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Primary frequency control applied to the wind turbine based on the DFIG controlled by the ADRC

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ABSTRACT

In this paper, we study the primary frequency control that allows the variable speed Aeolian to participate in the frequency regulation when a failure affects the network frequency. This method based on the control of the generator rotational speed or the control of pitch angle makes it possible to force the wind turbine to produce less power than its maximum available power, consequently we will create an active power reserve. This wind turbine must inject into the grid a part of its power reserve when the frequency drops, in contrary the wind turbine reserves more of energy. So, this work presents the performances of this control strategy for the different wind speed value. The results are obtained by a simulation in the MATLAB/SIMULINK environment.

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1. INTRODUCTION

Wind energy has experienced a strong development in the last decade in the world, which leads to an increasing insertion of this energy in the electrical networks [1-4]. However, the intermittent nature and irregularity of wind generation will impact the stability of the networks and the quality of energy produced and provided to users [5-6]. This situation leads to the definition of new technical connection conditions requiring new wind farms to contribute in the same way as conventional power plants, to the system services of the electricity networks to which they are connected [5-7]. Among these services, the frequency regulation of the network. So our goal is to synthesize a command to stabilize the frequency of the network after a change of frequency caused by an imbalance between production and consumption at its reference value. This control strategy is called the primary frequency control [6].

In this work we use the Active Disturbance Rejection Control (ADRC), which allowsthe stability of the Wind Energy Conversion System (WECS) based on a Double Fed Induction Generator (DFIG), this control is applied to the Rotor Side Converter (RSC) and the Grid Side Converter (GSC) as shown in the Figure 1 [8-10]. Wealso study the frequency control strategy mentioned before in order to force the Aeolian to participate in the frequency setting,according to the operating zone of the wind turbine two control strategies are presented, the first one when the speed of rotation and the power do not exceed their maximum values, so the control of the active power of the wind turbine is made by an action on the electromagnetic torque and by the control of the turbine rotational speed,the second one when we have a high wind speed, the control of power extracted from the wind is done by an action on the angle of orientation of the blades. Finally we present the simulation results of these controls and their interpretations.

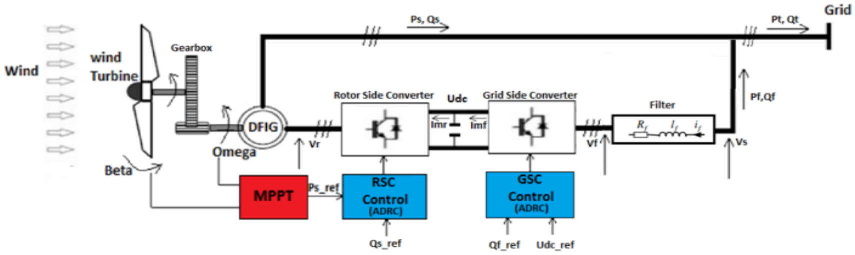

Figure 1. The wind energy conversion system structure

2. PRIMARY FREQUENCY CONTROL

Unlike conventional production systems, DFIG-based wind turbines have no relation to the grid frequency because of their variable speed operation, hence zero inertial response, and they do not participate in frequency stabilization.

To involve the Aeolian system in the primary setting of the grid frequency, it must produce an electrical power less than its maximum available power P_{MPPT} when the grid frequency is in a normal range around the nominal frequency in order to create a primary reserve. An instantaneous imbalance between production and consumption is synonymous with a frequency variation, so when the frequency drops, the wind turbine must provide a portion of its power reserve ΔP which is proportional to the variation of the frequency Δf to the grid. This portion power injected is based on the statismδcurve as shown in Figure 2, which is not fixed and depends on the maximum available power and the wind speed [11].

