ISSN 2278-3091
Volume 8, No.3, May - June 2019
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse16832019.pdf
https://doi.org/10.30534/ijatcse/2019/16832019

DFIG power reserve control based on ADRC during grid frequency fault

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ABSTRACT

This paper presents the participation of Variable Speed Wind Turbine (VSWT) based on Doubly Fed Induction Generator (DFIG) in primary frequency control. In case of grid frequency disturbances, the wind turbines must be able to participate in the frequency adjustment as peer the new technical regulations of electrical grid operators. The main objective of this article is to propose a control strategy for VSWT based on DFIG to create a power reserve and consequently participate in primary frequency control (PFC). The wind is a physical time-varying parameter, therefore, the control strategy adopted for wind turbine, to create a power reserve and support grid in case of frequency variation, should depend on wind speed, however, for high wind speed, the wind turbine control is ensured by pitch angle regulation, once the wind speed decreases, the control strategy switch automatically to regulation of wind turbine rotation speed. For both pitch angle and rotation speed control, Active disturbance rejection control (ADRC) has been applied to estimate and reject all disturbances in case of frequency fault. In this article we synthesize the ADRC controllers and the proposed wind turbine control strategy. The dynamic models of DFIG and wind system are simulated in Matlab-Simulink environment.

Key words: ADRC, DFIG, frequency control, Power reserve.

1. INTRODUCTION

In order to keep the grid power stable, several methods of detection and elimination of electrical grid faults are established [1]. However, the power quality becomes a serious issue for systems and electrical grid research teams [2]. The electrical grid system operator requires that wind turbine generators should participate in grid frequency adjustment caused by the imbalance between power production and consumption. The VSWT based on DFIG requires a new control strategy to adjust the grid frequency. Unlike the synchronous group, the DFIG speed is decoupled on grid frequency due to the uses of electronic converters to transit power between DFIG rotor and grid [3][4]. In case of grid frequency fault, the first control strategy consists to liberate a part of kinetic energy saved in wind turbine rotor and provide an extra power to support the grid. Another control strategy allows to drop the power generated by the wind turbine, in order to keep a part of wind power as frequency adjustment power [5]. In this article, the DFIG power is controlled by turbine speed when the wind speed is under 11m/s or by pitch control in case of high wind speed in order to create a power reserve and maintain the speed and turbine power around the nominal value.

1.1 Primary control

When the frequency value varies around a nominal value, the primary adjustment is implemented by the action of the speed regulators of the synchronous production units which act in general on the intake organs of the driving fluid to the turbine when the speed of the group (proportional to the frequency) deviates the set speed due to an imbalance between production and the consumption of the entire electrical system [6].

1.2 Secondary control

If the frequency variation is important, the PFC is not able to adjust the grid frequency. Therefore, another type of control, called "secondary control" is used. The secondary frequency control is an automatic adjustment which aims to bring back the frequency to its reference value and to restore the exchanges between different national interconnected grids to their contractual values. This adjustment is slower than the primary setting and takes place about 10 seconds after the frequency is stabilized by the primary control [7].

. 1.3 Tertiary control

The tertiary control is used when the frequency deviation cannot be fully absorbed by the primary and secondary control. This adjustment is not automatic, it is done manually by grid operators from the electrical power control center. The tertiary reserve is provided by the groups that don't operate at their maximum power and serves in particular to compensate for large and lasting frequency deviations.

2. ADRC

Based on Extended State Observer (ESO), the Active Disturbance Rejection Control ADRC is an advanced and robust control strategy [8][9], it proposes real-time estimation and cancellation of various internal or external perturbations. In general, for a system of n order, which can be written in the form:

$$y(t)^{(t)} = f(y(t)^{(n-1)}, y(t)^{(n-2)},..., y(t), d(t)) + bu(t) \quad (1)$$

Where:

u is a control low, f is a dynamic unknown parameter of the system, $d(t)$ is disturbance and b is a constant to be determinated. To estimate the total disturbance, we adopt the control law (Equation 2) for a linear system and (Equation 3) for a non linear system:

$$u = \frac{-f + u_0}{b} \quad (2)$$

$$u_0 = k_p\, fal(Y_{ref} - z_1, \alpha, \delta) \quad (3)$$

In equation 3, fal is a nonlinear function developed by Jingqing Han such as [10]:

$$fal(e,\alpha,\delta) = \begin{cases} |e|^{\alpha}\, sign(e) & if \quad |e| \geq \delta \\ \dfrac{e}{\delta^{1-\alpha}} & if \quad |e| \prec \delta \end{cases} \quad (4)$$

