3rd International Conference on Automation, Control, Engineering and Computer Science (ACECS'16)
Proceedings of Engineering & Technology (PET)
pp. 510-521

Study of wind speed's Impact on the aero generator output energy quality

Yahia Saoudi and Hsan Hadj Abdallah

Control and Energy Management Laboratory (CEMLab), ENIS, Sfax, Tunisia

saoudi.yahia@gmail.com

hsan.haj@enis.rnu.tn

ABSTRACT

The wind power production is scattering in many countries. However, the primary natural source, the wind, can revolutionize from constant to variable speed operation. For this reason, it is fundamental to find solution permitting the continuity of extracting wind power, guaranteeing all grid performance and improving the efficiency of both wind systems and grid. This paper presents an achievable method, which guarantees a best energy quality despite the wind variation. The mean idea is to insert an adequate reactive power compensator in the system. The proposed method has been validated by simulation with justification and rationalization the stability of the grid parameters. The study is done in real situations and with ordinary natural conditions. Indeed the selection of this method is based on many results of other research done in the same topics. However, the previous methods have demonstrated their limits under such our natural study conditions. The electric producer faces till now some problems, in frequency and voltage amplitude, despite using the classic method. The current study is available in onshore and even in offshore wind turbine farms and gives quite important stability results. Further these conditions, the present simulation contains some storms wind level. Despite these circumstances, the global system rests in stable state guaranteeing referenced power level.

Keywords: Wind Energy, Double Fed Induction Generator, Variable wind speed, Wind Turbine, STATCOM.

1. INTRODUCTION

The development and use of renewable energy has grown substantially in recent years. In the future, sustainable energy system will be based on the rational use of traditional sources and increased use of renewable energy. Naturally decentralized production, it is interesting to use at the place of consumption, transforming directly to heat or electricity as needed. Decentralized production of electricity from renewable energy sources provides greater security of supply for consumers as well as respecting the environment. However, the random nature of these sources requires us to develop design rules and use of these systems to operate in the best conditions [1, 2]. Several countries have already resolutely turned towards the wind using aero generator as system conversion. Such as the case of Germany, a world leader in installed wind power capacity of 23,903 GW followed by Spain in the European Union with 16,740 GW [1-3].

The benefit of wind energy and extracting free power is faced by an important problem, the variation of wind speed. To clarify this dilemma and its effects on our electric systems, the amplitude of voltage also frequency value, the generated power will be not suitable for using. But these two magnitudes are in forced link to the rotor speed. Consequently, they are in dependence to the wind speed. In the literature, there is a substantial research to get rid of this problem. The references [4-7] look to find solution by refining geometrical blades' form of wind turbine, this is really solution used for profitable improving of the global system. Thus the quality of produced power will be not touched as well as we hope. Referring to [8], the dilemma is treated differently. Author used some reactive sources compensator. Fairly, the coherent solution is around the injected and consumed powers. The limit of this method is the selection of source itself. The compensator must intervene taken in consideration the voltage amplitude evolution as well as frequency value of the grid. The author of reference [8] treated this problem by using synchronous generator to inject reactive power into the grid. But this method has another limit which is the transient in active power, due to suddenly variation, so perturbation especially in voltage amplitude will persist. This is very clear in his figures and understandable from his simulation results. In references [9-11], authors proposed an indirect voltage and frequency control achieved by controlling the stator flux while neglecting the stator resistance and imposing slip frequency to the rotor currents through an algebraic relationship. This estimation is not practical only for powerful generator, about his neglecting, also under fixed wind speed condition, about the slip, which is not usually spare. Another method consists to integrate a battery of capacity in transmission lines. However, this method can compensate reactive power but with graduate steps. The usage of this simplest method causes unlikely a kind of voltage amplitude degradation later on frequency value.

The global system wind turbine-generator must be able to provide the users with regulated voltage amplitude and frequency. According to references [9, 12-13] and in these cases, wound rotor induction machines (WRIM) present several advantageous characteristics working at variable speed while regulating the generated voltage and frequency.

So, we interest in this paper to evaluate the study of Wind Energy Conversion System (WECS) with the Doubly Fed Induction Generator (DFIG) works with grid operation under very variable wind speed condition. This situation shoves the turbine to produce very variable level of power. Under these circumstances, the amplitude of produced voltage as well as the value of frequency will not be stable, due to dips or pikes in power. The proposed solution makes turbine under different and real wind speeds, to generate electric power with simple turbine control, for safety reasons. In this case, the most practical and efficient device is the STATCOM, and may be some similar devices. Thus, stabilization of the produced power for the reason to stabilize voltage amplitude and frequency value is done by an integration of STATCOM devise. All simulations are done in the previous natural conditions. The method is based on the measurement of voltage and reactive power of the wind-turbine generator and the grid side, a control decision is taken to generate or absorb power transferred between the system and the grid by the STATCOM. In the case of pikes in voltage, the devise absorbs the reactive power, otherwise it compensates it by a re-injection into the grid. In the past, the controller made decision to disconnect the turbine from the grid when the wind is very variable. The main cause of this disconnection is based on the power flow measurement between the wind turbine and the grid and the perturbation due to this wind state. The power flow between wind turbine and the grid depends upon the availability of the wind.

