MODELING AND ROBUST CONTROL OF A GRID CONNECTED DIRECT Driven PMSG WIND TURBINE BY ADRC

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Abstract. In this paper, we present the modeling and control of a grid connected Variable Speed Wind Energy Conversion System (VS-WECS) based on a Direct DrivenPermanent Magnet Synchronous Generator (DD-PMSG). A new robust control has been proposed and utilized to operate the wind turbine so as to extract the maximum power from the wind energy and to ensure a unit power factor. This control is known as the Active Disturbance Rejection Control (ADRC) and it is based on the Extended State Observer (ESO). It consists in controlling, through the stator currents, the machine side converter in order to adapt the rotational speed of the generator to the different wind speed profiles (Maximum Power Point Tracking MPPT). In addition, it ensures the control of the DC bus voltage and the exchange of active and reactive powers between the wind turbine and the electrical power grid. In order to evaluate the performance of the proposed control a series of simulations are made under the MATLAB/SIMULINK environment. The results obtained by simulation show that the proposed strategy is efficient in terms of stability and precision as well as for the robustness with regard to the internal disturbances when varying the parameters of the machine.

Keywords
ADRC, ESO, MPPT, PLL, PMSG, wind turbine.

1. Introduction

In recent years, energy consumption is one of the biggest concerns because it is increasing in all its forms and it is associated with polluting effects, mainly caused by burning the fossil fuels (oil, gas, and coal). Facing up to these problems, several countries are turning to a new form of energy which is clean and inexhaustible "renewable energy" [1].

Among renewable energy sources, wind energy has the most significant energy potential and a relatively low cost of production, leading to a growing development of this sector on a global scale. Wind energy worldwide is increasing every year and production capacity has increased by a factor of 6.5 over the past ten years [2].

The total energy extracted from the wind depends not only on the incident wind speed, but also on the control applied to the WECS. Generally, the extraction of maximum wind power is achieved by using fully controlled variable speed wind turbine generators. The wind turbine rotational speed is regulated according to the incident wind speed to track the maximum wind power trajectory [3]. As a grid-connected power generation system, the wind turbine generator must have the ability to control the active and reactive powers injected to the grid. Variable speed wind turbine topologies comprise many different converters configurations, based on efficiency, cost, yearly energy capturing and the overall system control complexity [4].Permanent Magnet Synchronous Generators (PMSG) based variable speed wind turbines are considered as a suitable and practical technology in wind generation industry since they are self-excited, and thus permit high efficiency operations [5]. Additionally, the gearbox can be omitted owing to its capability of working at low rotational speed; or in other WECSs, the gearbox is one of the most critical mechanisms, as its failure is extremely expected, and, therefore, it requires careful and regular maintenance [6]. In this context, the present article de-
describes an exploitation of a PMSG based wind turbine.

Researchers are continuing to carry out investigations in order to improve the electromechanical conversion efficiency and the energy supplied quality. For PMSG variable speed WECS based on back-to-back converters, the power delivery is often controlled over the grid-side converter by using a PI controller [2] and [3]. However, it does not guarantee a zero steady-state error while controlling the currents, which is due to the presence of cross-coupling terms between d-q axis components, which results in an inappropriate power delivery [9].

In recent years, several publications have appeared documenting the application of the Active Disturbance Rejection Control (ADRC), which was originally proposed by Jingjin Han [10] and [11]. The prospective of ADRC as an effective new control strategy is evident in many case studies, where the technique is used to address a number of benchmark problems in diverse industry sectors, with promising results. However, to the authors best knowledge, very few publications are known external forces.

Our contribution in this paper is to develop a new robust control strategy for the grid connected based PMSG wind turbine by ADRC to extract the maximum power available from the turbine blades and to regulate the power delivery. For this purpose, this paper is structured as follows: the second chapter presents a general modeling of the wind energy conversion systems. In [8], the authors have proposed a predictive ADRC to overcome the time delay in wind turbine systems, and in [12], the authors have proposed an optimal MPPT control for parameters tuning based on optimization algorithms. Finally, in [13] the authors have discussed the rejection of lumped disturbance, including the system uncertainties in the internal dynamics and unknown external forces.