The ESO established for equation (4) as [15]:

$$\begin{cases} \dot{Z} = AZ + Bu + G(y - \hat{y}) \\ \hat{y} = CZ \end{cases} \quad (5)$$

With:

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}; B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}; C^T = \begin{bmatrix} 1 \\ 0 \end{bmatrix}; G = \begin{bmatrix} 2\omega_0 \\ \omega_0^{\ 2} \end{bmatrix} \quad (6)$$

For the non-linear structures, the state observer equation is written as [11]:

$$\begin{cases} \dot{z} = z_2 - a_1\, fal(e, \alpha_1, \delta_1) b_0 u \\ \dot{z}_2 = a_2\, fal(e, \alpha_2, \delta_2) \\ e = z_1 - y \end{cases} \quad (7)$$

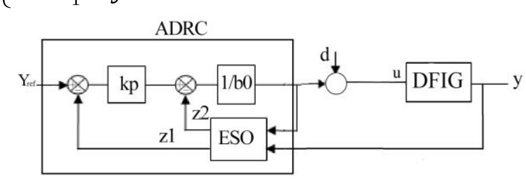

Figure 1: Architecture of ADRC controller

3. WIND TURBINE MODEL

The wind turbine converts kinetic energy captured by the shaft [8], thus aerodynamic P_a power and torque T_a appearing at the turbine rotor are given by the following expressions [12]:

$$\begin{cases} P_a = \dfrac{1}{2} C_p(\lambda, \beta) \rho S v^3 \\ T_a = \dfrac{1}{2\Omega_t} C_p(\lambda, \beta) \rho S v^3 \end{cases} \quad (8)$$

With:

$$\begin{cases} \lambda = \dfrac{\Omega_t R}{v} \\ C_p(\lambda, \beta) = 0.22(\dfrac{116}{\lambda_i} - 0.4\beta - 5) e^{-\frac{125}{\lambda_i}} + 0.0068\lambda \\ \lambda_i = \dfrac{1}{\lambda + 0.008\beta} - \dfrac{0.035}{\beta^3 + 1} \end{cases} \quad (9)$$

And:

C_p: Power coefficient

λ: Tip speed ratio

v: Wind speed (m/sec)

ρ: Air density (kg/m3)

R_R: Rotor radius (m)

β: Pitch angle

The generator electromagnetic T_e torque in Park frame is expressed as [8] [13]:

$$T_e = -\frac{3}{2} p \frac{L_m}{L_s} (\Phi_{ds} I_{dr} - \Phi_{qs} I_{ds}) \quad (10)$$

With:

p: Generator pole pair number

L_s, L_m: Stator and mutual inductance

Φ_{ds} ,Φ_{qs}: Direct and quadratic stator flux (Wb)

I_{ds}, I_{dr}: quadratic stator and rotor currents

The evolution of the turbine mechanical speed is given by equation (11) which is the fundamental equation of dynamics.

$$T_G - T_{em} = J \frac{d\Omega_t}{dt} + f\Omega_t \quad (11)$$

With:

J: Inertia moment

G: Multiplier coefficient

$f.\Omega_t$: Viscous friction torque

Ω_t: Turbine mechanical speed

T_G: Multiplier torque

This equation can be written as a canonical form of ADRC as follow:

$$\frac{d\Omega_t}{dt} = f(\Omega_t, d, t) + b_0\beta \qquad (12)$$

With:

b_0: constant to be determinated

f: total disturbances

4. CONTROL STRATEGY DURING FAULT

During the grid frequency fault, the DFIG should be controlled to provide an active power to the grid in order to adjust grid frequency.

In the literature, several techniques used by wind energy to adjust frequency are discussed, such as wind farm [16][17][18], frequency adjusting by speed rotation control [19][20][21], inertial response [22][23][24].

In this article we are focusing on DFIG active power control by acting on pitch angle β or the turbine rotation speed, in order to adjust the grid frequency.