The paper is organized as follows. In Section 2, we start by the global system configuration. We start with a detailed study applied to the wind turbine. The mathematical model of turbine used in this paper in order to simulate and to extract results. In Section 3, we discuss most used generator applied in wind turbine systems, which is the DFIGURE We introduce the global mathematical model written two axes frame. Section 4 treats the STATCOM device and an example from its various kinds. Section 5 gives the simulation results that we find by these previous mathematical models. Conclusions and perspectives are given in Section 6.

2. SYSTEM CONFIGURATION

Nowadays, the exploitation of wind to extract electric power is in progress. This extraction is based on large wind turbines. It can function on variable wind speed. To be in wished operation, the turbine must be regulated with pitch angle controls which are most of the major widespread wind turbines. They generally make use of a direct-driven synchronous generator (without gearbox) or a doubly fed induction generator (DFIG). In particular, DFIGs are very popular since the power electronic equipment only has to handle a fraction of the total system power.

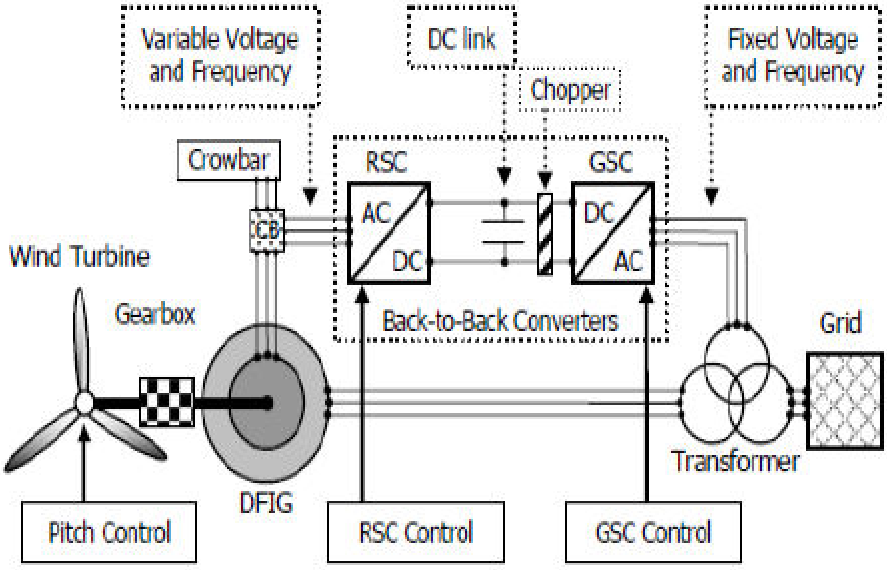

Figure 1. Global system aero generator- Grid

Therefore, in this paper a power system consisting of a wind turbine with a doubly fed induction generator connected to a three-phase grid has been considered without reactive compensator, as shown in. The stator of the induction generator is directly connected to the grid, while the rotor winding is connected via slip rings to a converter [14].

2.1. Wind turbines characteristics

The electric power extracted from a wind turbine is a function of the wind power available, the power curve of the generator and the ability of the machine to react to wind variations. The power and torque extracted from the wind can be expressed as [15]:

$$P_W = \frac{1}{2}\rho C_p(\lambda,\beta)AV_W^3 \tag{1}$$

$$T_W = \frac{P_W}{\omega_r} = \frac{1}{2}\rho C_T(\lambda,\beta)r_m AV_W^2 \tag{2}$$

Where:

$$C_p = 0,44(\frac{125}{\lambda_i} - 6,94)e^{-\frac{16,5}{\lambda_i}} \tag{3}$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda} + 0,002} \tag{4}$$

According to reference [15], the previous relations (3) and (4) are applied for the fixed wind speed and for variable wind speed we use these two ones (5) and (6):

$$C_p = 0,22(\frac{116}{\lambda_i} - 0,4\theta_p - 5)e^{-\frac{12,5}{\lambda_i}} \tag{5}$$

$$\lambda_i = \frac{1}{\lambda + 0,08\theta_p} + \frac{0,035}{\theta_p^3 + 1} \tag{6}$$

Where P_w is the mechanical power extracted by turbine applied to rotor in (W), T_w is the torque of turbine (N m). The V_w is the wind speed in (m/s), $A=(\pi r_m)^2$ the wind rotor swept area (m^3) and ρ is the air density in (kg/m^3). The rotor angular velocity is expressed by $\omega_r=\lambda V_w/r_m$ in (rad/s), r_m the turbine radius (m),C_p the rotor power coefficient, the percentage of the kinetic energy of the incident air mass that is converted to mechanical energy by the rotor (maximum value Betz's limit 59.3%) [14]. C_T the torque coefficient, C_p and C_T are non-linear function.

