Research Article

A Novel Adaptive Active Disturbance Rejection Control Strategy to Improve the Stability and Robustness for a Wind Turbine Using a Doubly Fed Induction Generator

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A novel and robust active disturbance rejection control (ADRC) strategy for variable speed wind turbine systems using a doubly fed induction generator (DFIG) is presented in this paper. The DFIG is directly connected to the main utility grid by stator, and its rotor is connected through a back-to-back three phase power converter (AC/DC/AC). Due to the acoustic nature of wind and to ensure capturing maximum energy, a control strategy to extract the available maximum power from the wind turbine by using a maximum power point tracking (MPPT) algorithm is presented. Moreover, a pitch actuator system is used to control the blades' pitch angle of the wind turbine in order to not exceed the wind turbine rated power value in case of strong wind speeds. Furthermore, the rotor-side converter is used to control the active and reactive powers generated by the DFIG. However, the grid-side converter is used to control the currents injected into the utility grid as well as to regulate the DC-link voltage. This paper aims to study and develop two control strategies for wind turbine system control: classical control by proportional integral (PI) and the proposed linear active disturbance rejection control (LADRC). The main purpose here is to compare and evaluate the dynamical performances and sensitivity of these controllers to the DFIG parameter variation. Therefore, a series of simulations were carried out in the MATLAB/Simulink environment, and the obtained results have shown the effectiveness of the proposed strategy in terms of efficiency, rapidity, and robustness to internal and external disturbances.

1. Introduction

The global strategy of energy has been oriented to the development of renewable energy resources (wind energy, solar energy, hydroenergy, etc.), which has many advantages as they are less concerned about the environmental degradation on the one hand, and on the other hand, their energy production cost is very low compared to the conventional resources. In recent years, wind energy has been classified as one of the most important and promising renewable energy sources; it is based on the variation of the wind speed. The wind turbine converts this wind into the aerodynamic power, which is converted into electrical power by using of electric generators such as doubly fed induction generator (DFIG), squirrel cage induction generator (SCIG), or permanent magnetic synchronous generator (PMSG).

In a variable speed wind energy conversion system, which is based on doubly fed induction generators, the DFIG stator side is directly connected to the utility grid and the rotor side is connected through a back-to-back three phase power converter (AC/DC/AC). Currently, this configuration type is the most widely used for variable speed wind energy conversion systems; its main advantage is as follows: it can operate in both subsynchronous and supersynchronous speeds [1]. And more importantly, it operates with a smaller power capacity converter (rotor and grid-side converters) compared to the fully rated power converter schemes.

During the last decades, the control of variable speed wind energy conversion systems has become an important factor to efficiency enhancement and to increase the energetics yield. Moreover, it can be split in three parts:

- (i) Maximum power point tracking (MPPT) algorithms are needed to improve the energy efficiency and to extract the maximum power available from the wind turbine. In this context, several research studies have been conducted in the literature. Among them, in [2], the authors deal with a review of maximum power point tracking algorithms for wind energy systems. It presents a comparison of different maximum power point algorithms by presenting the simulation of three selected control methods (optimal torque control, tip speed ratio control, and perturbation and observation control P&O) in terms of validity, efficiency, and speed of response.
- (ii) Pitch angle control is used to ensure that the extracted wind turbine system power does not exceed its rated value in case of the instantaneous changing nature of the wind; a pitch actuator system is used to regulate the blades' pitch angle of the wind turbine. In [3], the authors have designed a novel PI and PID-based pitch control techniques used for large wind turbine systems with the synthesis of the PI parameters.
- (iii) The control of the rotor-side converter and the grid-side converter: the first converter is used to control the stator powers (active and reactive powers) independently, and the second converter is used to control power exchange with the utility grid at rotor side as well as to regulate the DC-bus voltage. Noteworthy, several control techniques for the rotor- and grid-side converters have been discussed in the literature. Among them, in [4], the authors have proposed to control DFIG-based variable speed wind turbine by PI controller, in [5], the authors proposed a sliding mode control of doubly fed induction generator, in [6], the authors presented a backstepping control of DFIG generators for wide-range variable speed wind turbines, in [7], the authors discussed the modeling and fuzzy logic control of DFIG-based wind energy conversion systems, and in [8], the authors have proposed to control a doubly fed induction generator for wind energy conversion systems by RST controller.

Another control strategy has been proposed and utilized. Since the last 10 years, it is known as the active disturbance rejection controller (ADRC). Moreover, it is used for the applications in several areas. The main advantages of this controller lie on the real-time rejection of internal and external disturbances based on an observer, i.e., internal disturbances (as the variation of the internal parameters or the modeling errors) and external disturbances (like the voltage dips and frequency droops). We propose in this paper the application of wind turbine control by ADRC strategy; the first application is used to control the rotor-side converter to regulate the stator powers. Furthermore, it is used to control the grid-side converter to regulate the active and reactive powers injected into the utility grid as well as to control the DC-bus voltage.