Our contribution in this paper is to develop a new robust control strategy for the grid connected based PMSG wind turbine by ADRC to extract the maximum power available from the turbine blades and to regulate the power delivery. This chapter presents a general modeling of the wind energy conversion systems. The third chapter introduces the mathematical model of the Active Disturbance Rejection Controller. The fourth one gives the machine and the grid side converters control by ADRC while in the fifth chapter, the simulation results of the wind energy conversion system are presented.

2. Modeling of the DD-PMSG Wind Turbine Systems

In this chapter, we are interested in modeling all the wind energy conversion chain components, going from the wind kinetic energy conversion into mechanical energy to the connection with the power grid. The studied system is shown in Fig. 1 and it consists of:

- A three-bladed, horizontal-axis wind turbine operating at different wind conditions allowing us to convert the kinetic energy into mechanical energy.
- A permanent magnetic synchronous generator with a nominal power of 750 KW that converts the mechanical energy into electrical energy.
- Two back to back converters (Machine side and Grid side Converters) interconnected via a DC bus that allows the power exchange.
- A three-phase RL filter, which connects the converters to the electrical utility grid and reduces the current total harmonics distortion.

2.1. Wind Turbine Modeling

The turbine converts the aerodynamic energy of the wind into mechanical energy. Its modeling consists in expressing the extracted power \( P_{aero} \) as a function of the incident wind speed \( V \) and the operating conditions. It is expressed by:

\[
P_{aero} = C_p(\lambda, \beta) P_w = C_p(\lambda, \beta) \frac{\rho s v^3}{2},
\]

Its aerodynamic torque \( T_{aero} \) is given by the following expression:

\[
T_{aero} = \frac{1}{2\Omega} C_p(\lambda, \beta) \rho s v^3,
\]

where \( \rho \) is the air density, generally taken equal to 1.225 kg·m\(^{-3}\).

The wind turbine aerodynamic efficiency is represented by a power factor called \( C_p \) [15]. This coefficient depends on the turbine characteristics (speed ratio \( \lambda \) and pitch angle \( \beta \)). Figure 2 shows the change of \( C_p \) for different values of \( \beta \).

\[
C_p(\lambda, \beta) = 0.5176 \left( \frac{116}{\lambda} - 0.4\beta - 5 \right) e^{\frac{-31}{\lambda}} + 0.0068\lambda,
\]

\[
\lambda = \frac{\Omega R}{V},
\]

\[
\frac{1}{\lambda} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1},
\]

where \( \Omega \) is the turbine rotational speed.

The mechanical equation of the turbine shaft which is rigidly connected to the synchronous generator is given by:

\[
J \frac{d\Omega_t}{dt} = T_{aero} - T_{em} - f\Omega_t,
\]

where \( J \) is the system total inertia, \( f \) is the friction coefficient and \( T_{em} \) represents the generator electromagnetic torque.
The machine side converter is used to control the generator torque and speed while the grid side converter regulates the DC bus voltage and ensures the delivery of the produced active power to the main power grid.

Both converters are identical and can be used in both inverter and rectifier mode. Here we present the modeling of the grid side converter.

The modulated voltages are given by:
\[
\begin{align*}
V_{f-a} &= \frac{2s_{11} - (s_{12} + s_{13})}{3} U_{dc}, \\
V_{f-b} &= \frac{2s_{12} - (s_{11} + s_{13})}{3} U_{dc}, \\
V_{f-c} &= \frac{2s_{13} - (s_{11} + s_{12})}{3} U_{dc}.
\end{align*}
\]

The modulated current \( I_{inv} \) is given by:
\[
I_{inv} = s_{11}i_{fa} + s_{12}i_{fb} + s_{13}i_{fc}.
\]

Applying Park’s transformation, Eq. (11) and Eq. (12) become as follows:
\[
\begin{align*}
V_{f-d} &= s_d U_{dc}, \\
V_{f-q} &= s_q U_{dc}, \\
I_{inv} &= s_d i_{fd} + s_q i_{fq}.
\end{align*}
\]

