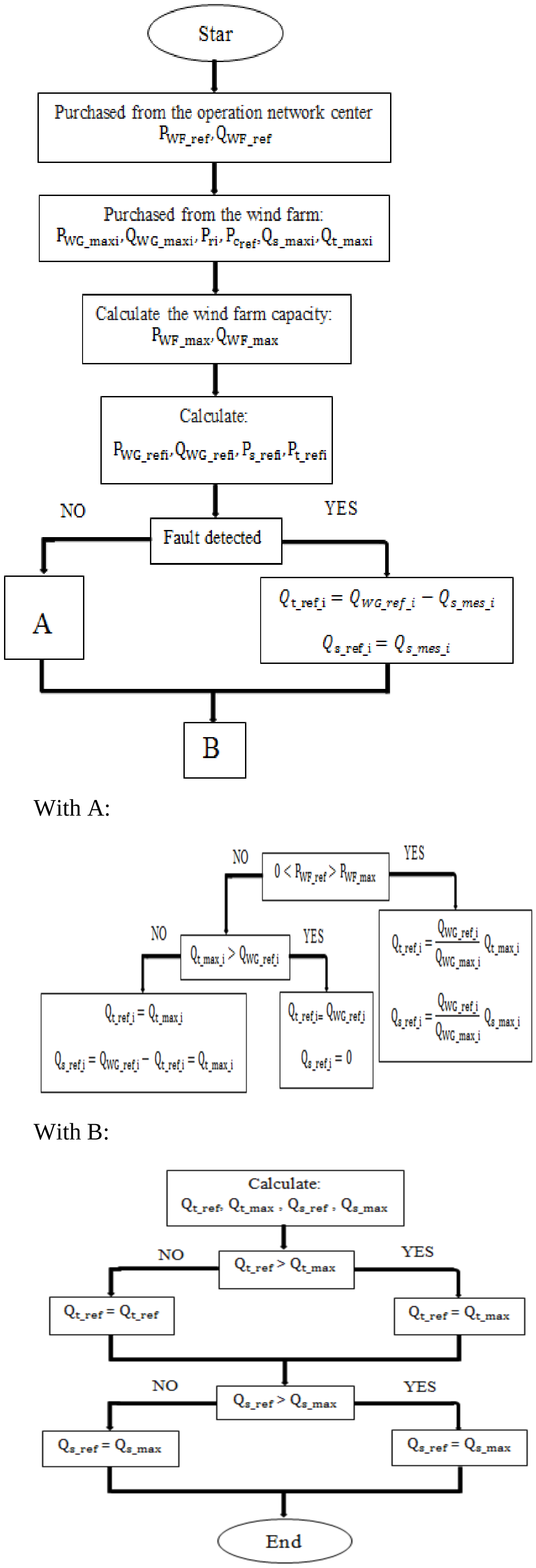

Fig.6. Proportional distributed algorithm

4. Simulation Results and Discussion

Our objective in this part is to validate the proportional distribution algorithm for the supervision of the active and reactive powers of a wind farm connected to the grid. We consider three wind turbine based on DFIG which undergo three wind profiles. Indeed, our power system is simulated under Matlab/Simulink connected to a DSP TMS320f28027 whose algorithm is integrated to calculate and send the power references to each of the three wind turbine conversion system in the various network operating modes. In this context, our system simulates the operation of the farm according to a plan of active and reactive powers imposed by the network manager. This control algorithm presents at the same time the central supervision and the local supervision of the wind farm. Concerning the first technique, the total control of the active and reactive powers of the farm is ensured according to an hourly production plan required by the network manager. On the other hand, the local supervision technique ensures the analysis of the power transfer from the wind farm and considers the maximum DFIG reactive power for each wind turbine within the production limits.

In our study, we deal with the case where the wind farm goes through two power control modes i.e. the MPPT and the fault operating modes. First, we deal with the first mode, the wind farm functions in "MPPT" mode to provide its maximum active power to the network. A detailed analysis shows that the grid converter compensates for the totality of the required reactive power because this one is lower than the maximum reactive power that it can generate when the DFIG stator produces only active power. In order to ensure the active power supervision according to the network manager's data, presents in the **Fig.7**, a disconnection of the first wind turbine occurred during $t \in [30s\ 44s]$, in the same way the second wind turbine was disconnected during $t \in [20\ 22]$ and $t \in [102\ 128]$. Finally the third wind turbine during $t \in [54s\ 70s]$ and $t \in [130s\ 148s]$, which led with the cancellation of its production. The supply of energy necessary for the load is thus assured by the two other wind turbines. Consequently, the powers generated by the wind farm always followed their references. Indeed, during the first period (t<150s) the reactive management was governed by the proportional distribution algorithm to distribute the reactive power to the three wind turbines of the farm. In the second case, an unpredicted mode called "fault" mode occurred, which simulated an electrical network failure. Indeed, at the moment t=150s a short-circuit occurred, the DFIG stator of the wind turbines remained connected to the network by absorbing active and reactive powers, while the rotor was short-circuited by the crow-bar, the latter functions as a motor by absorbing active and reactive powers.