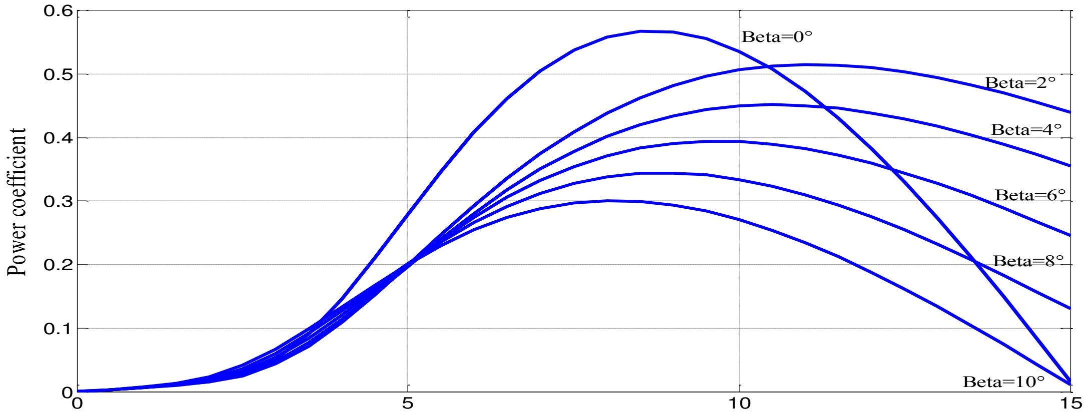

Figure 2. Evolution of power coefficient with rotor speed

A wind turbine is a wind driven turbine. Since the last century, wind sensor technology has continued to evolve. In the early forties that real prototype wind turbine air foil blades were used with successfully to generate electricity [2]. It is sized to develop a nominal power Pn from a nominal wind speed Vn. For winds speeds above Vn, the global system (wind turbine) must modify its aerodynamic parameters. The main object of this modification is to avoid any mechanical overloads, so that the power recovered by the turbine does not exceed the nominal power for which the turbine was designed. There are other dimensioning variables, Vmin the wind speed at which the turbine begins to supply power and Vmax the maximum wind speed beyond which the turbine must be stopped in order not to be damaged [1-2]. They are divided into two main categories: those with a vertical axis and those with axis horizontal.

The most common wind energy in our land is wind turbine with several MW, with three blades, horizontal axis, with a speed multiplier and power control pitch type by adjusting the angle of the blades. It is controlled by an industrial PLC and monitoring remotely software type «SCADA». To start, the hydraulic brake is released, the blades are moving and then the turbine starts to rotate with just wind effect. When the rotational speed is sufficient the wind turbine will be connected for electric energy production to an electric network.

On the other hand, like any power plant, the wind turbine has an auxiliary set consuming at operation and shutdown from 0 to about 1% of its nominal power. Wind turbines have a given wind range of operation, typically between 3 and 25 m/s, the power increases with wind speed until it reaches a nominal level. In this range (in kWm/s), we multiply the statistical distribution of wind, which for most sites can be modeled very well with a Weibull statistical distribution.

Between the tropics in the corridors wind in some good windy coasts or in specific corridors wind, wind turbines can generate electricity up to 99 % of the time. In inland areas, the production time varies between 6000 and 8000 hours per year. The state of the art of wind exceeds average 95-97%, reaching 99% per year on sites where the wind is more constant.

A wind turbine cost to purchase is between 1000 and 1500 € / kW depending on various factors, operation and maintenance around of 40 € / year / kW installed, and it has an average life expectancy of 20 years. The rate of acquisition of onshore wind kWh in France is guaranteed for ten years around 83 € / MWh (2009) and it is seen between 28 and 82 € / MWh. In Europe, the redemption rate varies between 50 MWh and 110 € [16].

2.2. Pitch control systems

There are various types of systems for controlling the pitch angle of the blades. The pitch angle is controlled either by rotating masses using centrifugal forces or by a hydraulic system or electric motors that require an external energy source [17]. The transfer of energy to the rotating blades significantly increases the manufacturing costs. The hydraulic system is still the most widely used in small and medium wind turbines power. However, the electric system is only used for very large wind turbines. The controller is adapted either for calibration of all the blades or on behalf of each of them independently. This independent regulation gives more degrees of freedom to the control system. The exploitation of these additional degrees of freedom is being studied by researchers [18].

The independence in blade pitch angle regulation is an important innovation that will introduce more intelligence in the control system of wind turbines. This independence may be the cause of danger. The risk that can be engendered is an imbalance aerodynamic lead applied to the turbine. An accurate system for measuring the angular position is, therefore, used to ensure that the setting angle of each blade is the same.

Many couples are involved in the study of dynamic control system of the pitch angle of blades [17]. The representation of these couples requires modeling the structural dynamics of the blade, the behavior of the air around the blades or the inclusion of friction in bearings. By giving these observations, it is decided to approach the control loop of the rate of change of the pitch angle by a linear first order system containing dynamic main defined by the time constant.

