MPPT and pitch control for wind turbine of DFIG with flywheel energy storage system

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***Abstract*—The type of distributed generation unit that is the subject of this paper relates to renewable energy sources, especially wind power. The wind generator used is based on a double fed induction Generator (DFIG). The stator of the DFIG is connected directly to the network and the rotor is connected to the network through the power converter with three levels. The objective of this work is to study the association a Flywheel Energy Storage System (FESS) in wind generator. This system is used to improve the quality of electricity provided by wind generator. It is composed of a flywheel; an induction machine (IM) and a power electronic converter. A maximum power tracking technique « Maximum Power Point Tracking » (MPPT) and a strategy for controlling the pitch angle is presented. The model of the complete system is developed in Matlab/Simulink environment / to analyze the results from simulation the integration of wind chain to networks.**

Keywords-component; doubly fed induction generator; flywheel energy storage system; induction machine; maximum power point tracking; pitch control.

I. INTRODUCTION

The development and use of renewable energy have experienced strong growth in recent years [1]. Among these energy sources, wind generators have a special place. Indeed one hand, wind power is expected to grow strongly in many areas, and secondly, the highly fluctuating energy due to large variations in wind speed, poses many problems for managers of the energy system for two reasons. We must ensure the balance between power generation and power consumption [2]. In addition, the power consumption is variable and unpredictable. Because of these restrictions, current wind generators can not operate without being associated with conventional energy [3]. In order to increase the penetration of wind energy and participate in ancillary services (voltage control, frequency, autonomous boot,...), a storage system is associated with the wind generator [4]. Inertial storage is an appropriate solution to wind turbines, where it offers better advantages over other types of storage, good dynamics, good performance, durability similar to the wind turbine [5].

Much of the wind turbines installed today are equipped with double fed induction Generator (DFIG). This generator provides electricity generation, variable speed, this allows then to better exploit the wind resources for different wind conditions [6]. The main advantage of DFIG is that the equipment of the power electronics is only a fraction of the power (20-30%), this means that losses in the converters power electronics, as well as costs are reduced.

The need for control of wind turbines back to their origins of Use. The main purpose was the limitation of the power and speed to protect the turbines from strong winds [7]. Therefore it is necessary to degrade a part of the kinetic power to avoid damage to the turbine and also the electrical machine. The speed limitation is obtained with the control of the pitch angle that increases so as to reduce the turbine speed and limit the power generated in the power rating [7],[8]. And to ensure maximum capture of wind energy, must be continuously adjust the rotational speed of the wind turbine. This is done by using the extraction technique of the maximum power MPPT (Maximum Power Point Tracking) [9]. Control of wind then seeks to maximize the extracted power from the wind when the wind speed is less than its nominal value and limit the electrical power when the wind speed is greater than the nominal value [9].

In this article we studied the association of an inertial energy storage system in the wind generator Fig. 1. We begin by modeling the wind turbine. MPPT control technique is developed, followed by controlling the pitch angle. Then the DFIG will be modeled and control strategy of active and reactive power will be presented. Then, will be interested in the modeling and control the FESS in torque. The model of the complete system is developed in Matlab/Simulink simulation results are discussed, and ends with conclusions.

II. WIND TURBINE MODELING

The aerodynamic torque produced by the wind turbine is given by:

$$T_{aer} = \frac{P_{aero}}{\Omega_t} = \frac{1}{2\Omega_t} C_p(\lambda, \beta).\rho\pi R_t^2 v^3 \tag{1}$$

Where $\boldsymbol{\rho}$ is the air density, $\boldsymbol{v}$ is the wind speed, and $\boldsymbol{R_t}$ is the turbine radius, Ω_t is the angular velocity of wind turbine.