2.4. DC Link and Filter Modeling

The connection of the energy conversion system with the electrical power grid is carried out via a RL filter \((L_f, R_f)\). It is used to prevent harmonic currents from spreading through the electrical power grid:
\[
\begin{align*}
V_{h-a} &= V_{fa} - R_f i_{fa} - L_f \frac{di_{fa}}{dt}, \\
V_{h-b} &= V_{fb} - R_f i_{fb} - L_f \frac{di_{fb}}{dt}, \\
V_{h-c} &= V_{fc} - R_f i_{fc} - L_f \frac{di_{fc}}{dt}.
\end{align*}
\]

Applying Park’s transformation, Eq. (15) becomes in d-q frame as follows:
\[
\begin{align*}
V_{gd} &= V_{fd} - R_f i_{fd} - L_f \frac{di_{fd}}{dt} + L_f \omega g i_{fq}, \\
V_{gq} &= V_{fq} - R_f i_{fq} - L_f \frac{di_{fq}}{dt} - L_f \omega g i_{fd}.
\end{align*}
\]
where \( v_{fd}, v_{fq} \) are the inverter voltage components, \( v_{gd}, v_{gq} \) are the grid voltages and \( i_{fd}, i_{fq} \) are the filter currents.

The modeling of DC Link Voltage is given by:

\[
\frac{dU_{dc}}{dt} = \frac{1}{C} (i_{inv} - i_{dc}), \tag{17}
\]

where \( C \) is the DC link Capacitor.

3. Active Disturbance Rejection Control

3.1. Mathematical Model of ADRC

ADRC is a robust control strategy proposed by Jingqing Han in 2009 [16], it mainly consists of three parts: Tracking Differentiator (TD), Extended State Observer (ESO), and Non-Linear State Error Feedback (NLSEF). The block diagram of a first order standard ADRC is shown in Fig. 3.

\[
\begin{align*}
\text{Block diagram of a first order LADRC} \\
\text{ADRC} \\
\text{Fig. 3: Block diagram of a first order Active Disturbance Rejection Controller.}
\end{align*}
\]

In Fig. 3, \( v \) is the input signal, \( v_1 \) is the input tracking signal; \( y \) is the system feedback signal; \( z_1 \) is the estimated tracking signal; \( z_2 \) is the total disturbances estimation; \( b_0 \) is the compensation factor; \( z_2/b_0 \) is the internal and external disturbances compensation; \( u_0 \) is the initial control object by NLSEF; \( u \) is the final control signal after disturbance compensation.

For a first-order controlled object, its mathematical model of ADRC is set as [17]:

\[
\begin{cases}
\varepsilon_0 = v_1 - v,
\frac{d\varepsilon_1}{dt} = -rfal(\varepsilon_0, \alpha, \delta_0),
\varepsilon = z_1 - y,
\frac{dz_1}{dt} = z_2 - \beta_01 fal(\varepsilon, \alpha, \delta) + bu(t),
\frac{dz_2}{dt} = \beta_02 fal(\varepsilon, \alpha, \delta),
\varepsilon_1 = v_1 - z_1,
u_0 = \beta_1 fal(\varepsilon_1, \alpha_1, \delta_1),
u = u_0 - \frac{\dot{z}_2}{b_0}.
\end{cases} \tag{18-20}
\]

where the mathematical model of the TD is defined by Eq. (18). The model of ESO is given by Eq. (19), and for NLSEF block it is represented by Eq. (20). \( \beta_{01,02,1} \) are output error factors, \( fal(\varepsilon, \alpha, \delta) \) is the best function which is defined by Eq. (21). \( \delta \) is the filtering factor to ESO, and \( \alpha \) is a nonlinear factor.

In practice, the ADRC controller needs to adjust a large number of parameters and adjusting these parameters is complicated. So as to reduce the model complexity and the controller computational, a Linear ADRC design method is proposed and applied to the DD-PMSG Wind Energy Conversion System.