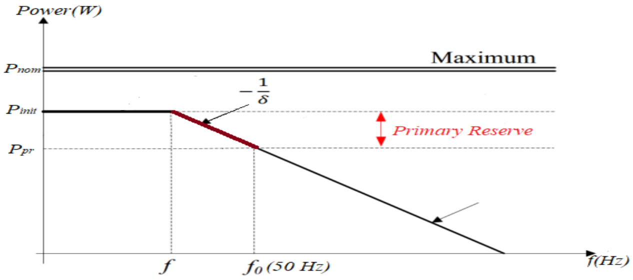

Figure 2. The statism curve

Usually the calculation of statism δ is defined by the following expression:

$$\delta = \frac{\frac{f(t)-f_0}{f_0}}{\frac{P_{init}(t)-P_{pr}}{P_{nom}}} \tag{1}$$

Where f is a wind group frequency, f_0 is a network reference frequency, $P_{init}$the instantaneous power produced by a group, P_{pr}programmed reserve power and $P_{nom}$is a nominal power of wind turbine.

So two means of control are possible to lower the value of the C_p coefficient of power (i.e. active power) [12]: Either by an acceleration of the speed of the turbine, or by an increase of the angle of orientation of the blades (pitch angle).

2.1. Active power management by controlling the mechanical rotation speed

This control is used when the wind speed is below the rated speed that the turbine can withstand; the principle of this method is to create a $(1-K)P_{init}$ power reserve while adjusting the electromagnetic torque of the generator and maintain the pitch angle at 0° as shown in Figure 3 [13-15].

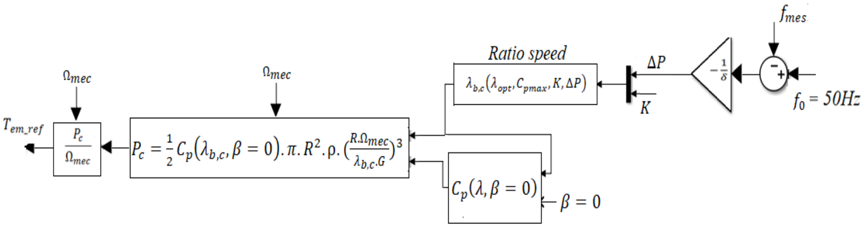

Figure 3. Frequency control loop of a variable speed wind turbine system

G: is the coefficient multiplier of Gearbox

As shown in Figure 4 the primary reserve is made by reducing the power coefficient with a shift from operating point A to point B and by increasing the mechanical rotational speed (i.e. increasing the ratio speed λ) [16-19].The point A corresponds to the maximum power extracted from the wind and to the optimal rotation speed, while the operating point B corresponds to the power created after reservation. When there is an imbalance of the production-consumption ratio, that is to say a frequency instability the operating point move towards another operating point ***C*** to inject into the network the quantity of power ΔP which corresponds to this variation.

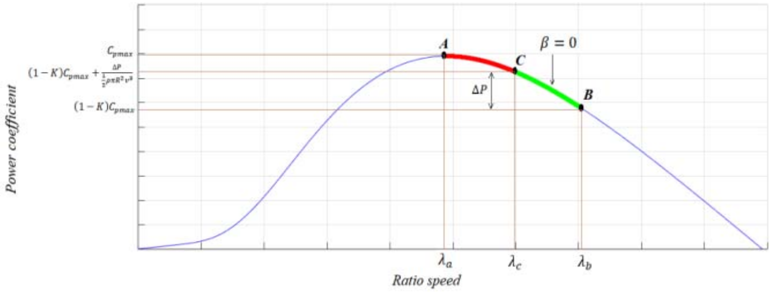

Figure 4. Displacement of the operating point by increasing the turbine rotation speed

The aerodynamic power at point ***C*** is determined by the (16) [11]:

$$P_c = (1 - K)P_{MPPT} + \Delta P \tag{2}$$

With:

$$\Delta \mathrm{P} = -\frac{1}{\delta}(\mathrm{f}_0 - \mathrm{f}_{\mathrm{mes}}) = -\frac{1}{\delta}\Delta \mathrm{f} \tag{3}$$

We deduce the power coefficient at point ***C***:

$$C_p(\lambda_c, \beta = 0) = (1 - K)C_{pmax} + \frac{\Delta P}{\frac{1}{2}\rho\pi R^2 v^3} \tag{4}$$