In this work, the main contributions are the development and comparison of two control methods in terms of efficiency, rapidity, and robustness, and also the response of the internal behaviour of wind energy conversion system based on DFIG. However, this paper is structured as follows. Section 2 presents the dynamic modeling of wind turbine system based on DFIG. Section 3 details the mathematical theory of active disturbance rejection controller. The maximum power point tracking algorithm and the blade orientation system control are given in Section 4. The control of wind energy conversion system using DFIG through two control methods (PI controller and linear ADRC controller) is demonstrated in Section 5. The remainder of the paper presents the simulation results and discussion.

2. Dynamic Modeling of Wind Turbine System

In this section, the DFIG variable speed wind energy conversion system control method is presented (active and reactive powers control). The wind energy conversion systems topology based on a DFIG is the most commonly used structure for large variable wind speed power plants [9]. As shown in Figure 1, the DFIG wind turbine generates the active power from the generator stator side (stator power). Moreover, it also generates or absorbs active power from the generator rotor side (rotor power) depending on the slip. The wind energy conversion system consists of the following main components: turbine, gearbox, DFIG generator with power converters (AC/DC/AC), DC-link, filter, transformer, and the grid.

2.1. Wind Energy Conversion System Mechanical Model. The turbine captures the wind kinetic energy and converts it to a torque that rotates the rotors blades (mechanical energy). The formula of aerodynamic power P_{aero} available from the turbine rotor can be given by

$$P_{\text{aero}} = C_p(\lambda, \beta)P_w = \frac{1}{2}\rho A_t C_p(\lambda, \beta)w^3, \quad (1)$$

where P_w is the wind power; C_p is the power coefficient; β and λ represent the blades' pitch angle and the turbine tip speed ratio, respectively; $A_t = \pi R^2$ is the turbine blade area; w is the wind speed; and ρ represents the air density [10].

The aerodynamic torque T_{aero} is given by the following expression:

$$T_{\text{aero}} = \frac{1}{2\omega_{\text{tur}}} \rho A_t C_p(\lambda, \beta)w^3, \quad (2)$$

where ω_{tur} is the turbine speed and R is the turbine blade radius. The wind turbine aerodynamic is characterized by a power coefficient; it is a nonlinear equation which depends on λ and β ; it is expressed by

$$C_p(\lambda, \beta) = k_1 \left(k_2 \frac{1}{\lambda^j} - k_3 \beta - k_4 \right) \exp(-k_5/\lambda^j) + k_6 \lambda, \quad (3)$$

where

FIGURE 1: Structure of a wind turbine system using a DFIG.

$$\frac{1}{\lambda^j} = \frac{1}{\lambda + k_7\beta} - \frac{k_8}{\beta^3 + 1}, \quad (4)$$

$$\lambda = \frac{R\omega_{tur}}{w},$$

with $k_1 = 0.5176$, $k_2 = 166$, $k_3 = 0.4$, $k_4 = 5$, $k_5 = 21$, $k_6 = 0.0068$, $k_7 = 0.08$, and $k_8 = 0.035$.

As shown in Figure 2, the aerodynamic coefficient has a maximum power point (point M) when $\beta = 0^\circ$ and $\lambda = 8.1$ (with $C_p^{\max} = 0.48$).

The gearbox torque T_g and mechanical angular speed ω_{mec} are given by

$$T_g = \frac{T_{aero}}{G}, \quad (5)$$

$$\omega_{mec} = G\omega_{tur},$$

where G is the gearbox ratio.

The system mechanical equation is

$$J \frac{d\omega_{mec}}{dt} = T_g - T_{em} - f\omega_{mec}, \quad (6)$$

where T_{em} and f are the DFIG electromagnetic torque and the friction coefficient, respectively. J represents the total inertia which can be calculated by

$$J = \frac{J_{tur}}{G^2} + J_{DFIG}, \quad (7)$$

where J_{DFIG} and J_{tur} are the inertias of the aggregated generator and the turbine.

2.2. Dynamic Model of DFIG. In order to model the DFIG, it is assumed that the stator and rotor windings are placed sinusoidally and symmetrically, and the magnetical saturation effects of all the windings are neglectable. Figure 3 illustrates the block of the generator phase in dq frame reference.

The stator and rotor windings equations are presented by (8)–(11):

FIGURE 2: The aerodynamic coefficient characteristics of the wind turbine system.

FIGURE 3: Schematic diagram of the DFIG equivalent circuit [11].

$$\frac{d\Psi_{sd}}{dt} = -R_s i_{sd} + \omega_s \Psi_{sq} + v_{sd}, \quad (8)$$

$$\frac{d\Psi_{sq}}{dt} = -R_s i_{sq} - \omega_s \Psi_{sd} + v_{sq}, \quad (9)$$

$$\frac{d\Psi_{rd}}{dt} = -R_r i_{rd} + \omega_r \Psi_{rq} + v_{rd}, \quad (10)$$

$$\frac{d\Psi_{rq}}{dt} = -R_r i_{rq} - \omega_r \Psi_{rd} + v_{rq}, \quad (11)$$

where v_{sd} and v_{sq} are the stator voltages in the direct-quadrature frame and v_{rd} and v_{rq} are the rotor voltages in the direct-quadrature frame. i_{sd} and i_{sq} are the direct and quadrature stator currents, i_{rd} and i_{rq} are the direct and