3.2. Linear ADRC Design

The LADRC consists of a proportional controller and an ESO [18]. The uncertainties of the system and the external disturbances are considered as a generalized disturbance. The ESO is used to estimate the system states and the generalized disturbance. The proportional controller drives the tracking error between the output of the system and the reference signal to zero. The block diagram of a first order LADRC is depicted in Fig. 4.

\[
\begin{align*}
\text{Block diagram of a first order Linear ADRC} \\
\text{LADRC} \\
\text{Fig. 4: Block diagram of a first order Linear ADRC.}
\end{align*}
\]

Considering a First Order System where the plant dynamics is given by:

\[
\frac{dy(t)}{dt} = -\frac{1}{T} y(t) + bu(t). \tag{22}
\]

External disturbance \( d \) can be added to the process by replacing \( b \) with \( b = b_0 + \Delta b \), where \( b_0 \) will characterise the system known part and \( \Delta b \) the (unknown) modeling errors part.

\[
\frac{dy(t)}{dt} = -\frac{1}{T} y(t) - \frac{1}{T} d(t) + b_0 u(t) + \Delta bu(t) = f(y, d, t) + b_0 u(t), \tag{23}
\]

where \( f(y, d, t) \) represents the system general total disturbances.
Let \( x_1 = y, \ x_2 = f, \) and \( \dot{f} = h. \)

The process state-space model is presented by:

\[
\begin{align*}
\dot{x} &= Ax + Bu + Eh, \\
y &= Cx,
\end{align*}
\]

(24)

with: \( A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \ B = \begin{bmatrix} b \\ 0 \end{bmatrix}, \ C = \begin{bmatrix} 1 & 0 \end{bmatrix}, \ E = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \ x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}. \)

The Linear Extended State Observer (LESO) is used to estimate the system state variables and the total disturbances of the system. It is represented by the following model [13]:

\[
\begin{align*}
\dot{z} &= A_2 z + B u + L (y - \hat{y}), \\
\dot{\hat{y}} &= C z,
\end{align*}
\]

(25)

where \( z \) is the observed states vector, \( z = [z_1 \ z_2]^T \) \((z_1 \ is \ the \ estimation \ of \ x_1 \ and \ z_2 \ is \ the \ estimation \ of \ x_2)\), \( \hat{y} \) is the estimated output, and \( L \) is the observer gain vector defined as:

\[ L = [2 \omega_0 \ \omega_0^2]^T, \]

(26)

\( \omega_0 \) is determined by the placement of the poles in closed-loop to ensure both fast observer dynamics and minimal perturbations sensitivity.

The control law of the system is:

\[ u = \frac{u_0 - z_2}{b_0}, \]

(27)

where \( u_0 \) is a virtual controller. We suppose that \( z_2 \) is a correct estimation of \( f(z_2 \approx f). \) By replacing Eq. (27) into Eq. (23) we obtain:

\[
\hat{y} = f + b_0 \frac{u_0 - z_2}{b_0}, \\
= f - z_2 + u_0 \approx u_0.
\]

(28)

Therefore, the system Eq. (28) can be controlled by a proportional controller \( K_p. \)

\[ u_0 = K_p (r - z_1) = K_p (r - \hat{y}), \]

(29)

\( r \) is the reference input signal to track.

The controller tuning is chosen as \( K_p = \omega_c = 4/T_{\text{settle}}, \) where \( T_{\text{settle}} \) is the closed loop desired settling time. \( \omega_0 \) is taken as \( \omega_0 = 3 \sim 7 \omega_c. \)

4. Control of the Machine Side Converter by LADRC

The MSC control is achieved by using the Linear Active Disturbance Rejection Controller that regulates the stator currents with its references, where \( I_{\text{sd ref}} \) is set to zero and \( I_{\text{sq ref}} \) is given by the Optimal Torque Control OTC-MPPT [19] block displayed in Fig. 6.