We express the power coefficient $\mathrm{C_p}(\lambda, \beta = 0)$ by its interpolation polynomial of degree 2 as a function of λ and β = 0° [11]:

$$C_p(\lambda) = -0.0179\lambda^2 + 0.2744\lambda - 0.5522 \tag{5}$$

The resolution of (4) by replacing $C_p(\lambda_c, \beta = 0)$by its interpolation polynomial of the (5) makes it possible to express the speed ratio at the point ***C***:

$$\lambda_C = \lambda_{opt} + \frac{-(a_1+2.a_2\lambda_{opt})-\sqrt{(a_1+2.a_2\lambda_{opt})^2-4.a_2(a_2\lambda_{opt}{}^2+a_1\lambda_{opt}+a_0+\alpha)}}{2.a_2} \qquad (6)$$

With:

$$\begin{cases} \alpha = \frac{\Delta P}{\frac{1}{2}\rho\pi R^2 v^3} \\ a_0 = -0.5522 \\ a_1 = 0.2744 \\ a_2 = -0.0179 \end{cases} \qquad (7)$$

When the grid frequency is stable at (f_0=50 Hz) $\Delta P = 0$, then the operating point of the wind turbine is at point B, consequently the power coefficient at point B and the speed ratio are given by:

$$\begin{cases} C_p(\lambda_b, \beta = 0) = (1-K)C_{pmax} \\ \lambda_b = \lambda_{opt} + \frac{-(a_1+2.a_2\lambda_{opt})-\sqrt{(a_1+2.a_2\lambda_{opt})^2-4.a_2(a_2\lambda_{opt}{}^2+a_1\lambda_{opt}+a_0)}}{2.a_2} \end{cases} \qquad (8)$$

The electromagnetic torque T_{em_ref}expressed by the (9), requires the wind generator to move from operating point ***A*** to point ***B*** in order to achieve a power reserve, and during a frequency imbalance, it changes the operating point from the point ***B*** to ***C*** in order to inject the corresponding power:

$$T_{em\_ref} = \frac{1}{2}\rho\pi R^3 v^3 C_p(\lambda_c)\frac{1}{\lambda_c G} \qquad (9)$$

2.2. Active power management by the pitch control

According to the power-speed characteristic Figure 5 of the wind turbine when the wind speed is high, the power captured by the turbine and its rotational speed reach their maximum values. In this case, we cannot have the desired power reserve only by increasing the rotation speed. Under these conditions and in order to create the power reserve, the speed of rotation must be kept almost close to its maximum value, and also, we added another control strategy based on the control of the orientation angle of the blades [20-22].

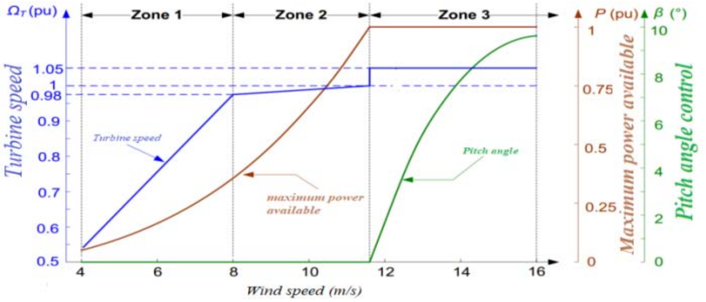

Figure 5. The power-speed characteristic

The Figure 6 shows the principle of this control which allows the displacement of the operating points on the power coefficient characteristic as a function of the ratio speed λ and for different values of β. The operating point ***A*** corresponds to the optimal rotation speed and to the maximum power captured by the turbine P_{MPPT} for $\beta = 0°$. The displacement of the operating point ***A*** to the point ***B*** which corresponds to the maximum rotation speed does not allow the creation of the desired power reserve $(1-K)\ P_{MPPT}$. For this purpose, by using the pitch angle control, the angle of orientation of the blades β is increased, which makes it possible to reduce the captured power of the wind and to set the operating point at the point ***E*** that allows to create the desired power reserve [11], when we have an imbalance frequency the operating point moves from point ***E*** to ***F*** in order to inject the corresponding power. The Control loops for pitch angle control and power control are shown in the Figure 7.