quadrature rotor currents, Ψ_{sd} and Ψ_{sq} are the direct-quadrature frame stator fields, and Ψ_{rd} and Ψ_{rq} are the direct-quadrature frame rotor fields. Also, R_s and R_r are the stator and the rotor phase resistances; ω_r and ω_s are the rotor electrical speed and the stator electrical speed, respectively. The equations of stator and rotor fields are

$$\begin{aligned}\Psi_{sd} &= (L_m + L_{s\sigma})i_{sd} + L_m i_{rd}, \\ \Psi_{sq} &= (L_m + L_{s\sigma})i_{sq} + L_m i_{rq}, \\ \Psi_{rd} &= (L_m + L_{r\sigma})i_{rd} + L_m i_{sd}, \\ \Psi_{rq} &= (L_m + L_{r\sigma})i_{rq} + L_m i_{sq},\end{aligned}\quad (12)$$

where L_m is the mutual inductance and $L_{s\sigma}$ and $L_{r\sigma}$ are the stator leakage inductance and the rotor leakage inductance, respectively [9].

The electrical active and reactive powers (P_s and Q_s) delivered by generator stator side and generator rotor side can be written as follows:

$$\begin{aligned}P_s &= v_{sd}i_{sd} + v_{sq}i_{sq}, \\ Q_s &= v_{sq}i_{sd} - v_{sd}i_{sq}, \\ P_r &= v_{rd}i_{rd} + v_{rq}i_{rq}, \\ Q_r &= v_{rq}i_{rd} - v_{rd}i_{rq}.\end{aligned}\quad (13)$$

The electromagnetic torque equation is then

$$T_{em} = -\frac{pL_m}{L_s}(\Psi_{sd}i_{rd} + \Psi_{sq}i_{rq}). \quad (14)$$

2.3. Dynamic Model of DC-Link and Filter. A commonly used dynamic Park model of the grid side can be expressed by (15)–(19):

$$v_{id} = R_f i_{fd} + L_f \frac{di_{fd}}{dt} - \omega_g L_f i_{fq} + v_{gd}, \quad (15)$$

$$v_{iq} = R_f i_{fq} + L_f \frac{di_{fq}}{dt} + \omega_g L_f i_{fd} + v_{gq}, \quad (16)$$

where v_{fd} , v_{fq} and v_{id} , v_{iq} are direct component and quadrature component of the filter voltage and the source inverter voltage; i_{fd} and i_{fq} are the filter current components in d - q frame; and R_f and L_f are the resistance and the inductance of the filter.

The active and reactive filter powers injected or absorbed from the grid can be written as follows:

$$P_f = v_{fd}i_{fd} + v_{fq}i_{fq}, \quad (17)$$

$$Q_f = v_{fq}i_{fd} - v_{fd}i_{fq}. \quad (18)$$

The DC-bus voltage equation can be written as follows:

$$i_{dc} = C \frac{dv_{dc}}{dt} = i_r - i_f, \quad (19)$$

where the currents i_r and i_f are the rotor-side current and the filter current, respectively; v_{dc} is the DC-link voltage; i_{dc} is the DC-bus current; and C is the capacitor [12].

3. Mathematical Theory of Active Disturbance Rejection Control

The active disturbance rejection control (ADRC) strategy is a novel adaptive robust strategy; it was proposed by Jingqing Han in 1995 [13, 14]. The main aim of this strategy is to estimate and compensate in real time the various external and internal disturbances; it is based on an extended state observer (ESO). In this work, we have developed and applied a linear ADRC in order to reduce the model complexity and design compared to the nonlinear ADRC.

3.1. Linear ADRC Design. We consider a nonlinear process (m -dimensional) variable in time, where $u(t)$ and $y(t)$ are the input and output signals, respectively; it can be written as follows:

$$\begin{aligned}y^{(m)}(t) &= d_{\text{int}}(y(t), y^{(1)}(t), y^{(2)}(t), \dots, y^{(m-1)}(t), u(t)) \\ &\quad + d_{\text{ext}}(t) + b_0 u(t),\end{aligned}\quad (20)$$

where $d_{\text{int}}(y(t), y^{(1)}(t), y^{(2)}(t), \dots, y^{(m-1)}(t), u(t))$ represents the nonlinear internal dynamic of the system, which is assumed to be unknown, and $d_{\text{ext}}(t)$ and b_0 represent the external disturbances and the known system parameter, respectively.

If we bring together all the disturbances affecting the system to be controlled: $d(t) = d_{\text{int}}(t) + d_{\text{ext}}(t)$. Wherein, the system equation is rewritten in the following form:

$$y^{(m)}(t) = d(t) + b_0 u(t). \quad (21)$$

Instead of looking for a model of $d(t)$, ADRC offers another way that significantly reduces the dependence of the control on accurate system modeling, as the proposed strategy consists in estimating $f(t)$ and then cancelling it in real time using an appropriate control signal $u(t)$.