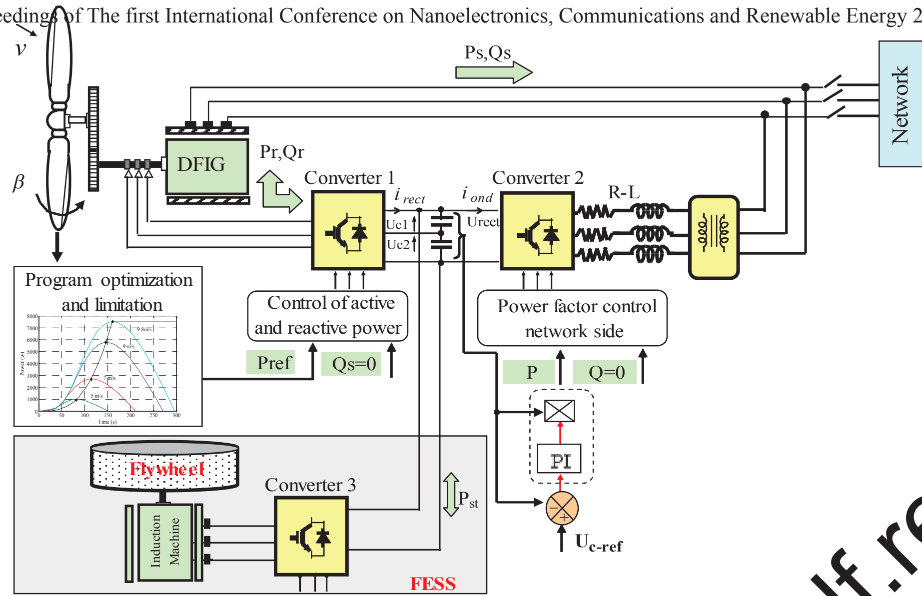

Figure 1. Scheme of the studied device.

The power coefficient Cp is a function of the speed ratio λ and the pitch angle of the blades β (Fig. 2). In this work, it is given by the expression [10]:

$$C_P(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4 - 5\right).\exp\left(\frac{21}{\lambda_i}\right) + 0.0068\lambda \tag{2}$$

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

The speed ratio λ is expressed by the following relationship

$$\lambda = \frac{\Omega_t R_t}{v} \tag{3}$$

The dynamic equation of the wind turbine is given by:

$$J\frac{d\Omega_{mec}}{dt} = T_g - T_{em} - f\Omega_{mec} \tag{4}$$

$$\begin{cases} \Omega_{mec} = G\Omega_t \\ T_{aero} = GT_g \end{cases} \tag{5}$$

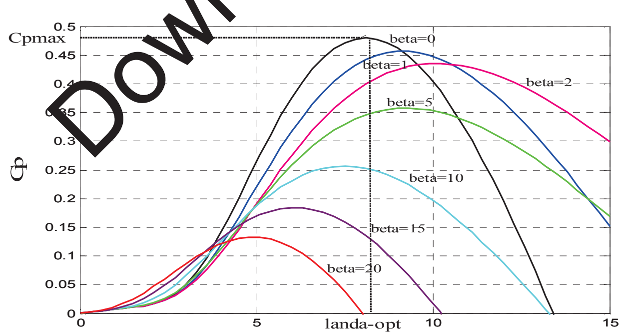

Figure 2. Representation of Cp as a function of λ for differente values of β

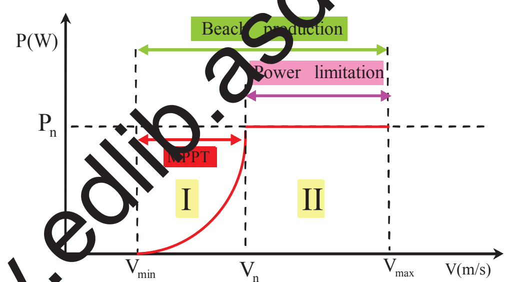

Figure 3. Areas of operation of wind turbines

According to [9], two zones control are distinguished according to the wind speed Fig. 3