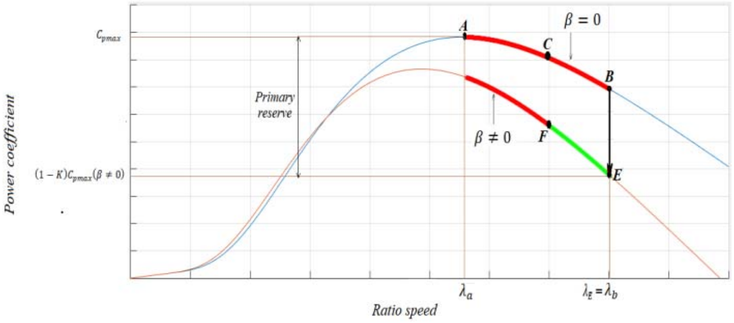

Figure 6. Displacement of the operating point by changing the angle β

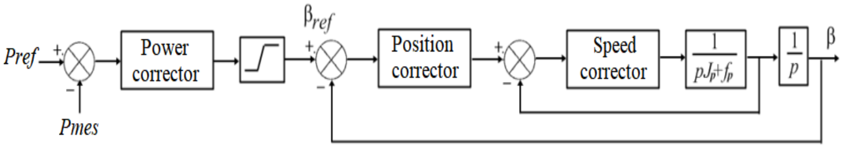

Figure 7. Block diagram of the system of orientation of the blades

The speed regulator and the power corrector are the Proportional Integral (PI) type, for the position corrector we have chosen a Proportional type corrector (P). The saturation value of the wedging angle in position is 90°[23], [24].Thereference power making it possible to decrease the angle of orientation of the blades, thus to allow the wind turbine to reserve the power or to inject into the network a quantity of power ΔP is given by the following expression:

$$P_{ref} = (1-K)P_{MPPT} + \Delta P \tag{10}$$

3. SIMULATION AND INTERPRETATIONS

In this part we test the participation of the wind turbine controlled by ADRC at the primary frequency regulation. For that, we choose different values of the power reserve (K %) and different values of wind speeds. We took the wind speedconstant during the time of simulation, the grid frequency drop with -1Hz from the instant 14s to the instant 19s, then increases by + 0.8Hz from the instant 21s to the instant 26s Figure 8, The statism of the primary frequency setting system is set at 4% and the DFIG and its control system are assumed ideal.

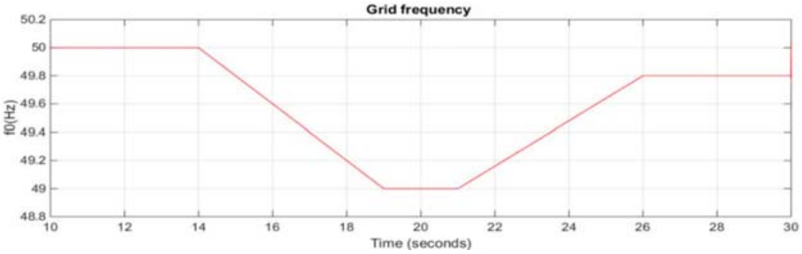

Figure 8. The grid frequency

3.1. Evaluation of the speed control strategy

In this case the wind speed values used is less than the nominal wind speed of the wind turbine used (≤11.07m/s) and the angle of orientation of the blades is kept at zero. From the results obtained in Figures 9, 10, 11 and 12 it is noted that the mechanical rotation speed and the electromagnetic torque force the generator to rotate at a speed higher than the optimal speed and also degrade the coefficient of power thus allowing the wind turbine to create a reserve of power. During the frequency drop create at the instant 14s the electromagnetic torque begins to increase proportionally to the frequency drop, contrary to the mechanical rotation speed which decreases and causes an increase in the power coefficient (i.e. active power). From the instant 21s the electromagnetic torque begins to decrease and requires the rotor to increase its rotational speed which leads to the degradation of the power coefficient and the reconstitution of the power reserve.