3. Asynchronous generators

In the field of wind power generation, the asynchronous squirrel cage machines still dominate in the current uses especially in motor mode. The reasons of this domination refer to simplicity in construction, the cost of maintenance and simplicity in command the motor mode as well as generator. The integration of this one to wind turbine seems directly connected to the network. But when it comes to make a variable speed drive, they rather prefer machines wound rotor doubly fed that offer excellent performance.

3.1 DFIG modeling

The doubly fed induction machine is one from the various types of electric machines. Looking to the reversibility of these kinds of systems, the doubly fed induction machine can be a power electric producer, in this mode it is called Doubly Fed Induction Generator (DFIG).

The studying of this generator starts as every kind of system with the mathematic model. For simplification reasons, the equations will be in two axes frame (dq). The voltage stator and rotor equations are given as following:

$$\begin{cases} v_{ds} = -R_s i_{ds} + \dfrac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \\ v_{qs} = -R_s i_{qs} + \dfrac{d\varphi_{qs}}{dt} + \omega_s \varphi_{ds} \end{cases} \tag{7}$$

$$\begin{cases} v_{dr} = -R_r i_{dr} + \dfrac{d\varphi_{dr}}{dt} - (\omega_s - \omega_r)\varphi_{qr} \\ v_{qr} = -R_r i_{qr} + \dfrac{d\varphi_{qr}}{dt} + (\omega_s - \omega_r)\varphi_{dr} \end{cases} \tag{8}$$

The fluxes produced by windings of the stator and rotor are present with these relations:

$$\begin{cases} \varphi_{ds} = -L_s i_{ds} - L_m (i_{dr} + i_{ds}) \\ \varphi_{qs} = -L_s i_{qs} - L_m (i_{qr} + i_{qs}) \end{cases} \tag{9}$$

$$\begin{cases} \varphi_{dr} = -L_r i_{dr} - L_m (i_{dr} + i_{ds}) \\ \varphi_{qr} = -L_r i_{qr} - L_m (i_{qr} + i_{qs}) \end{cases} \tag{10}$$

The global mathematic model is given by these equations:

$$\begin{cases} \dfrac{d\varphi_{ds}}{dt} = \omega_{dq}\varphi_{qs} - \dfrac{1}{\tau_s}\varphi_{ds} + \dfrac{M}{\tau_s} i_{dr} + v_{ds} \\ \dfrac{d\varphi_{qs}}{dt} = -\omega_{dq}\varphi_{ds} - \dfrac{1}{\tau_s}\varphi_{qs} + \dfrac{M}{\tau_s} i_{qr} + v_{qs} \\ \dfrac{di_{dr}}{dt} = -\beta\omega_r\varphi_{qs} + \dfrac{\beta}{\tau_s}\varphi_{ds} + (\omega_{dq} - \omega_r) i_{qr} - \gamma i_{dr} - \beta v_{ds} + \dfrac{1}{\sigma L_r} v_{dr} \\ \dfrac{di_{qr}}{dt} = \beta\omega_r\varphi_{ds} + \dfrac{\beta}{\tau_s}\varphi_{qs} - (\omega_{dq} - \omega_r) i_{dr} - \gamma i_{qr} - \beta v_{qs} + \dfrac{1}{\sigma L_r} v_{qr} \end{cases} \tag{11}$$

Where:

$$\sigma = 1 - \frac{M^2}{L_s L_r}, \tag{12}$$

$$\beta = \frac{1-\sigma}{M\sigma}, \tag{13}$$

$$\tau_s = \frac{L_s}{R_s}, \tag{14}$$

$$\tau_r = \frac{L_r}{R_r}, \tag{15}$$

$$\gamma = \frac{1-\sigma}{\sigma\tau_s} + \frac{1}{\sigma\tau_r}, \tag{16}$$

During recent years, the sizes of installed wind parks have grown in all over the world. The generated power produced by these sources cannot be looked as small power generators. This considerable power must be sent to the grid. While voltage amplitude and frequency depend respectively to reactive and active powers injection or absorption, their effect while connecting to the grid cannot be neglected [20]. The behavior of wind parks in normal operation may cause dips of voltage in the grid, exceeding frequency limits and voltage amplitude perturbation. The primordial reason of this problem is variable wind speed. In the first hand, the way out is to treat the steady state performance of the wind park. In the other hand, it is to contribute to voltage control by injecting reactive power. The voltage controller must have dynamic performance to overtake balanced or unbalanced voltage dips [21].

4. STATCOM

The STATCOM is a static synchronous compensator. It is also known as a static synchronous condenser STATCON. It is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act also as a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power.

Response of STATCOM

Usually a STATCOM is installed to control and regulate electricity networks that have a poor power factor and often poor voltage regulation. The most common use is for voltage stability. A STATCOM is a voltage source converter (VSC)-based device, with the voltage source behind a reactor. The voltage source is created from a DC capacitor and therefore a STATCOM has very little active power capability. This active power capability can be increased if a suitable energy storage device is connected across the DC capacitor.