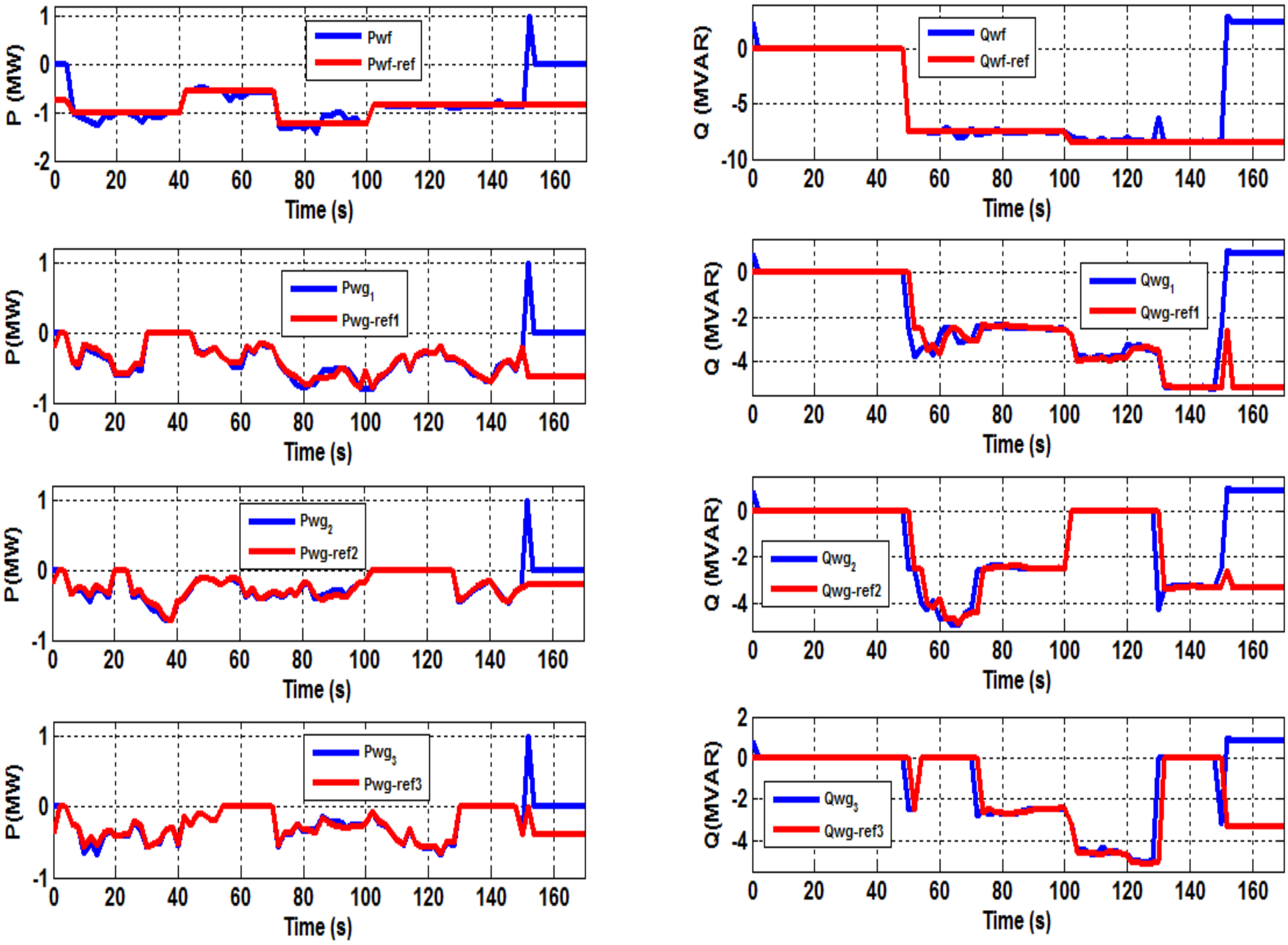

Fig.7. Simulation results of the centralized supervision power

Thus we can say that the compensation of the reactive power is only assured by the grid converter within its maximum capacity limit, and in this case, it functions as a STATCOM. So, we deduce that our power system does not take part in the supply of the reactive power.

According to **Fig.7**, we note that the first wind turbine has the greatest active power production capacity, thus it accepted the highest active power reference and the weakest reactive power reference. On the other hand, the second wind turbine with the greatest reactive power production or consumption, received the weakest active reference power and the highest reactive power reference.