A. Maximum Power Point Tracking(MPPT)Strategy

Equation (6) gives the expression of the maximum power obtained using the strategy MPPT which automatically adjusts the specific rate to its optimal value (λ_{opt}), to obtain the coefficient maximum power (C_{pmax}).

$$P_{MPPT} = \frac{1}{2}\frac{\rho\pi R_t^5 C_{p\max}}{\lambda_{opt}^3}\Omega_t^3 \tag{6}$$

Maximizing the power is represented in the form of simplified block diagram given in Fig. 4

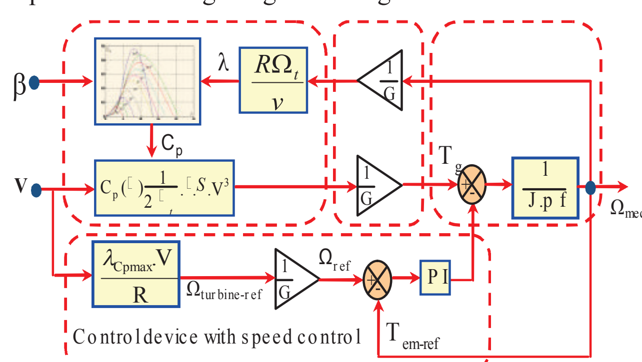

Figure 4. Diagram bloc of the MPPT extracted with control speed

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B. Pitch Angle Control

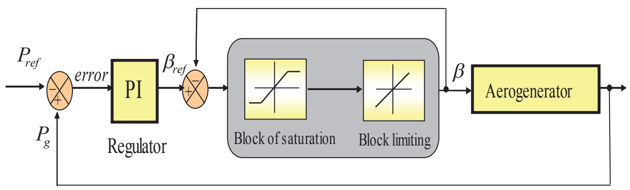

Figure 5. Pitch angle control strategy

The orientation system of the blades used essentially to limit the power generated. With such a system, the blades are turned by a control device called (pitch control). The reference pitch angle β_{ref} comes control of mechanical power P_g, regulated around its nominal power using the PI controller Fig. 5.

III. MODELLING AND CONTROL OF THE DFIG

Electric and magnetic relations governing the operation of the DFIG according to [6] are:

$$\begin{cases} v_{ds} = R_s.i_{ds} + \frac{d}{dt}\Phi_{ds} - \omega_s\Phi_{qs} \\ v_{qs} = R_s.i_{qs} + \frac{d}{dt}\Phi_{qs} + \omega_s\Phi_{ds} \\ v_{dr} = R_r.i_{dr} + \frac{d}{dt}\Phi_{dr} - \omega_r\Phi_{qr} \\ v_{qr} = R_r.i_{qr} + \frac{d}{dt}\Phi_{qr} + \omega_r\Phi_{dr} \end{cases} \quad (7)$$

$$\begin{cases} \Phi_{ds} = L_s.i_{ds} + M.i_{dr} \\ \Phi_{qs} = L_s.i_{qs} + M.i_{qr} \\ \Phi_{dr} = L_r.i_{dr} + M.i_{ds} \\ \Phi_{qr} = L_r.i_{qr} + M.i_{qs} \end{cases} \quad (8)$$

The active and reactive powers (stator and rotor) of the DFIG can be written as:

$$\begin{cases} P_s = v_{ds}i_{ds} + v_{qs}i_{qs} \\ Q_s = v_{qs}i_{ds} - v_{ds}i_{qs} \\ P_r = v_{dr}i_{dr} + v_{qr}i_{qr} \\ Q_r = v_{qr}i_{dr} - v_{dr}i_{qr} \end{cases} \quad (9)$$

The electromagnetic torque is expressed as:

$$T_e = -P\frac{M}{L_s}(\Phi_{qs}.i_{dr} - \Phi_{ds}.i_{qr}) \quad (10)$$

By choosing a reference two-phase (d, q) related to the rotating stator field and aligning the stator flux vector Φ_s with the axis, we can write $\Phi_{ds}= \Phi_s$ and $\Phi_{qs}=0$ [5],[6]: Then the torque is simplified as indicated below:

$$T_{em} = -p\frac{M}{L_s}\Phi_s.i_{qr} \quad (11)$$

If we neglect the resistance of the stator winding R_s, we obtain: $V_{ds}= 0$ and $V_{qs}=V_s=\omega_s.\ \Phi_{ds}$.