The reactive power produced by the STATCOM depends on the amplitude of the voltage source. If the terminal voltage of the VSC is higher than the AC voltage amplitude at the point of connection, the STATCOM generates reactive current. However, when the amplitude of the voltage source is lower than the AC voltage amplitude, it absorbs reactive power. The response time of a STATCOM is shorter than that of an SVC. This character is mainly due to the fast switching times and period commutation provided by the IGBTs of the voltage source converter.

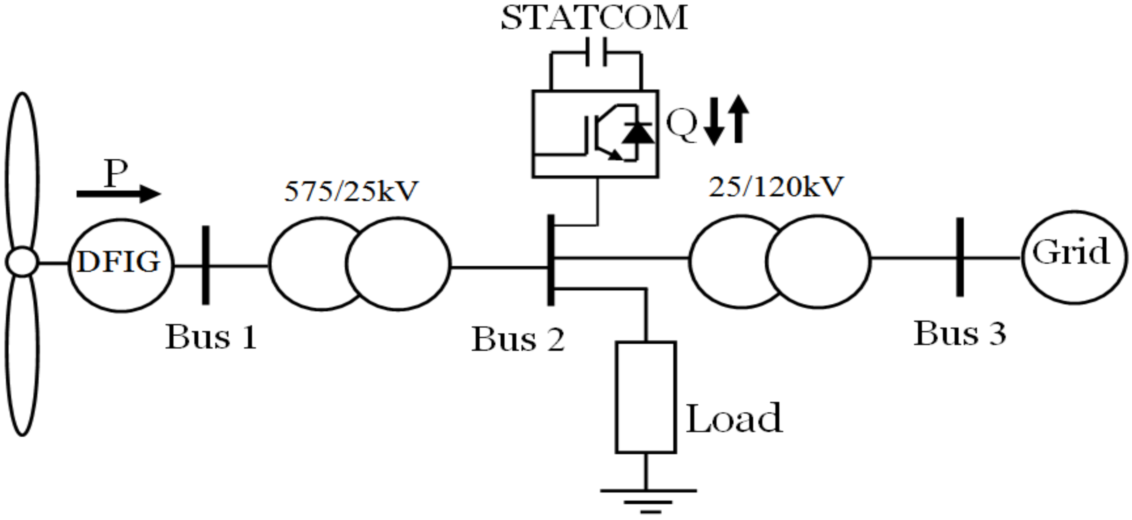

Figure 6. Power transfering between systems' parts

The STATCOM also provides better reactive power support at low AC voltages amplitude than an SVC.

The simulation is done as presented in figure 6. The consumption or generating of reactive power by STATCOM is linked to voltage amplitude variation. While the latter is related indirectly to wind speed, so its improvement needs the adequate FACTS device.

4.1. Modeling STATCOM

The Static Synchronous Compensator (STATCOM) is shunt connected reactive compensation equipment. It is capable to generate or absorb reactive power. The switching mode between generating and absorptions can be varied so as to maintain control of specific parameters of the electric power system.

The STATCOM provides operating characteristics similar to a rotating synchronous compensator, (as well as synchronous motor or synchronous generator), without the mechanical inertia [22]. The STATCOM provides rapid controllability of the three phase voltages, both in magnitude and phase angle. The STATCOM basically consists of a step-down transformer with a leakage reactance, a three-phase GTO or IGBT voltage source inverter (VSI), and a DC capacitor.

The injected powers from STATCOM in the grid are given by the equations (17):

$$\begin{aligned} P_{inj} &= V_i(i_d \cos(\theta_i) + i_q \, sin(\theta_i)) = V_d i_d + V_q i_q \\ Q_{inj} &= V_i(i_d \, sin(\theta_i) - i_q \cos(\theta_i)) = -V_d i_d + V_q i_q \end{aligned} \quad (17)$$

Where i_d and i_q are the reference d and q axis currents of the ac system. The control variables are the current injected by the STATCOM and the reactive power injected into the system.

5. Simulation results

In this paper, we have used very variable wind speed. Its amplitude of is real and may get some storm speed's values. The object is to taste performance and the adaptability of the proposed method. In this section, we illustrate all important figures. We start by the presentation of wind turbine without STATCOM connected to the grid and its effect under very variable wind speed. This figure 7 shows clearly the impact of wind speed variation on the produced power. Indeed, when the speed of wind decreases, it means that the primary power drops with time.