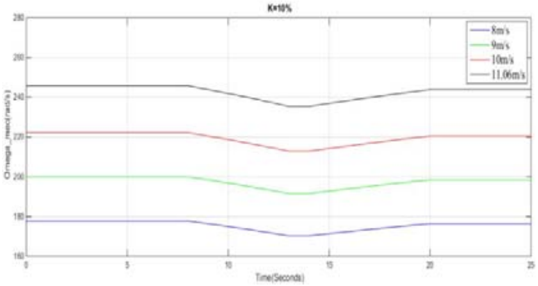

Figure 9. Mechanical rotation speed for different wind speed values and a constant value of the power reserve (K=10%)

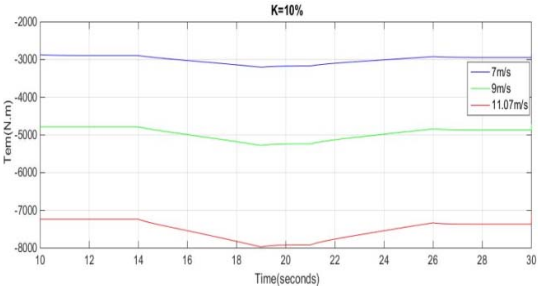

Figure 10. Electromagnetic torque for different wind speed values and a constant value of the power reserve (K=10%)

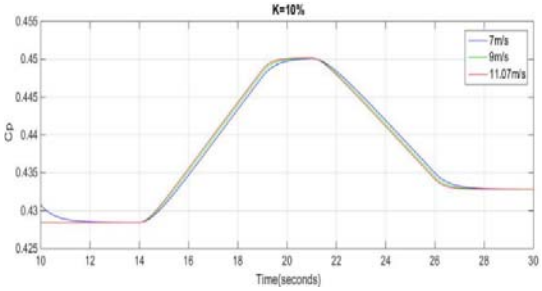

Figure 11. Power Coefficient for different wind speed values and a constant value of the power reserve (K=10%)

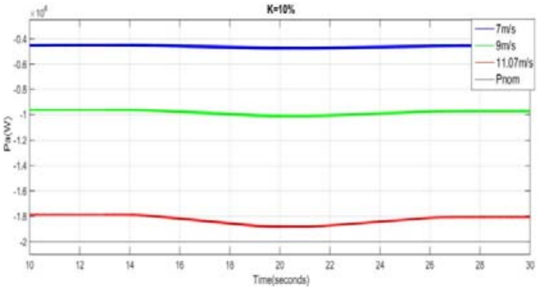

Figure 12. Active power for different wind speed values and a constant value of the power reserve (K=10%)

According to the Figures 13 and 14 we also notice that the evolution of the rotational speed and the active power for the percentage of power reserve K=10% is different to those for the cases of K=15% and K=20%. This difference is explained by the initial position of the operating point before the frequency default and by the non-linearity of the power-speed characteristic of the wind turbine. But the reaction of this Aeolian to the variation of frequency remains the same for all percentages of reserve taken.

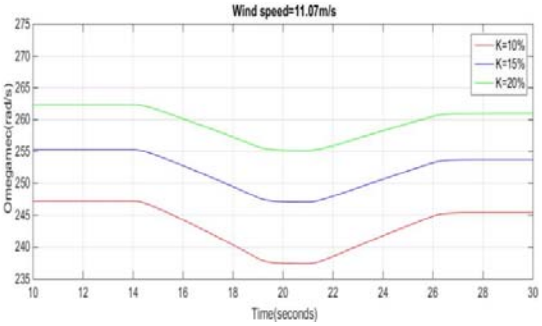

Figure 13. Mechanical rotation speed for different power reserve (K %) values and a constant wind speed value

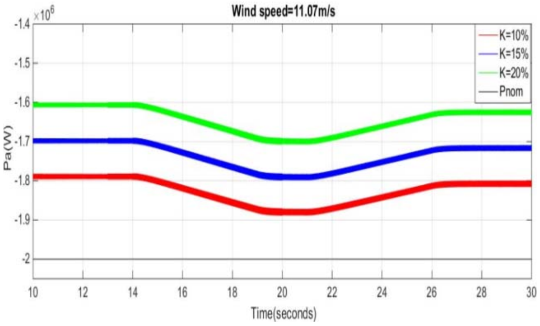

Figure 14. Active power for different power reserve (K %) values and a constant wind speed value

3.2. Evaluation of the pitch angle control

In that event the wind speed values used is superior to the nominal wind speed of the wind turbine used (≥11.07m/s).As shown in the Figure 15, the angle β follows its set points generated by the control loop of the blade orientation system.