The stator active and reactive power and rotor voltages can then be expressed only versus these rotor currents as:

$$\begin{cases} P_s = -v_s\frac{M}{L_s}i_{qr} \\ Q_s = \frac{v_s\Phi_s}{L_s} - \frac{v_sM}{L_s}i_{dr} \end{cases} \quad (12)$$

$$\begin{cases} v_{dr} = R_r i_{dr} + (L_r - \frac{M^2}{L_s})\frac{di_{dr}}{dt} - g\omega_s(L_r - \frac{M^2}{L_s})i_{qr}; \\ v_{qr} = R_r i_{qr} + (L_r - \frac{M^2}{L_s})\frac{di_{qr}}{dt} + g\omega_s(L_r - \frac{M^2}{L_s})i_{dr} + g\omega_s\frac{Mv_s}{\omega_s L_s}. \end{cases} \quad (13)$$

IV. FLYWHEEL ENERGY STORAGE SYSTEM

With the aim to involve a variable wind speed services systems, energy storage type inertial is considering a flywheel mechanically coupled to an asynchronous machine and driven by a power converter as shown in Fig. 1. E_v Energy stored in the flywheel J_v to the expression:

$$E_V = \frac{1}{2}J_v\Omega_v^2 \quad (14)$$

To calculate the inertia of the wheel, it is based on a power supply for a time Δt: we want the storage to provide the inertial rated P_{IMn} during a time Δt when energy is needed $E_v= P_{IMn}.\Delta t$ given by: $\Delta E_v=1/2J_v.\Delta\Omega_v^2$ and $\Delta\Omega_v^2 = \Delta\Omega_{vMAX}^2 - \Delta\Omega_{vMIN}^2$ we get:

$$J_v = \frac{2P_{IMn}\Delta t}{(\Omega_{vMAX}^2 - \Omega_{vMIN}^2)} \quad (15)$$

The induction machine is chosen according to these advantages in terms of simplicity and robustness of the rotating parts, the benchmark model in the Park, with the rotor flux orientation ($\Phi_{qr}=0$, $\Phi_{dr}=\Phi_r$) can be described by following equations:

$$\begin{cases} \frac{d\Phi_{dr}}{dt} = -\frac{R_r}{L_r}\Phi_{dr} + (\omega_s - p\omega)\Phi_{qr} + \frac{MR_r}{L_r}i_{ds} \\ \frac{d\Phi_{qr}}{dt} = -\frac{R_r}{L_r}\Phi_{qr} - (\omega_s - p\omega)\Phi_{dr} + \frac{MR_r}{L_r}i_{qs} \\ \frac{di_{ds}}{dt} = \frac{MR_r}{\sigma L_s L_r^2}\Phi_{dr} + \frac{Mp\Omega}{\sigma L_s L_r}\Phi_{qr} - \frac{R_{sr}}{\sigma L_s}i_{ds} + \omega_s i_{qs} + \frac{1}{\sigma L_s}v_{ds} \\ \frac{di_{qs}}{dt} = \frac{MR_r}{\sigma L_s L_r^2}\Phi_{qr} - \frac{Mp\Omega}{\sigma L_s L_r}\Phi_{dr} - \frac{R_{sr}}{\sigma L_s}i_{qs} - \omega_s i_{ds} + \frac{1}{\sigma L_s}v_{qs} \\ T_{em-ref} = \frac{pM}{L_r}\Phi_{dr}i_{qs} \end{cases} \quad (16)$$