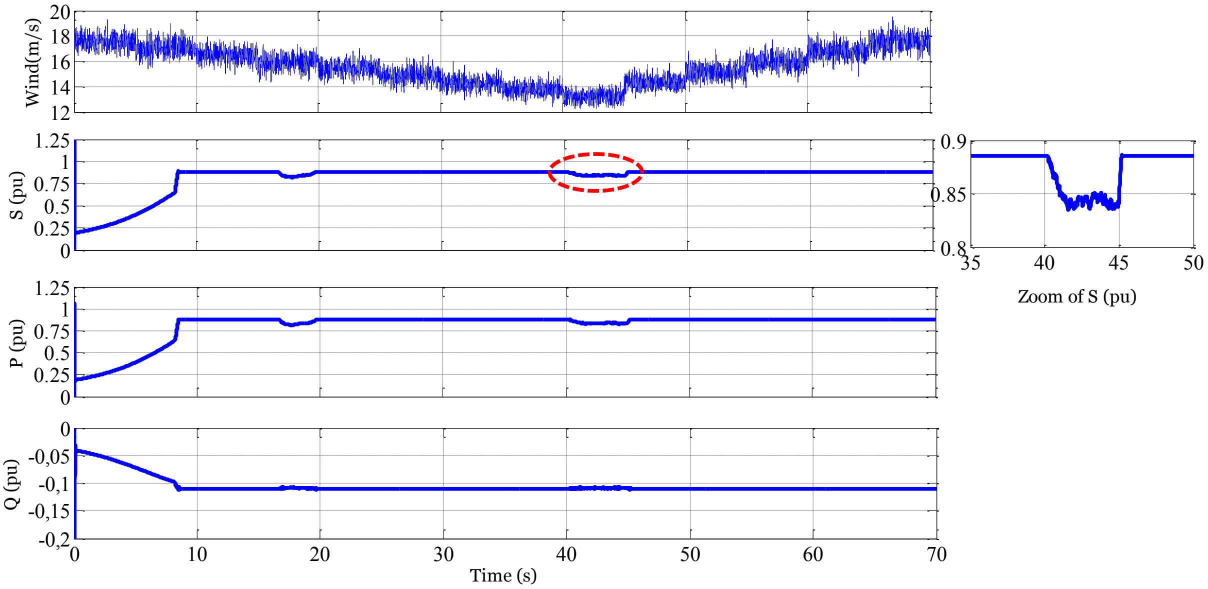

Figure 9. Evolution of different powers with wind variation

Consequently, the converted physical magnitude power (wind power) to electric power will decrease too. While this latter is the image to mechanical one, so the generated power by the machine, which is the active one, will has the same evolution as rotor speed. To more clarify figures, we make zoom where red ellipse and the zoomed figure is the follow one.

Looking to the figure 8, it is understandable that the generated active power is in forced link to the rotor speed. According to these results, three important remarks must be indicated. The first one is the sensibility of the generated power to the wind variation. From 22min to 32min the wind speed ratio makes a deep, the produced power makes the same thing too. The following figure shows clearly the level of power dropping. This response of power may be explained by decreasing of primary power which is the wind power. The second remark is absorption of the reactive power by the generator given from the grid.

This consumption is the cause of negative sign. The value of this magnitude is about tithe of nominal generator power. The third remark is the domination of active produced power than the reactive one. This property is very specially for this kind of generator, from here we can deduce that the DFIG is an active power generator comparing with synchronous one.
The increase of pitch angle is done to maximize contact area between blades and wind, so to maximize the absorbed power from wind, but this impracticable looking to the decrease of the wind power itself. As consequence, the active power drops too.

For this reason and if the wind stills in drooping, the generator will turn off, so the reduction in fluxes that means reduction in consumed reactive power, as we see reactive part figure.

Despite the existence of pitch angle controller, the rotor speed persists in right condition of generating mode but the depth in produced power is shown in the figure 8. The outcome of this profundity is instability in voltage amplitude also in frequency value too. Consequently, the pitch controller cannot assure stability in powers by access to blades angle, so the necessity to another device.