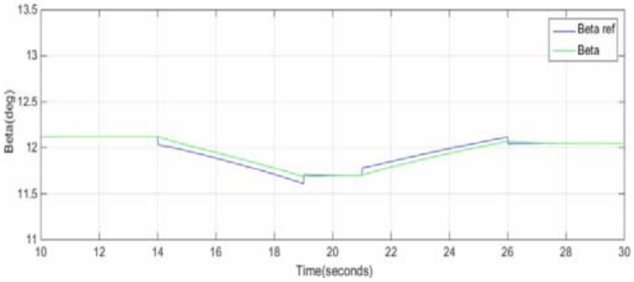

Figure 15. The angle of orientation of the blades and its reference

The Figures 17 and 18 show the evolution of active power and the mechanical rotation speed for different wind speeds and with a constant power reserve percentage. We notice that the rotation speed is close to its maximum value; therefore, moving the operating point to create a power reserve can no longer be done only by increasing the mechanical speed, then the addition of the pitch angle control is essential to create the necessary reserve. According to the Figure 16 we notice that the angle of orientation of blades increase proportionally to the wind speed.

When the frequency drop at the instant 14s the pitch angle begins to decrease proportionally to the frequency drop, which decreases the mechanical rotation speed that causes an increase of power produced. From the instant 21s the angle of orientation of blades begins to increase which makes it possible to increase the mechanical rotational speed which leads to the degradation of the power coefficient thus allowing to restore the power reserve.

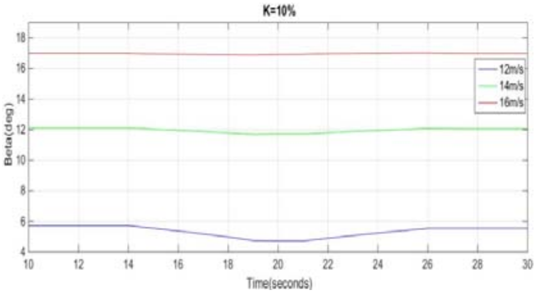

Figure 16. The angle of orientation of the blades for different wind speed values

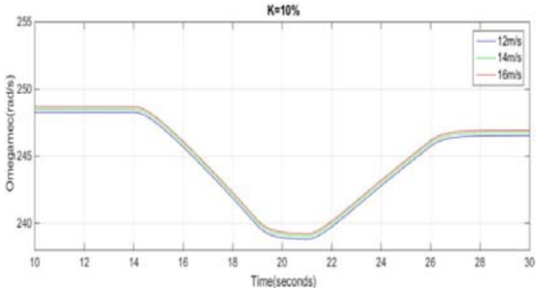

Figure 17. Mechanical rotation speed for different wind speed valuesand a constant value of the power reserve (K=10%)

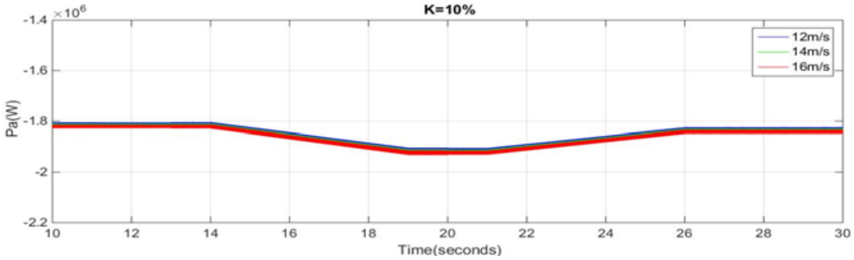

Figure 18. Active power for different wind speed values and a constant value of the power reserve (K=10%)

As the Figures 19, 20 and 21show that for each percentage of reserve the angle of orientation of the blades is defined in order to create a power reserve, and also the mechanical rotation speed does not shift its maximum value. We notice the evolution of the mechanical rotation speed and the active power for the different percentages (K %) of the power reserve are different because of the initial position of the operating point before the frequency failure and also by the increase or decrease of the angle of orientation of the blades.