5. Conclusion

This article presents an active and reactive powers supervision algorithm in a wind farm. In order to supervise the active and reactive powers, a centralized supervision algorithm ensuring a proportional power distribution was implemented. Thus, it ensures the wind farm operation without saturation because their power references are defined within their maximum production capacity. Indeed, it attributes the highest power references to the wind turbines with the greatest production capacity. An analysis of the powers exchanged between the grid and the wind turbine was carried out in order to estimate the maximum production capacity of the active and reactive powers of each wind turbine and, consequently, of the wind farm. This estimation allows a correct operation of the implemented algorithm. A local reactive power algorithm was proposed for each wind turbine in order to coordinate the distribution of the reactive power references between the DFIG stator and the grid converter. This added reactive compensation flexibility for the wind farm by considering three operating modes. Eventually, the simulation results of different operating modes were presented in order to show the validity of the algorithm used for the centralized power supervision of the wind farm and also to confirm the advantages of the proposed local supervision algorithm.

References

[1] J. Zhao, X. Li, J. Hao, J. Lu, “Reactive power control of wind farm made up with doubly fed induction generators in distribution system” Electric Power Systems Research, Elsevier, vol. 80, no. 06, pp. 698-706, June 2010.

[2] T. Ghennam, B. Francois, E.M. Berkouk, "Local supervisory algorithm for reactive power dispatching of a wind farm", 13th European Conference on Power Electronics and Applications (EPE 2009), Barcelona, Spain, 5-8 September 2009.

[3] W. Ouled Amor, A. Ltifi, M. Ghariani "Study of a wind energy conversion systems based on double fed induction generator'', IREMOS, Vol 7, N 4, August 2014

[4] A. Beugniez, T. Ghennam, B. François, E. M. Berkouk, B. Robyns, "Centralized supervision of reactive power generation for a wind farm", 12th European conference on power electronics and applications (EPE 2007), Aalborg, Denmark 02-05, September 2007.

[5] A. Ahmidi "Participation de parcs de production éolienne au réglage de la tension et de la puissance réactive dans les réseaux électriques", Thèse de doctorat en génie électrique de l'Ecole Centrale de Lille, pp. 1-200, décembre 2010.

[6] P. Cartwright, L. Holdsworth, J.B. Ekanayake and N. Jenkins, "Co-coordinated voltage control strategy for a Doubly Fed Induction Generator (DFIG)-based wind farm", IEE Proceeding, generation, transmission and distribution. vol. 151, no.4, pp. 495-502, July 2004.

[7] J. Fortmann, M. Wilch, F. W. Koch, I. Erlich, "A Novel Centralized Wind Farm Controller Utilising Voltage Control Capability Of Wind Turbines", 16th PSCC, Glasgow,Scotland, July 14-18, 2008.

[8] A. D. Hansen, P. Sorensen, F. Iov, F. Blaabjerg, "Centralised power control of wind farm with doubly fed induction generators", Renewable and Sustainable Energy, vol. 31, no. 07, pp. 935–951, 2006.

[9] Y. Li, Y. Cao, Z. Liu, Y. Liu, Q. Jiang, "Dynamic optimal reactive power dispatch based on parallel particle swarm optimization algorithm", Computers and Mathematics with Applications, vol. 57, no. 11-12, pp. 1835-1842, 2009.

[10] A. Beugniez, "Supervision centralisée du réglage de la puissance réactive d'un parc d'éoliennes reliée sur le réseau de haute tension", Master recherche en énergie électrique et développement durable, 2006.

Nomenclature

P_v	kinetic power (KW)
λ	tip speed ratio
β	pitch angle (°)
C_p	power coefficient
S	area blade (m^2)
R	blade radius (m)
ρ	air density ($\rho = 1.22\ kg/m^3$).
V	wind speed (m/s)
C_{aero}	aerodynamic torque
Ω_t	Mechanical turbine speed (rad/s)
G	multiplication ratio
C_{em}	electromagnetic torque
C_{vis}	viscous friction torque
C_{mec}	mechanical torque
Ω	rotational speed (rad/s)
C_g	speed multiplication torque
f	viscous friction coefficient
j	inertia ($kg.m^2$)
V_{sdq}	d and q components stator voltages (V)
V_{rdq}	d and q components of the rotor voltages (V)
i_{sdq}	d and q components stator currents (A)
i_{rdq}	d and q components rotor currents (A)
ϕ_{sdq}	d and q components stator flux (Wb)
ϕ_{rdq}	d and q components rotor flux (Wb)
R_s, R_r	stator and rotor winding resistance (Ω)
W_s, W_r	stator and rotor pulse (rad/s)
L_s , L_r	stator and rotor winding inductance (H)
M	mutual inductance (H)
p	number of poles
V_{Gdq}	d and q grid voltage (V)
P_s, P_r	stator and rotor active power (KW)
Q_s, Q_r	stator and rotor reactive power (KVAR)