This type of control is used even with high wind speed to maintain produced power by a wind turbine in its nominal value.

4.1 High wind speed

If the wind speed exceeds 11m/s, the turbine mechanical power and rotation speed are around their maximal value, so the rotation speed should be maintained constant.

The main purpose of this control strategy is to modify the wind turbine operating point by changing the pitch angle which creates a power reserve as shown in the figure below.

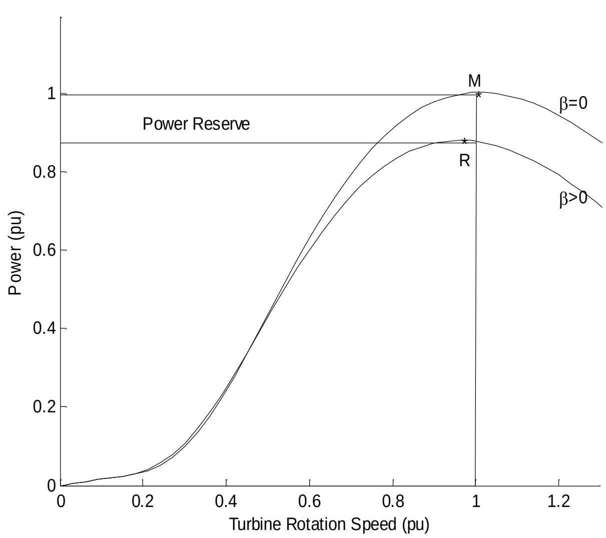

Figure 2: Power reserve by changing pitch angle

4.2 Low wind speed

In case of low wind speed, the frequency adjustment is ensured by turbine rotation speed control. To create a power reserve, when the wind speed is under 11m/s, the turbine operating point should be changed from point M (maximum power) to point R (reserve power), as shown in the figure below:

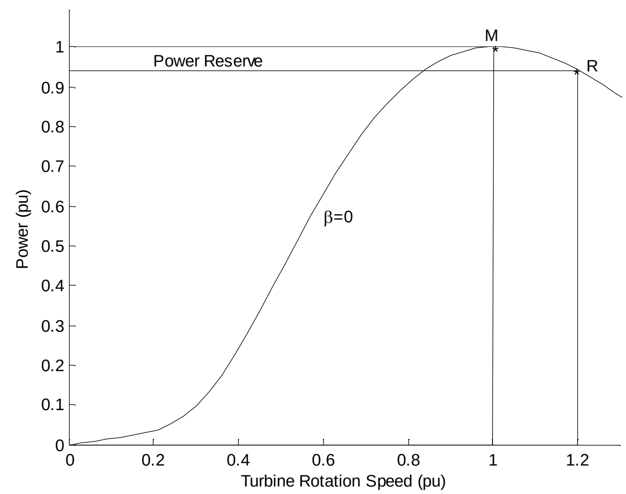

Figure 3: Power reserve creation by acting on rotation speed

To change the wind turbine operating point, the DFIG electromechanical torque reference should be calculated as per desired power reserve. The pitch angled is maintained at β=0.

For the Maximum power tracking point (MPPT) strategy, the usual control strategy adopted for the wind turbine, the electromechanical torque is given by the following expression:

$$T_{em-ref-MPPT} = \frac{1}{2G^3\lambda^3_{opt}} C_{p\_max}\rho\pi R^5\Omega_t^2 \qquad (13)$$

To modify the turbine functioning point from M(C_{p-max}, λ_{opt},β=0) to pint R(C_{p-res}, λ_{res},β=0), the new reference of electromechanical torque Tem-ref-res should be established and applied to the DFIG in order to obtain the needed power;

$$T_{em-ref-res} = \frac{1}{2G^3\lambda^3_{res}} C_{p\_res}(\lambda_{res}, \beta=0)\rho\pi R^5\Omega_t^2 \qquad (14)$$

The speed ration λ_{res} in point R is given by:

$$\lambda_{res} = \frac{R\omega_R}{G_t v} \qquad (15)$$

This speed ration can be calculated by solving the following equation;

$$C_p(\lambda_{res}) = -0.0158\lambda^2_{res} + 0.2508\lambda_{res} - 0.5302 \qquad (16)$$