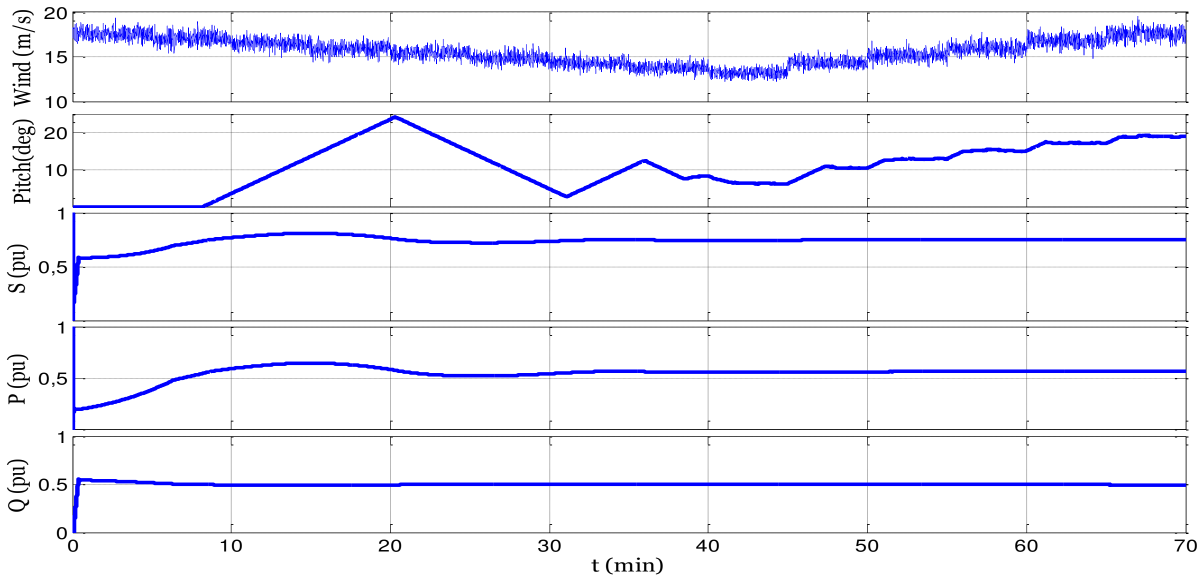

Figure 12. The stabilization of produced powers with wind speed variation

The figure 10 shows the evolution of produced powers by the aero generator. It is remarkable, comparing with the figure 8 for instance, that the reactive power will be not negative as in the seventh figure. Besides, the depth shown in active power, the image of rotor speed, is vanished. So, the stability in voltage amplitude and frequency will in secure.

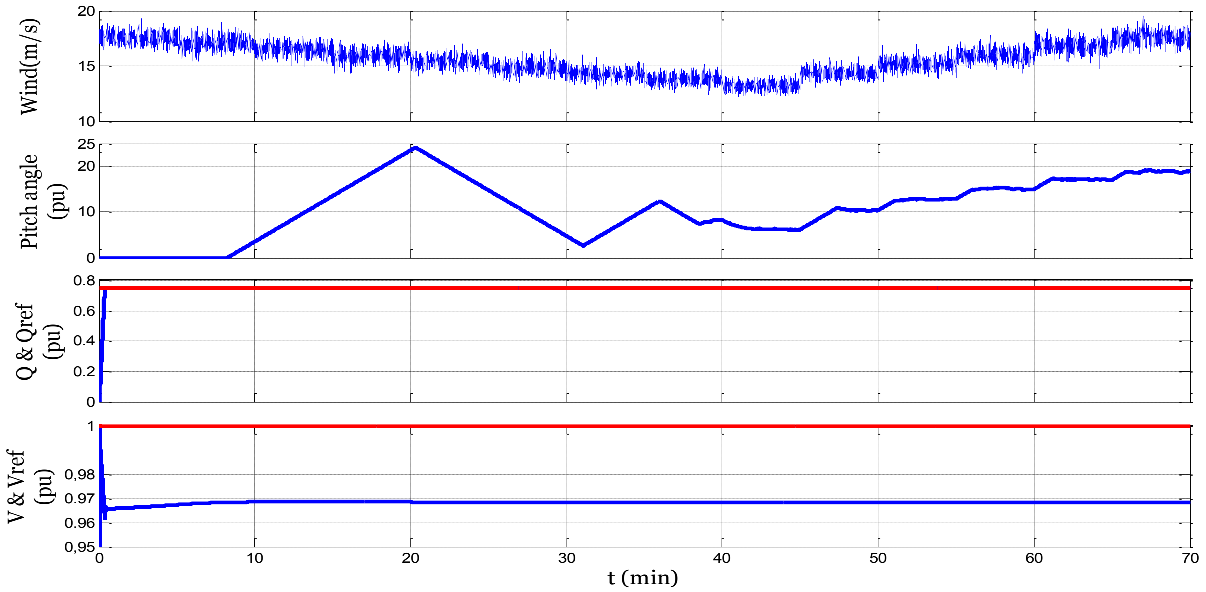

Figure 14. Stability of produced voltage despite wind speed variation

Indeed the amplitude of produced voltage is in powerful relationship with rotor speed. This relation can be justified by Lenz formula. Despite this link, the figure 12 indicates a very stable produced voltage. This stability persists even with variable wind speed. This faithfulness in voltage amplitude and its reference even in reactive power and its reference is solved by the adequate device used for regulation. It is possible that the dilemma noted previously is solved. The aim object guarantees this result is the right time for switching STATCOM's mode form reactive consumer or producer and inversely.

6. CONCLUSION

A simple method for voltage regulation applied in wind farm, to extract energy with induction generator, is described in this paper. Further, extraction of electric power may be improved using rotor windings. The access to this system is possible by double fed induction generator than any other generator. In addition, it is susceptible to exploit rotor's power. However, the wind's speed is very variable. The main object treat in this paper is how to gain wind power without any grid perturbation. The discussed solution is less costly, easier and very practical traditional ones. Using the MATLAB software, it's shown that impact of wind speed variation does not cause any voltage dips or transit in the grid. However, control systems for variable speed wind turbines should continue to evolve towards more and more effective and innovative control systems. This method may need to traditional sensor for power tracking control. Therefore, the global system wind generators-grid is proposed and tested for variable speed wind in the present paper, with guarantee stability and performance of the global system. The integration of squirrel cage generator and other FACTS device will the aim of next paper.