As a result, the canonical form of linear ADRC is given by

$$\dot{y}(t) = d(t) + b_0 u(t). \quad (22)$$

3.2. Extended State Observer (ESO). The extended state observer is a Luenberger observer that estimates the term $f(t)$ and then compensates the effect of disturbances $d(t)$ on the system; therefore, we consider an extended state vector with an additional state representing the total disturbances of the system:

$$x = [x_1 x_2 \dots x_{m-1} x_m x_{m+1}]^t = [y \dot{y} \dots y_m d(t)]^t. \quad (23)$$

The system representation in matrix form:

$$\begin{cases} \dot{x} = Ax + Bu + Ed, \\ y = Cx, \end{cases} \quad (24)$$

with

$$\begin{aligned}
A_{(m+1,m+1)} &= \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}, \\
B_{(m+1,1)} &= [0 \ 0 \ \cdots \ b_0 \ 0]^T, \\
C_{(m+1,1)} &= [1 \ 0 \ \cdots \ 0 \ 0], \\
E_{(m+1,1)} &= [0 \ 0 \ \cdots \ 0 \ 1]^T.
\end{aligned} \quad (25)$$

The Luenberger state observer (ESO model) can be designed as

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y}), \\ \hat{y} = C\hat{x}, \end{cases} \quad (26)$$

where $L = [\beta_1 \ \beta_2]^T$ and $\hat{x} = [\hat{x}_1 \ \hat{x}_2]^T$ represent the observer gain vector and the estimated variables vector, respectively [15].

The error between x and $\hat{x}$ can be given by

$$\varepsilon = x - \hat{x}. \quad (27)$$

Therefore, the dynamics of error estimation is

$$\dot{\varepsilon} = (A - LC)\varepsilon, \quad (28)$$

where

$$A - LC = \begin{bmatrix} -\beta_1 & 1 & 0 & \cdots & 0 \\ -\beta_2 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -\beta_n & 0 & 0 & \cdots & 1 \\ -\beta_{m+1} & 0 & 0 & \cdots & 0 \end{bmatrix}. \quad (29)$$

In order to ensure asymptotic convergence of the estimation error ($\varepsilon \rightarrow 0$ when $t \rightarrow \infty$), the observer requires that the parameters of the gains vector L are chosen in such a way that $(A - LC)$ forms a Hurwitz matrix, that is to say, the poles of its polynomial characteristic $P_{\text{ESO}}(s)$ of $(A - LC)$ are all with strictly negative real parts [16].

$$\begin{aligned}
P_{\text{ESO}}(s) &= \det(sI_{(m+1)} - (A - LC)) = s^{(m+1)} + \beta_1 s^{(m)} \\
&\quad + \beta_2 s^{(m-1)} + \cdots + \beta_m s + \beta_{(m+1)}.
\end{aligned} \quad (30)$$

Ultimately, placing all observer poles at one location is also known as “bandwidth parameterization” [13]. Taking into account all these constraints, the cutoff pulse of the extended state observer ω_o is chosen to have a suitable stabilization time; its $(m+1)$ poles are placed to $-\omega_o$.

We can compute the necessary observer gains for the common pole location from its characteristic polynomial:

$$\begin{aligned}
P_{\text{ESO}}(s) &= s^{(m+1)} + \beta_1 s^{(m)} + \beta_2 s^{(m-1)} + \beta_3 s^{(m-2)} + \cdots \\
&\quad + \beta_m s + \beta_{(m+1)} = (s + \omega_{\text{obs}})^{m+1}.
\end{aligned} \quad (31)$$

The general expression of observer's gains is given by

$$\beta_i = \frac{(m+1)!}{(m+1-i)!i!} \omega_{\text{obs}}^i. \quad (32)$$

From equation (32), the extended state observer gains for a first-order plant are given by

$$\begin{pmatrix} \beta_1 \\ \beta_2 \end{pmatrix} = \begin{pmatrix} 2\omega_{\text{obs}} \\ \omega_{\text{obs}}^2 \end{pmatrix}, \quad (33)$$

and ω_{obs} is chosen in order to ensure both fast dynamics and stability of the observer.

3.3. The Control Law. By taking into consideration the estimated variables, a control law is determined to eliminate the effect of total disturbances acting on the system:

$$u(t) = \frac{u_0(t) - \hat{x}_{m+1}(t)}{b_0}. \quad (34)$$

Then, system 30 becomes

$$y(t) = d(t) - \hat{x}_{m+1}(t) + u_0(t). \quad (35)$$

If $\hat{x}_{m+1}(t) \approx f(t)$, then the system is

$$y(t) = u_0(t). \quad (36)$$

To implement the disturbance rejection, the actual state feedback control law is designed by

$$u_0(t) = K_p(r(t) - \hat{x}(t)), \quad (37)$$

where $r(t)$ is the reference signal. Since $\hat{x}_1(t), \dots, \hat{x}_m(t)$ is a correct estimation of $y(t), \dots, y^{(m-1)}(t)$, the design of a linear active disturbance rejection controller can be presented by

$$\begin{cases} \dot{\hat{x}}(t) = (A - LC)\hat{x}(t) + Bu(t) + Ly(t), \\ u(t) = K_p(\hat{r}(t) - \hat{x}(t)), \\ \hat{x}_1(t) = \hat{y}(t), \\ \hat{x}_2(t) = \hat{f}(t). \end{cases} \quad (38)$$

Figure 4 presents the active disturbance rejection control strategy and corrector structure linear ADRC.