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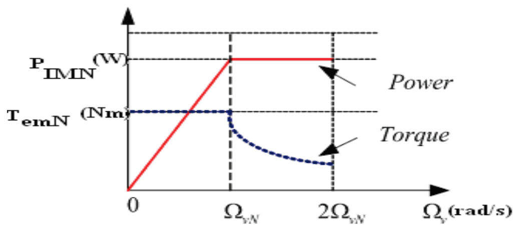

Figure 6. Allure power and torque versus speed

Two areas of operation for the electrical machine shown in Fig. 6 [5].

For, $0 \leq \Omega_v \leq \Omega_{vN}$ the nominal torque of the machine is available, but the maximum power is variable, depending on the speed ($P_{IM} = k\ \Omega_v$) and smaller than the nominal power. This area does not have much interest in FESS.

For $\Omega_v > \Omega_{vN}$ the power is a maximum and corresponds to the nominal power of the machine, the electromagnetic torque is inversely proportional to the speed of rotation ($T_{em}=k/\Omega_v$). This is the area of operation used in FESS because here the power of the machine is available for any speed.

The induction machine with inertial storage will be used in the speed range below $\Omega_{vN} \leq \Omega_v \leq 2\Omega_{vN}$.Thus allowing operation at rated power constant.

From a reference power P_{v-ref}, one can deduce the torque electromagnetic reference of the machine, T_{em-ref}, causing the flywheel by a measure of the speed of rotation, Ω_{v-mes}.

$$T_{em-ref} = \frac{P_{v-ref}}{\Omega_{v-mes}} \quad (17)$$

The electromagnetic torque reference shall be limited to nominal torque for the speed range including between 0 and the nominal speed, beyond the rated speed, the torque will decrease in order to keep the product $T_{em-ref}.\Omega_v$ constant. The torque reduction is carried out by the defluxing of the machine beyond the synchronous speed. Weakening of the law is as follows:

$$\Phi_{dr-ref} = \frac{P_{v-ref} L_r}{pMi_{qs}} \frac{1}{\Omega_{v-mes}} \quad (18)$$

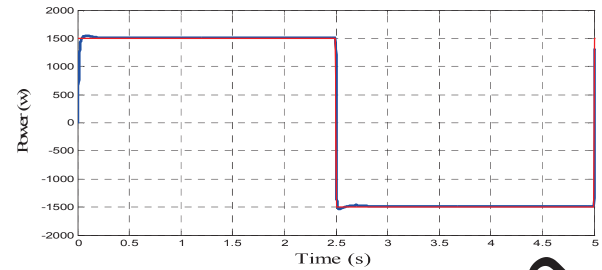

Figure 8. The power delivered or absorbed by the IM

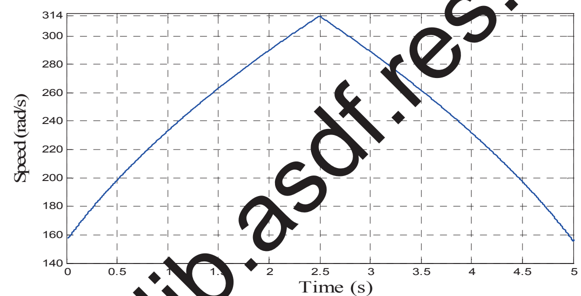

Figure 9. Speed of the flywheel

The flux estimate is given by the following equation:

$$\Phi_{dr-estimé} = \frac{M}{1 + \frac{L_r}{R_r} S} i_{ds-mes} \quad (19)$$

Fig. 7 shows the block diagram of the control of **FESS** the currents **i_{ds-ref}** and **i_{qs-ref}** are determined by the flow regulator for the d-axis current, and the electromagnetic torque reference for the q-axis current. The electromagnetic torque being calculated from equation (17), the quadrature current is determined by inverting the torque equation (16).