In order to create R% power reserve the new power factor for wind turbine will be:

$$C_p(\lambda_{res}) = (1-R)C_{p-\max} \qquad (17)$$

To set the turbine rotation speed at ω_R, the new reference of electromechanical torque should be:

$$T_{em-ref-res} = \frac{v^2}{2\lambda_{res}} C_{p\_res}(\lambda_{res}, \beta = 0)\rho\pi R \qquad (18)$$

Each power reserve corresponds to a C_P and speed ratio located on the characteristic curve between point M (Maximal power) and point R (Maximal reserve).

$$\begin{cases} C_{p-res} \prec C_p \prec C_{p-\max} \\ \lambda_{opt} \prec \lambda \prec \lambda_{res} \end{cases} \qquad (19)$$

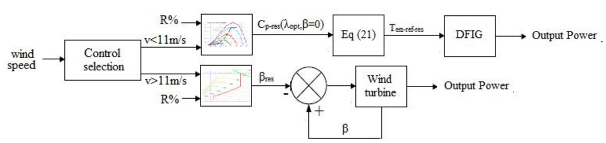

Figure 4: Control strategy implementation

5. SIMULATION AND RESULTS

In order to test the proposed control strategy, the simulations results have been performed through MATLAB/simulink environment, the DFIG, turbine, and ADRC parameters are listed in table 1 in appendix:

The wind profile applied for the turbine is given in figure 5, if the wind speed is under 11m/s, the wind turbine control is insured by rotation speed as per in Area 1 and 3 in figure 5(a), else the control by pitch angle is activated as per in Area 2.

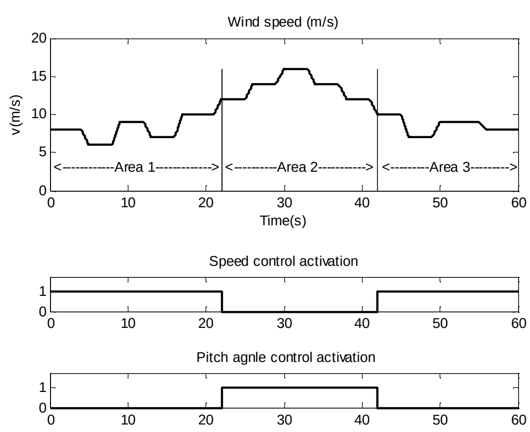

Figure 5: Wind speed profile and control strategy activation.

The figure above shows three operation areas for wind turbine:

- Area 1: from 0 to 21s, wind speed is under 11m/s, therefore, the wind turbine control insured by rotation speed.
- Area 2: from 22 to 41s, wind speed exceeds 11m/s, consequently, the wind turbine control insured by pitch control.
- Area 3: wind speed decreases from 42s to the end of the simulation, as result, the rotation speed control is activated once again.

When the rotation speed is activated, the pitch angle is maintained at the zero value β=0, as per area 1 and 2. However, for area 3, the turbine rotation speed and output turbine power are both maintained at the maximal value which is respectively 1.2wn and 1.2Pn. In this area the turbine control by pitch angle has a double objective of creating power reserve and maintains the power and speed around safe value preventing the turbine from any damage.

Figure 6 shows the turbine output power for a 10% power reserve, according to wind profile previously applied to the turbine. As we can conclude from the figure, at all simulation time, for any grid support, a power reserve is available in the wind turbine output, Nonetheless, in Area 2, the maximal power captured from wind is limited by pitch angle activation whatever the wind speed, this area does not last more than 10% of the turbine functioning time.

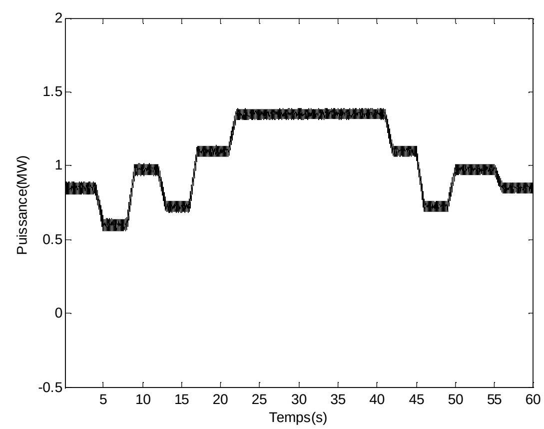

Figure 6: Turbine output power for a 10% reserve.