The tuning of the proportional gain of the linear controller is given by $k_p = \omega_c = 4/t_r$, where t_r is the process desired time [18]. And for ω_{obs} , it is taken in a range of $\omega_{\text{obs}} = 3 \sim 10\omega_c$.

4. MPPT Algorithms and Pitch Angle Control

4.1. MPPT Algorithms (Optimal Torque Control). As mentioned previously in the introduction, the maximum power point tracking algorithm is a technique which is used to extract the maximum power from the turbine for different wind speeds. As described in [19], the available MPPT algorithms can be classified as either with or without wind sensors. The authors in [2] have demonstrated the superiority of the optimal torque control (OTC) method in terms of simplicity and accuracy (because it does not measure the wind speed directly). The principle of this method is to maintain the tip speed ratio to an optimum value in order to maximize the power coefficient ($\lambda = \lambda^{\text{opt}}$; $C_p = C_p^{\text{max}}$).

FIGURE 4: Linear ADRC structure [17].

The maximum aerodynamic power can be rearranged as follows:

$$P_{\text{aero}}^{\max} = \frac{1}{2} \rho A_t \frac{C_p^{\max}}{\lambda_{\text{opt}}^3} \frac{R^3}{G^3} \omega_{\text{mec}}^3. \quad (39)$$

The optimal aerodynamic torque can be expressed by

$$T_{\text{aero}}^{\text{opt}} = K_{\text{opt}} \omega_{\text{mec}}^2, \quad (40)$$

where the optimal torque coefficient is

$$K_{\text{opt}} = \frac{1}{2} \rho A_t \frac{C_p^{\max}}{\lambda_{\text{opt}}^3} \frac{R^3}{G^3}. \quad (41)$$

4.2. Pitch Angle Control. The blade orientation system is essentially used to limit the power extracted by adjusting the blade pitch angle β . The blade positioning mechanism consists in orienting the blades at a reference β^{ref} angle by means of a hydraulic or electrical system. The choice of this angle generally comes from an external loop to regulate either the turbine speed or the generated mechanical power. With such a system, the blades are rotated by a device called the pitch control [20].

The reference of the pitch angle β comes from the mechanical power control P_p , regulated around its nominal power. As long as the speed of the wind does not reach its nominal value (around 12 m/s), the blade orientation mechanism does not intervene and β is 0. Beyond that, the regulation intervenes and the angle varies between 0° and 10° .

The equation of pitch angle β can be expressed by

$$\beta = \frac{1}{1 + T_\beta s} \beta^{\text{ref}}, \quad (42)$$

where s is a Laplace operator and T_β is the time constant of the pitch servo. The pitch angle control scheme is depicted in Figure 5.

Generally, the pitch angle rate $\dot{\beta}$ varies around 10 degrees, and the angle β varies between 0 and 45 degrees [3].

5. The Novel Adaptive Active Disturbance Rejection Control Strategy of Wind Turbine System

The control strategies of the variable speed wind turbine system based on a DFIG connected into grid are developed in this section. The first strategy is the classical one based on the proportional integral (PI) controller, and the other one is the novel strategy based on the linear ADRC. We began with the classical control strategy by the proportional integral.

5.1. Wind Turbine System Control by PI. The rotor-side converter controllers are used to control the stator active and reactive powers. Furthermore, the grid-side converter controllers are used to regulate the DC-link voltage and to control the grid powers (active and reactive) as shown in Figure 6.

5.1.1. Rotor-Side Converter Control. To control the rotor-side converter, we have applied the indirect stator field oriented control (ISFOC), in which the stator field vector Ψ_s is oriented along the axis d . Then, the stator field components are $\Psi_{sq} = 0$; $\Psi_{sd} = \Psi_s$ [21].

it is assumed for high power machine that the resistance R_s is negligible and that the stator field Ψ_s is constant when the grid is stable.

The DFIG model can be written as

$$\frac{di_{rd}}{dt} = -c_1 i_{rd} + \omega_r i_{rq} + c_2 v_{rd}, \quad (43)$$

$$\frac{di_{rq}}{dt} = -c_1 i_{rq} - \omega_r i_{rd} - \omega_r c_3 \Psi_s + c_2 v_{rq}, \quad (44)$$

where $c_1 = R_r / \sigma L_r$; $c_2 = 1 / \sigma L_r$; $c_3 = L_m / \sigma L_s L_r$; $\omega_r = \omega_g - p \Omega_{\text{mec}}$

The expression of the rotor angle is

$$\theta_r = \int (\omega_g - \omega_{\text{mec}}) dt. \quad (45)$$

The compensation and the coupling terms are

$$e_{rd} = \frac{1}{c_2} \omega_r i_{rq}, \quad (46)$$

$$e_{rq} = \frac{1}{c_2} \omega_r i_{rd} + \frac{c_3}{c_2} \omega_r \Psi_s.$$

The electromagnetic torque equation is then

$$T_{\text{em}} = -\frac{3}{2} \frac{p L_m \Psi_s i_{rq}}{L_s}. \quad (47)$$

The active and reactive powers can be described by

FIGURE 5: Block diagrams of the blade pitch angle control.