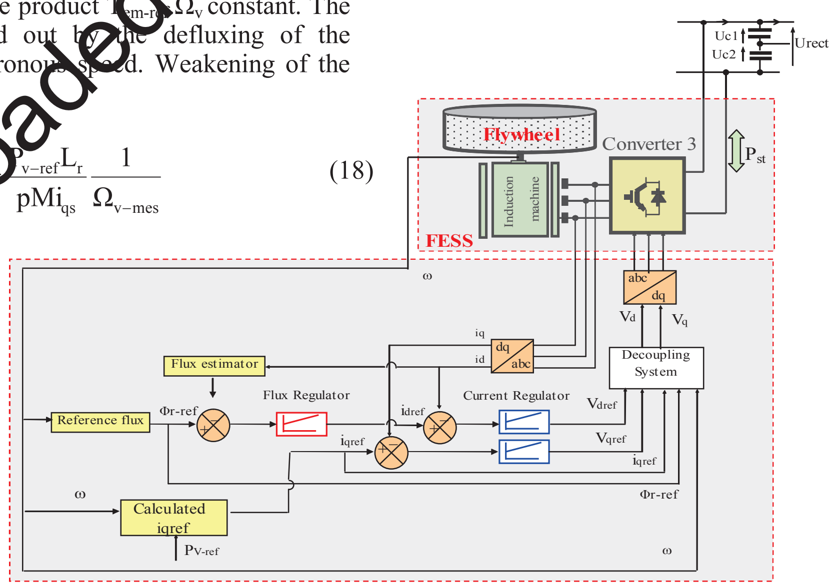

Figure 7. Block diagram of the control system of inertial storage

Fig. 8 and Fig. 9. illustrate the operation of the storage system inertial. The value of the inertia coefficient was calculated for a speed range between 157 and 314 rad/s, and a rated power of 1.5kW during a time corresponding to 2.5s. The initial velocity of the steering wheel is fixed 157rad/s. When the storage reference power P_{v-ref}, is set at 1.5kW, the speed increases of 157 to 314 rad/s. the system stores energy. When the power is fixed to -1.5kW, the speed decreases of 314 to 157rad/s. The system provides energy.

The main function of the FESS is to smooth the power output of the wind generator which can cause several problems in the network. To reduce has minimum the fluctuations of this power; FESS should ensure compensation for variations in wind power. The reference power of FESS is determined by the difference between the power generated by the wind generator P_{wind} and the power it takes to deliver network or on isolated loads P_{regl}, according to the principle illustrated in Fig. 10.

$$P_{v-ref} = P_{regl} - P_{wind} \tag{20}$$

V. Simulation Result

The model of the system and its control was simulated using Matlab Simulink. The simulation starts with the initial conditions. The initial mechanical speed is ((λ_{opt}.4 /R).G) and initial wind speed (4m/s). Considering a variable speed wind that touches two areas of functioning of the wind (varies below and above the nominal speed (9.8 m/s) Fig. 11.

The total power delivered to the grid by the DFIG, equal to the algebraic sum of the power to the rotor and the stator according to the convention Fig. 12.

The results confirm the correct operation of the control system within two operating area. Indeed, for low winds (area I), the mechanical speed of the asynchronous machine is controlled by the electromagnetic torque to optimize the power profile extracted maintaining the power coefficient of the turbine at its maximum value, wind then operate in MPPT and the pitch angle is zero. If the power returned to the network by the DFIG reaches its nominal value for speeds strong wind (area II), the orientation system the blades is to protect of wind surcharges by limiting the power converted. The mechanical speed and kept nominal, and the coefficient of performance is reduced due to the variation of the pitch angle. Figs. 13, 14 and 15.

In what follows we showed the simulation results of the association of FESS with a IM of 1.5kW to 7.5kW wind turbine. In the event that the network must receive a constant power of -6.4kW Fig. 17. The setting of the DC bus is provided by the three-level converter network is kept constant Fig. 18.