REFERENCES

1. J. WILKES, J. MOCCIA, The European Wind Energy Association, EWEA Wind in power 2012 European statistics, *(February 2013).*
2. L. LOUZE Decentralized Production of Electricity, Modeling and Control of a Self Excited Asynchronous Generator, *(University Mentouri, Constantine, Republic of Algeria, 2010).*
3. S. SIDEC, Industrial Corporation for the Development of Energy and Cogeneration, *(Document 2009).*
4. G. SIEROS, P. CHAVIAROPOULOS, J. D. SØRENSEN, B. H. Bulder and P. Jamieson Upscaling wind turbines: theoretical and practical aspects and their impact on the cost of energy, *Wind Energ. 2012; 15:3–17, DOI: 10.1002/we.527*
5. J. SEYDEL and A. ALISEDA, Wind turbine performance in shear flow and in the wake of another turbine through high fidelity numerical simulations with moving mesh technique, *Wind Energ. 2013; 16:123–138, DOI: 10.1002/we.535*
6. N.SEZER-UZOL O. UZOL, Effect of steady and transient wind shear on the wake structure and performance of a horizontal axis wind turbine rotor, *Wind Energ. 2013; 16:1–17, DOI: 10.1002/we.514*
7. A. BOSSAVY, R. GIRARD and G. KARINIOTAKIS, Forecasting ramps of wind power production with numerical weather prediction ensembles, *Wind Energ. 2013; 16:51–63, DOI: 10.1002/we.526*
8. K. LU, L. HELLE, Reactive power control and fault ride through capabilities of synchronous generator, *Aalborg University, 2011.*
9. D.G. FORCHETTI, J.A. SOLSONA, G.O. GARCÏA, M.I. VALLA, A Control Strategy for Stand-Alone Wound Rotor Induction Machine, *(Electric Power Systems Research 77, 163–169, 2007).*
10. R.S. PÊNA, R. CARDENAS, J. CLARE, G. ASHER, Control Strategy of Doubly Fed Induction Generators for Wind Diesel Energy System, in: 28th Annual Conference of the IEEE Industrial Electronics Society, *(IECON02, Sevilla, pp. 3297–3302, Spain, 2002).*
11. R.S. PÊNA, R. CARDENAS, G. ASHER, J. CLARE, J. RODRIGUEZ, P. CORTES, Vector Control of a Diesel-Driven Doubly Fed Induction Machine for a Stand-Alone Variable Speed Energy System, in: 28th Annual Conference of the IEEE Industrial Electronics Society, IECON02, vol. 2, *(Sevilla, pp. 985–990, Spain, 2002).*
12. G.K. SING, Self-Excited Induction Generator Research a Survey, Electr. Power Sys. Res. *(Elsevier 69 107–114, 2004).*
13. R. DATTA, V.T. RANGANATHAN, Variable-Speed Wind Power Generation Using Doubly Fed Wound Rotor Induction Machine, a Comparison with Alternative Schemes, *IEEE Trans. Energy Convers. 17, 414–421, (2002).*
14. V. CALDERARO, V. GALDI, A. PICCOLO, P. SIANO, A Fuzzy Controller for Maximum Energy Extraction from Variable Speed Wind Power Generation Systems, *(Electric Power Systems Research 78, 1109–1118, 2008).*
15. D. SAIDANI, Modeling, Control and Testing of Self-Excited Asynchronous Generator for Wind Conversion System of Local Grid, Ph D Thesis in High Scientific and Technical School of Tunisia, *(September 2010).*
16. S. DOMINIONI, File Renewable Energy, *(Mining Engineers Journal, May / June 2010).*

17. S. HEIER, Grid Integration of Wind Energy Conversion Systems, *(Wiley, ISBN 0-471-97143-X, 2000).*

18. BOSSANYI EA, The Design of Closed Loop Controllers for Wind Turbines, *(Wind Energy, Vol.3, p. 149-163, 2000).*

19. T. AHMED, O. NORO, K. MATSUO, Y. SHINDO and M. NAKAOKA, Minimum Excitation Capacitance Requirements for Stand-Alone Wind Turbine Coupled to Self Excited Induction Generator with Voltage Regulation Based on SVC, (The 25th International INTELEC'03, Telecommunications Energy Conference, p. 396-403), *(Oct. 2003).*

20. Planning Levels for Harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the United Kingdom, Energy Networks Association, *(London W2 2HH, 2012).*

21. The Grid Code, Issue 3, Revision 16, National Grid Electricity Transmission plc, Warwick 6DA, *(May 2006).*

22. NARAIN G.HINGORANI, LASZLO GYUGYI, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, *(IEEE Press, Wiley-Interscience, New York 2000).*

Appendix

Power system data in per unit value:
Wind turbine data:
Nominal power=9 MW, speed at A=0,7 (pu), speed at B=0,71 (pu), speed at C=1,2 (pu), speed at D=1,21 (pu),
Generator data:
Nominal power=9 MW, Un=575V, f=50Hz, p=3, Lm=2,9 (pu),