FIGURE 6: The PI control strategy of the DFIG used in WTS.

$$P_s = -\frac{3}{2} \frac{L_m}{L_s} v_g i_{rq}^{\text{ref}}, \quad (48)$$

$$Q_s = \frac{3}{2} \left(-\frac{L_m}{L_s} v_g i_{rd}^{\text{ref}} + \frac{\Psi_s}{L_s} v_g \right). \quad (49)$$

From equations (47) and (49), we can derive the reference currents i_{rq}^{ref} and i_{rd}^{ref} to regulate the active power produced by the DFIG and to control the reactive power supplied or absorbed by the generator:

$$i_{rq}^{\text{ref}} = -\frac{2}{3} \frac{L_s}{p \Psi_s L_m} P_{\text{aero}}^{\text{opt}}, \quad (50)$$

$$i_{rd}^{\text{ref}} = \frac{2}{3} \left(\frac{\Psi_s}{L_m} - \frac{L_s}{v_g L_m} Q_s^{\text{ref}} \right), \quad (51)$$

where the torque $P_{\text{aero}}^{\text{opt}}$ is generated by MPPT and Q_s^{ref} is the reference reactive power; it is given as zero in normal operations ($Q_s^{\text{ref}} = 0$) to obtain a unit power factor [22].

5.1.2. Grid-Side Converter Control. Among the most used techniques to control the grid-side converter, we can find the voltage oriented control (VOC) or the direct power control (DPC) techniques. However, as described in [3, 9–23], the VOC is considered to be more efficient due to lower energy losses and lower current distortion compared to direct

power control (DPC). Hence, $v_{gd} = 0$ and $v_{gq} = v_g$. Then, the power P_f and Q_f are expressed in following equations:

$$P_f = \frac{3}{2} v_g i_{fq}, \quad (52)$$

$$Q_f = \frac{3}{2} v_g i_{fd},$$

and the filter currents are

$$\frac{di_{fd}}{dt} = -c_4 i_{fd} + \omega_g i_{fq} + c_5 v_{id}, \quad (53)$$

$$\frac{di_{fq}}{dt} = -c_4 i_{fq} - \omega_g i_{fd} + c_5 (v_{iq} - v_g), \quad (54)$$

where $c_4 = R_f/L_f$ and $c_5 = 1/L_f$.

The compensation and the coupling terms are

$$e_{fd} = -\frac{1}{c_5} \omega_g i_{fq}, \quad (55)$$

$$e_{fq} = v_g + \frac{1}{c_5} \omega_g i_{fd}.$$

The direct reference current i_{fd}^{ref} is

$$i_{fd}^{\text{ref}} = \frac{2}{3 v_g} Q_f^{\text{ref}}, \quad (56)$$

where Q_f^{ref} is the reference reactive power; it is given as zero to obtain a unit power factor in grid side.

Figure 6 shows the block diagram of the DFIG wind energy conversion system by PI control strategy.

Finally, there are many methods to tune the PI controller parameters (gains K_p and K_i) of rotor-side control and grid-side control. As described in [3], the compensation method for the closed loop system is not complex and it is effective, which is shown in Figure 7.

$C(s)$ is the PI controller. The transfer functions are $I_r(s)$, $V(s)$, and $I_f(s)$ of the rotor currents, DC-bus voltage, and grid currents, respectively, which are

$$\begin{aligned} C(s) &= K_p + \frac{K_i}{s}; \\ I_r(s) &= \frac{k_r}{1 + \gamma_r s}; \\ V(s) &= \frac{1}{Cs}; \\ I_f(s) &= \frac{k_f}{1 + \gamma_f s}, \end{aligned} \quad (57)$$

where: $k_r = 1/R_r$, $k_f = 1/R_f$, $\gamma_r = \sigma L_r/R_r$, and $\gamma_f = L_f/R_f$.

The rotor-side converter PI controller parameters are

$$\begin{aligned} K_p^{i_r} &= \frac{3\gamma_r}{t_{rc}k_r}; \\ K_i^{i_r} &= \frac{3}{t_{rc}k_r}, \end{aligned} \quad (58)$$

where t_{rc} is the settling time for the rotor currents.

The grid-side converter PI controller parameters:

(i) For the grid currents:

$$\begin{aligned} K_p^{i_f} &= \frac{3\gamma_f}{t_{rf}k_f}; \\ K_i^{i_f} &= \frac{3}{t_{rf}k_f}. \end{aligned} \quad (59)$$

(ii) For the DC-link voltage:

$$\begin{aligned} K_p^{V_{dc}} &= 2\zeta C\omega_0; \\ K_i^{V_{dc}} &= C\omega_0^2; \\ \omega_0 &= \frac{3}{t_{rv}\zeta}, \end{aligned} \quad (60)$$

where t_{rf} and t_{rv} are the settling time for the grid currents and the DC-link voltage, respectively and ζ is the damping coefficient; it is generally between $0 < \zeta < 1$ in terms of stability. Thus, in regulation loops of the grid side, we will take into consideration that the outer loop (v_{dc}) has a slower

FIGURE 7: The method to tune the PI controller parameters [24].

response time than the dynamics of the inner loop (i_f) [25, 26].