Fig. 19. Corresponds to the power storage unit. This power can be positive or negative depending on wind conditions that allow the charging or discharging, it is limited to1.5Kw. When the reference power is positive, FESS stores electric energy the speed flywheel increases. FESS captures the electrical energy when the reference power became negative the flywheel speed decreased Fig. 20. The components of direct and quadrature rotor flux of the induction machine are shown in Fig. 21. The quadrature component is always zero, which justifies the rotor flux oriented control.

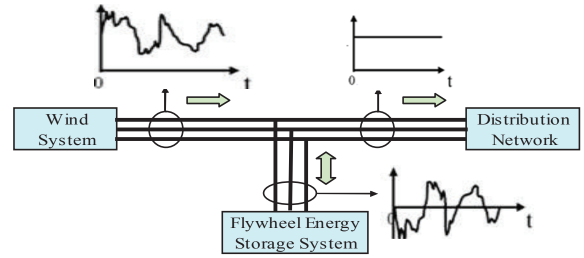

Figure 10. Power to smooth by FESS

Conclusion

This article presents the modeling and control of a chain of wind generation based asynchronous machine dual power, associated with an inertial storage system via the DC bus. Control of the DC bus voltage and provides by the network side converter. A MPPT technique has been applied and favored maximizing the power. However, to avoid damaging the machine in case of strong winds, a control of the pitch angle β was applied to limit the power of the wind generator to its nominal value (7.5kW). Then the FESS is controlled by a reference power obtained as a function of the power generating and power to send to the network, the aim was to smooth the power injected into the network to participate in ancillary services. The simulation results clearly show the storage and energy release.

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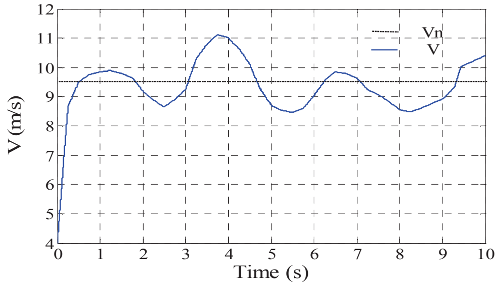