4.1. MPPT Analysis for Variable Wind Speed Turbine

To ensure maximum power extraction from the wind turbine, the rotational speed must be maintained at the optimum value of the tip speed ratio \( \lambda_{\text{opt}} \) which makes the turbine operating at \( C_p = C_{\text{p max}}. \)

Considering the relationship between the wind speed \( V \) and the tip speed ratio \( \lambda \) in Eq. (4), the wind turbine power can be expressed as a function of the rotational speed \( \Omega_m: \)

\[ P_t = 0.5 \rho \pi R^5 \frac{C_p (\lambda, \beta)}{\lambda^3} \omega_m^3. \]

(30)

Replacing \( \lambda \) by \( \lambda_{\text{opt}} \) and place in \( C_p (\lambda, \beta) = C_{\text{p max}}, \) the wind turbine maximum power can be expressed as:

\[ P_{t \text{ max}} = K_{\text{opt}} \omega_m^3, \]

(31)

where \( K_{\text{opt}} \) is a coefficient given by:

\[ K_{\text{opt}} = 0.5 \rho \pi R^5 \frac{C_{\text{p max}}}{\lambda_{\text{opt}}^3}. \]

(32)

So the torque reference \( T_{\text{em- ref}} \) is expressed as follows:

\[ T_{\text{em- ref}} = K_{\text{opt}} \omega_m^2. \]

(33)
4.2. LADRC Design for Machine Side Control

The Zero Direct axis Control (ZDC) is used to obtain the references of currents used in control [20]. The three phase stator currents \( i_{abc} \) are converted into d-q axis frame using Park’s transformation technique, and then, the d-axis current \( i_d \) is to be set to zero and the q-axis current \( i_q \) is to be set equal to the stator current \( i_s \).

\[
i_s = \sqrt{i_d^2 + i_q^2} = i_q. \quad (34)
\]

Consequently, for \( i_d = 0 \) the electromagnetic torque can be controlled by \( i_q \):

\[
T_{em} = \frac{3}{2} P \psi f_i q. \quad (35)
\]

Hence:

\[
T_{em-ref} = \frac{3}{2} P \psi f i qref, \quad (36)
\]

\[
i_{qref} = \frac{2}{3P} T_{em-ref}. \quad (37)
\]

The stator currents regulations is achieved by two ADRC controllers, where the equations of \( i_d \) and \( i_q \) are adapted to the canonical from of ADRC.

\[
\frac{dy(t)}{dt} = f(y, d, t) + b_0 u(t). \quad (38)
\]

For the d-axis current we have:

\[
\frac{di_d(t)}{dt} = -\frac{R_s}{L_d} i_d + \omega_c i_q \frac{L_q}{L_d} + \frac{v_d}{L_d}, \quad (39)
\]

where:

\[
\begin{align*}
    f(y, d, t) &= -\frac{R_s}{L_d} i_d + \omega_c i_q \frac{L_q}{L_d}, \\
    b_0 &= \frac{1}{L_d}, \\
    u &= v_d.
\end{align*}
\]

And for the q-axis we have:

\[
\frac{di_q(t)}{dt} = -\frac{R_s}{L_q} i_q - \omega_c i_d \frac{L_d}{L_q} - \psi_L L_q + \frac{v_q}{L_q}, \quad (40)
\]

and:

\[
\begin{align*}
    f(y, d, t) &= -\frac{R_s}{L_q} i_q - \omega_c i_d \frac{L_d}{L_q} - \psi_L, \\
    b_0 &= \frac{1}{L_q}, \\
    u &= v_q.
\end{align*}
\]

5. Control of the Grid Side Converter by LADRC

The grid side converter is used to deliver the generated power into the electrical grid. The LADRC controller is used to stabilize the dc-link voltage and to adjust the active and reactive powers delivery into the grid during wind variations to achieve unity power factor. The GSC can be controlled either by Voltage Oriented Control (VOC) or Direct Power Control (DPC) technique. VOC is considered to be more efficient due to lower energy losses and to lower current distortion compared to DPC [21].

As illustrated in Fig. 7, VOC is used to control the GSC and it involves a dual-loop control structure: an outer loop to control the DC link voltage and an inner loop to control the grid currents.

The Phase Locked Loop device (PLL) is used to obtain the phase angle and frequency from the grid voltages [22]. The d-axis component of the synchronous reference frame is aligned with the grid voltage \( v_{gd} = v_g \) and the q-axis component was set to zero \( v_{gq} = 0 \).