5.2. Wind Turbine System Control by ADRC. As mentioned previously in the Section 3, the active disturbance rejection control (ADRC) is a novel and robust control strategy. Similar to the control by PI, we elaborate the rotor-side converter and the grid-side converter controls by linear ADRC. Figure 8 shows the block diagram of the DFIG wind turbine system by ADRC control strategy connected into grid.

5.2.1. Linear ADRC Design for Rotor-Side Converter. To control rotor-side converter by ADRC, we have used two linear ADRC controllers which control the wind turbine system powers to extract the available maximum power from the wind turbine. Ultimately, to design the ADRC regulator on rotor side, we have achieved the rotor current regulations by two linear ADRC controllers, wherein equations (43) and (44) are adapted to the canonical form of linear ARDC:

$$\frac{di_{rdq}}{dt} = f_t^{i_{rdq}}(t) + b_0^{i_{rdq}} u^{i_{rdq}}(t). \quad (61)$$

(i) The design of the linear ADRC controller for d -axis rotor current loop i_{rd} :

(1) Total (external and internal) disturbances affecting the rotor current i_{rd} :

$$f_t^{i_{rd}} = -c_1 i_{rq} + \omega_r i_{rd} + (c_2 - b_0^{i_{rq}}) v_{rq}. \quad (62)$$

(2) Known parts of the controlled system parameters:

$$b_0^{i_{rd}} = c_2. \quad (63)$$

(3) Control inputs of the rotor current i_{rd} :

$$u^{i_{rd}} = v_{rd}. \quad (64)$$

(ii) The design of the linear ADRC controller for q -axis rotor current loop i_{rq} :

(1) Total (external and internal) disturbances affecting the rotor current i_{rq} :

$$f_t^{i_{rq}} = -c_1 i_{rd} + \omega_r i_{rq} - \omega_r c_3 \Psi_s + (c_2 - b_0^{i_{sq}}) v_{rq}. \quad (65)$$

(2) Known parts of the controlled system parameters:

$$b_0^{i_{rq}} = c_2. \quad (66)$$

FIGURE 8: The ADRC control strategy of the DFIG used in WECS.

(3) Control inputs of the rotor current i_{rq} :

$$u^{i_{rq}} = v_{rq}. \quad (67)$$

5.2.2. Linear ADRC Design for Grid-Side Converter. The grid-side converter is used to control the active power injected into the utility grid through the regulation of the DC-link voltage and to control the reactive power to achieve a unity power factor for wind variations. The voltage oriented control (VOC) based linear ADRC is used here and the controllers are designed as follows:

(i) The filter current controllers:

Similar to the rotor-side control, the filter currents are adapted to canonical form of linear ADRC. Replacing equations (53) and (54) into equation (68):

$$\frac{di_{fdq}}{dt} = f_t^{i_{fdq}}(t) + b_0^{i_{fdq}} u^{i_{fdq}}(t). \quad (68)$$

(1) Total (external and internal) disturbances affecting the rotor current (i_{rd} and i_{rq}):

$$\begin{cases} f_t^{i_{fd}} = -c_4 i_{fd} + \omega_g i_{fq} + (c_5 - b_0^{i_{fd}}) v_{id}, \\ f_t^{i_{fq}} = -c_4 i_{fq} + \omega_g i_{fd} - c_5 v_g + (c_5 - b_0^{i_{fq}}) v_{iq}. \end{cases} \quad (69)$$

(2) Known parts of the controlled system parameters:

$$\begin{cases} b_0^{i_{fd}} = -c_5, \\ b_0^{i_{fq}} = -c_5. \end{cases} \quad (70)$$

(3) Control inputs of the rotor currents (i_{rd} and i_{rq}):

$$\begin{cases} u^{i_{fd}} = v_{id}, \\ u^{i_{fq}} = v_{iq}. \end{cases} \quad (71)$$

(ii) The DC-link voltage controller:

In equation (19), motivated by the work in [3, 9–27], we neglect all the losses in converters, wherein, the powers P_r and P_f can be written as follows: $P_r = i_r v_{dc}$ and $P_f = i_f v_{dc}$.

The DC-link voltage equation:

$$\frac{dv_{dc}^2}{dt} = \frac{2}{C} P_r - \frac{3}{C} v_g i_{fq}. \quad (72)$$

Furthermore, we substitute $U = v_{dc}^2$:

$$\frac{dU}{dt} = c_6 P_r - c_7 i_{fq}, \quad (73)$$

where $c_6 = 2/C$ and $c_7 = (3/C) v_g$.

After adaptation of the DC-Link voltage equation to the canonical form, Linear-ADRC design for DC-Link voltage regulation is as follows.

(1) Total (external and internal) disturbances affecting the DC-link voltage v_{dc} :

$$f_t^{v_{dc}} = -c_6 P_r + (-k_7 - b_0^{v_{dc}}) i_{fq}. \quad (74)$$

(2) Known parts of the controlled system parameters:

$$b_0^{v_{dc}} = c_7. \quad (75)$$

(3) Control inputs of the DC-link voltage v_{dc} :

$$u^{v_{dc}} = i_{fq}. \quad (76)$$

FIGURE 9: The wind speed profile.