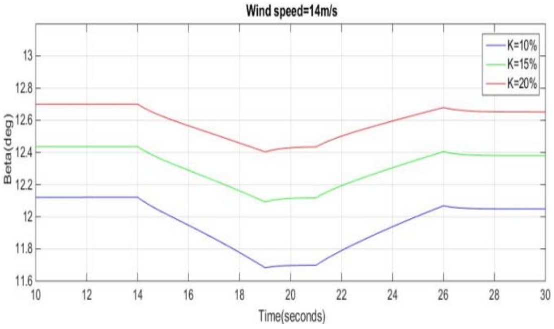

Figure 19. The angle of orientation of the blades for different power reserve (K %) values

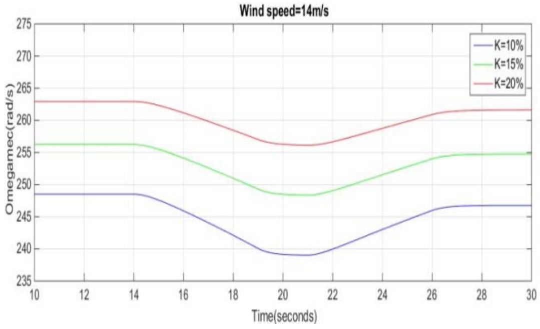

Figure 20. Mechanical rotation speed for different power reserve (K %) values and a constant wind speed value

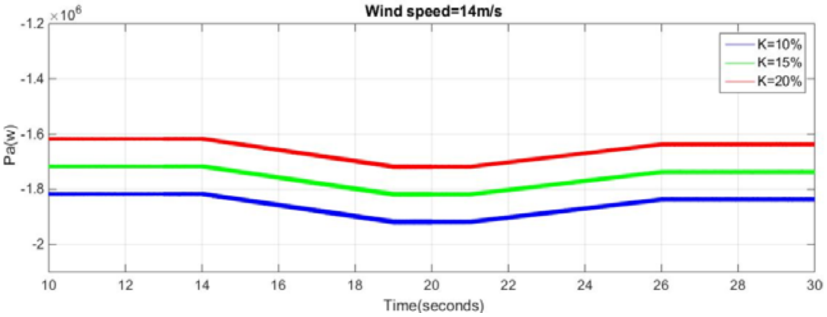

Figure 21. Active power for different power reserve (K%) values and a constant wind speed value

4. CONCLUSION

In order to force the wind turbine to participate in the frequency adjustment a control strategy has been studied and developed, to operate the wind turbine in a non-optimal state to create a primary reserve for all wind speeds by using two methods, such as the control of the rotation speed via the electromagnetic torque and thus the control of the orientation angle of the blades.

The first method is used when the wind speed is lower than the nominal speed that the turbine can capture (11.07m/s). This control strategy is made by increasing the mechanical rotation speed via the electromagnetic torque. When the wind speed exceeds this nominal speed of the turbine, the second method is used which makes it possible to increase the angle of orientation of the blades to create a reserve of power and thus to maintain the speed of rotation and the Generator power must not exceed their maximum values.

As the results show, for all wind speed values the wind turbine produces a portion of his available power when the grid frequency is stable and releases the stored energy when the grid frequency drops to support the grid, and gradually returns to its initial value after the grid frequency has returned to its nominal value.

APPENDIX

Table 1. Parameters of DFIG

Parameters	Value
Rated power **Ps**	2 Mw
Pole pairs **p**	2
Rotor resistance **Rr**	$2.9\ 10^{-3}\Omega$
Stator resistance **Rs**	$2.6\ 10^{-3}\Omega$
Mutual inductance **M**	$2.5\ 10^{-3}$H
Rotor inductance **Lr**	$2.587\ 10^{-3}$H
Stator inductance **Ls**	$2.587\ 10^{-3}$H

Table 2. Parameters of Wind Turbine

Parameters	Value
Gearbox coefficient G	92.6
Moment of inertia J	1000 Kg/m2
Viscous friction f	0.0024
Length of one blade R	40 m
Air densityρ	1.225 Kg/m2

Table 3. The ADRC Parameters

K_p	200	K_{pc}	100	K_{pf}	250
β_1	3600	β_{1C}	1200	β_{1f}	2000
β_2	3240000	β_{2C}	360000	β_{2f}	1000000
b_0	$5.8454*10^3$	b_{C0}	$4.14*10^5$	b_{f0}	-400

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