Figure 11. Wind Speed

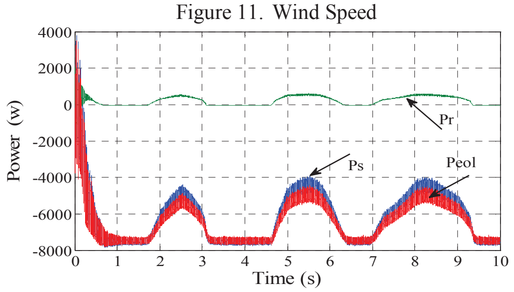

Figure 12. Variation in the power to the rotor and stotor

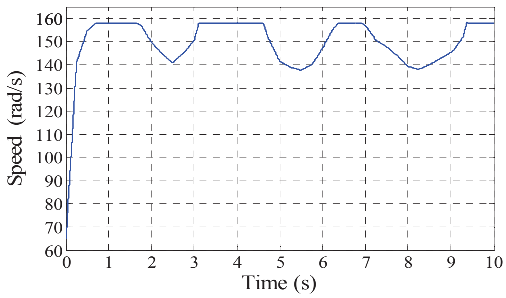

Figure 13. Mechanical Speed

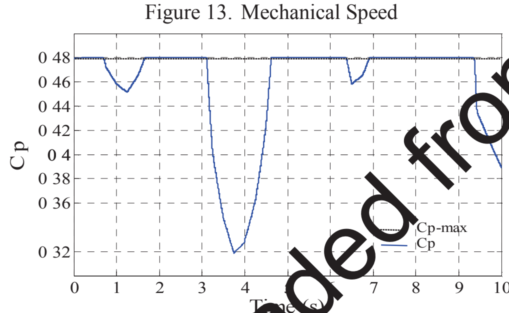

Figure 14. Power Coefficient

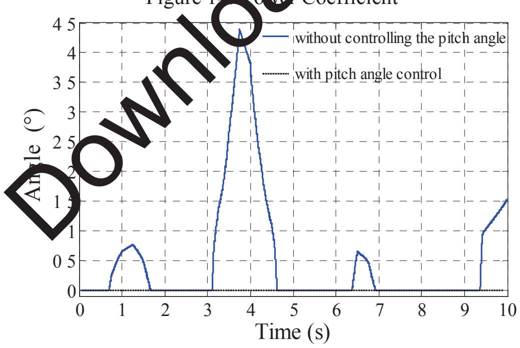

Figure 15. Pitch Angle

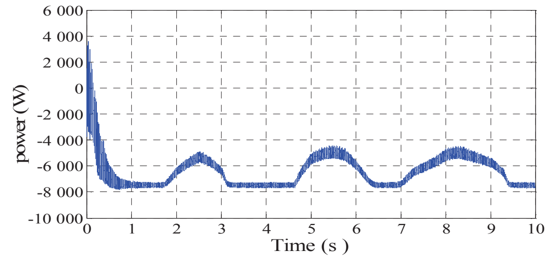

Figure 16. Power delivered by the wind

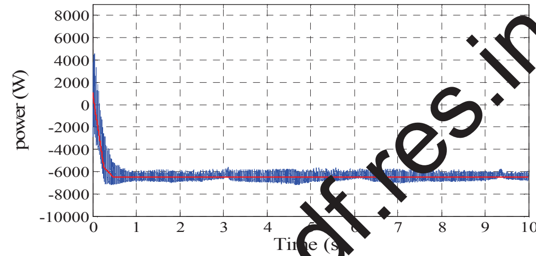

Figure 17. Power delivered to the network

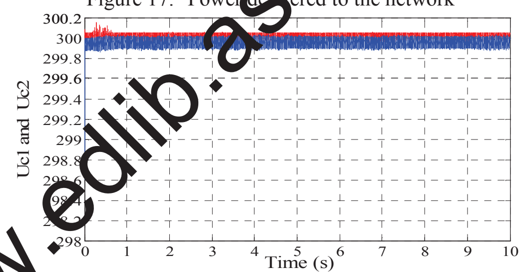

Figure 18. The DC bus voltage

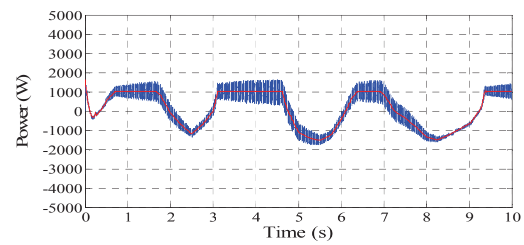

Figure 19. Electric power of the FESS

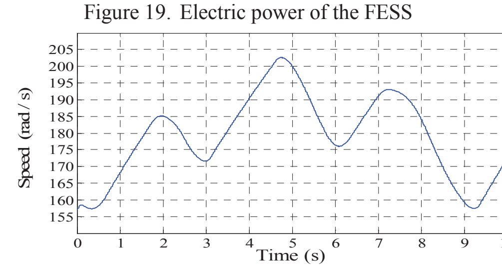

Figure 20. Speed of the flywheel

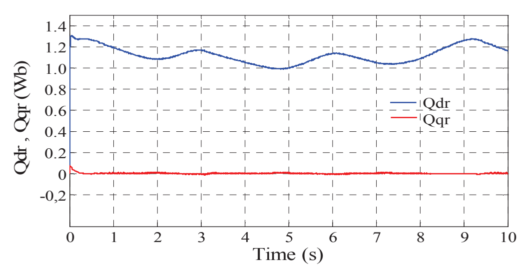

Figure 21. Direct and quadrature component of the flow of IM