FIGURE 10: (a) The aerodynamic yield C_p and (b) the tip speed ratio λ . FIGURE 11: (a) The mechanical speed of generator ω_{mec} and (b) the blades' pitch angle β .

6. Simulation Results and Discussion

In this work, we mainly aim to develop and compare two strategies of wind turbine system control based on a DFIG to evaluate the dynamical performances and sensitivity to DFIG parameter changes. The system parameters of turbine, DFIG, filter, and grid are given in Appendix. Furthermore, the proposed wind turbine system control has been simulated using the Matlab/Simulink environment.

Figure 9 illustrates the variable wind speed profile applied on wind turbine system.

Figure 10 illustrates the mechanical characteristic of the turbine, as the power coefficient and the tip speed ratio. Figure 11 shows the generator mechanical speed and the angle of blade orientation system.

As illustrated in previous figures, due to the pitch control, the mechanical speed of the generator does not exceed the rated value when the wind speed exceeds its rated value. Moreover, once the pitch angle increases, the

FIGURE 12: (a) The stator active power P_s and (b) the stator reactive power Q_s . FIGURE 13: (a) The error between P_s and P_s^{ref} and (b) the error between Q_s and Q_s^{ref} .

FIGURE 14: (a) The currents generated through stator and (b) the currents generated through rotor.

tip speed ratio and the power coefficient of turbine decrease.

Figure 12 depicts the active and reactive power generated by the DFIG. Moreover, Figure 13 depicts the amount of

error between reference powers and measured powers for linear ADRC approach and PI approach.

Three phase winding stator currents and three phase winding rotor currents generated by DFIG are shown in Figure 14.

FIGURE 15: (a) The DC-link voltage V_{dc} and (b) the total power injected into the grid P_{gt} .

FIGURE 16: (a) Error between Q_s and Q_s^{ref} for 20% L_s and (b) error between Q_s and Q_s^{ref} for 20% L_r .

It can be noticed in Figure 14 that the three phase currents generated through rotor and stator of the DFIG depend on the wind speed. More importantly, for rotor currents, it can be seen that there is a power change between the grid and generator (subsynchronous mode and super-synchronous mode).

Figure 15 presents the DC-link voltage and the total power injected into the utility grid (stator power P_s and rotor power P_r).

To evaluate the dynamical performances of the two controls strategies when changing DFIG parameters, it is necessary to change by considering parametric variation of the rotor inductance L_r and stator inductance L_s by an increase of 20% to their nominal value. The results of this test are depicted in Figure 16.

Finally, from the previous simulation results of the control applied on the wind turbine system based on DFIG, Table 1 summarizes the performance comparison of the control Methods.

7. Conclusion

This paper presents a dynamic modeling and control of a wind turbine based on DFIG; we have been interested in the

TABLE 1: Comparison of the control methods.

Technique	Precision	Rapidity	Efficiency	Robustness
PI control	Yes	Fast	Yes	Less
ADRC control	Yes	More fast	Yes	More

TABLE 2: The parameters of the turbine.

Parameters	Values
The rated power	1.5 MW
The rated wind speed	12 m/s
Density of air	1.225 kg/m ³
Blade radius	31 m
The gearbox ratio G	59

internal behaviour of the variable speed wind system while taking into account the internal disturbances. Moreover, we have proposed and detailed the classical indirect stator flux oriented method (ISFOC) based on the PI controller and the new method by linear ADRC.

Due to wind fluctuation, the optimal torque algorithm is used to extract the maximum wind power in one hand, and in the other hand, to control the active and reactive powers exchanged with the utility grid independently, we have used

TABLE 3: The parameters of the DFIG.

Parameters	Values
The rated power P_n	1.5 MW
The rated voltage U_n	690 V
The nominal frequency	50 Hz
The rated rotor speed	1750 tr/min
The number of pole pairs	2
The stator resistance R_s	2.65 m Ω
The rotor resistance R_r	2.63 m Ω
The stator leakage inductance $L_{s\sigma}$	0.1687 mH
The rotor leakage inductance $L_{r\sigma}$	0.1337 mH
The magnetizing inductance L_m	5.4749 mH

TABLE 4: The parameters of the grid side.

Parameters	Values
The DC-link voltage V_{dc}	1320 V
The DC-link capacitance C	10028.7 μ F
The filter resistance R_r	0.1838 Ω
The filter inductance L_r	0.61187 mH

the rotor side converter (for the stator powers control) and the grid side converter (for controls the filtre powers and DC bus voltage).

Ultimately, the simulation results demonstrate that the ADRC control strategy gives very good dynamical performances and it is not sensitive to DFIG parameter changes unlike the classic control strategy by the proportional integral.

Appendix

The WEC-System parameters used for the simulation are given in Table 2 for the turbine and Table 3 for the generator parameter and for the grid side parameter Table 4 [28].

Data Availability

This paper does not include any data.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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