For the same reserved power quantity, figure 7 shows the turbine rotation in rad/s, for all simulation time, the turbine rotation speed increases proportionally to the wind speed and decrease in area 3. However, in area 2, the rotation speed keeps constant at the maximal value 1.2Wn. The speed limitation ensures the protection of the turbine from any accidental damage.

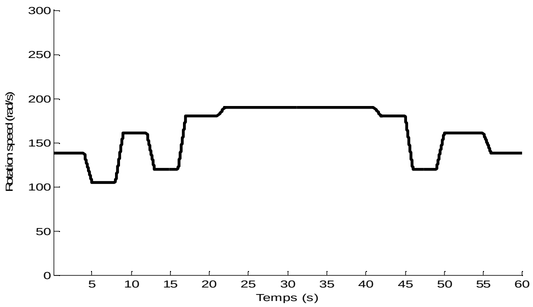

Figure 7: Turbine rotation speed.

When the speed of rotation decreases respectively at t=5s, t=12s, t45s and t=55s the turbine releases kinetic energy stored in the rotating system, this kinetic energy injects additional power into the grid, The wind turbine generates, in some instants after the fall of the speed of rotation, an electrical power higher than the power of the wind picked up by the wind turbine.

The figure below, shows the turbine outputs powers for different power reserve, the power reserve is approximately constant when the turbine is controlled by pitch angel β, The power reserve is imposed by the dispatching according to the power requirement in the electrical grid, the more the required power reserve at the wind turbine is large, the lower the output power of the turbine, which affects the performance of the wind system.

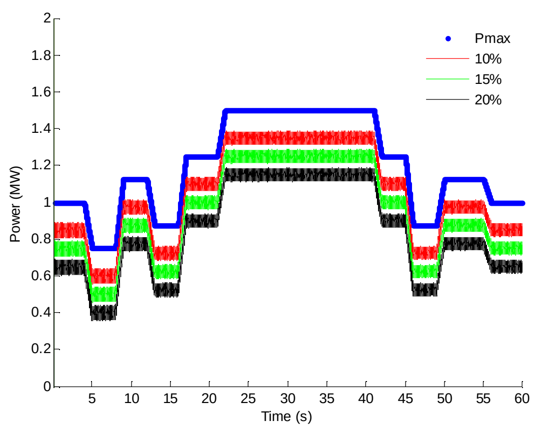

Figure 8: Turbine output power for deferent power reserve 10%, 15% and 20%.

For fixed wind speed in figure 8, each power reserve corresponds to a speed of rotation of the turbine in the area where the control is ensured by the speed of rotation (area 1 and 3). Thus, each power reserve corresponds to a power coefficient value,

We can also conclude from figure 2 and 3 that the power coefficient is inversely proportional, the more power reserve is high, the more power coefficient is small.

6. CONCLUSION

This paper investigated the participation of wind turbine to primary frequency control, in this article, different types of frequency control has been presented, such as primary control, secondary and tertiary frequency control.

The control strategy proposed in this article is based on turbine rotation speed control and pitch angle control. In order to participate to the frequency adjustment, the wind turbine has to function under its maximal power, once grid frequency drops, the control low adopted for wind turbine changes the output power reference to inject more power in the grid, as result, the participation of frequency adjustment and power grid stability.

For the lower wind speed, the power reserve is controlled by rotation speed control, in the other case, the turbine control is ensured by pitch angle. The simulation results presented in this article shows that for whatever power reserve requested by the grid operator, the wind turbine can create this reserve, however, the more the power reserve is important, the more the wind system performances are badly affected.

APPENDIX

Table 1: Simulation Parameters

	Parameters	**Value**
DFIG	Rated power	1.5MW
	Voltage	690V – 50Hz
	Pole pairs	2
Turbine	C_{p_max}	0.47
	λ_{opt}	8.1
	Moment of inertia	60kg.m2
ADRC	controller gain	130
	Parameter b_0	0.04
	Observer bandwidth	300
Simulink	Fixed step size	10*1.65e-5

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