The active and reactive powers are then given by:

\[
\begin{align*}
    P_g &= \frac{3}{2} v_g d f_d, \\
    Q_g &= -\frac{3}{2} v_g d f_q. \quad (43)
\end{align*}
\]

5.1. DC Bus Voltage Control by LADRC

The power across the DC link Capacitor C, can be expressed by:

\[
P_{dc} = U_{dc}(i_{rec} - i_{inv}). \quad (44)
\]

By substituting Eq. [17] by Eq. (44), we get:

\[
P_{dc} = C U_{dc} \frac{dU_{dc}}{dt}. \quad (45)
\]

If all the losses in the filter, the power electronics converters, and in the capacitor are neglected, the exchanged powers on the DC bus are expressed by:

\[
P_{dc} = P_{in} - P_{g}. \quad (46)
\]
where $P_{m}$, $P_{g}$ are the generator and grid powers respectively.

By taking into account Eq. (43), Eq. (44) and Eq. (45), the DC bus voltage can be expressed by:

$$CU_{dc} \frac{dU_{dc}}{dt} = U_{dc}i_{rec} - \frac{3}{2}v_{gd}i_{fd}. \quad (47)$$

Or:

$$\frac{dU_{dc}^2}{dt} = \frac{2U_{dc}}{C}i_{rec} - \frac{3}{2}v_{gd}i_{fd}. \quad (48)$$

We put $X = U_{dc}^2$:

$$\frac{dX}{dt} = \frac{2\sqrt{X}}{C}i_{rec} - \frac{3}{2}v_{gd}i_{fd}. \quad (49)$$

so we obtain:

$$\begin{cases}
  f(y, d, t) = \frac{2\sqrt{X}}{C}i_{rec}, \\
  b_0 = -\frac{3}{2}v_{gd}, \\
  u = i_{fd}.
\end{cases} \quad (50)$$

### 5.2. Control of Filter Currents by LADRC

The external voltage regulation loop makes it possible to maintain the voltage across the capacitor $U_{dc}$ and to generate the current reference $i_{fd-ref}$ for the internal current loop.

For the current $i_{fq-ref}$, it is calculated by the desired delivery of reactive power.

$$i_{fq-ref} = -\frac{2}{3v_{gd}}Q_{f-ref}. \quad (51)$$

Then, similar to the machine side control, the filter currents are given in canonical form of ADRC.

For d-axis current:

$$\frac{di_{fd}}{dt} = \frac{1}{L_f}(-R_fi_{fd} - v_{gd} + L_f\omega_gi_{fq}) + \frac{v_{fd}}{L_f} \quad (52)$$

with:

$$\begin{cases}
  f(y, d, t) = \frac{1}{L_f}(-R_fi_{fd} - v_{gd} + L_f\omega_gi_{fq}), \\
  b_0 = \frac{1}{L_f}, \\
  u = v_{fd}.
\end{cases} \quad (53)$$

For q-axis current:

$$\frac{di_{fq}}{dt} = \frac{1}{L_f}(-R_fi_{fq} - L_f\omega_gi_{fd}) + \frac{v_{fq}}{L_f} \quad (54)$$

with:

$$\begin{cases}
  f(y, d, t) = \frac{1}{L_f}(-R_fi_{fq} - L_f\omega_gi_{fd}), \\
  b_0 = \frac{1}{L_f}, \\
  u = v_{fq}.
\end{cases} \quad (55)$$

### 6. Results and Discussion

To validate the theoretical study and the effectiveness of the presented control strategy, a complete structure of WECS composed of a variable speed wind turbine, a PMSG, and an electronic power converters connected to the grid are designed under MATLAB Simulink environment.

To examine the tracking effectiveness of the proposed control, a variable wind speed profile is applied as shown in Fig. 8. The simulation parameters are given in App. A.

As can be noticed in Fig. 11, the power coefficient has been maintained at its optimal value ($C_{pmax} = 0.48$) which shows the effectiveness of the MPPT strategy in terms of maximum power extraction.
The response of the linear ADRC shows a good tracking characteristics as highlighted in Fig. 12 and Fig. 13 where the direct axis current $I_d$ was maintained to zero and the quadrature current $I_q$ track its references. The generated currents are shown in Fig. 14.

Figure 15 shows that the DC link voltage $V_{dc}$ is maintained at its reference with some fluctuations which are due to the stochastic nature of wind speed. Also we notice in Fig. 16 and Fig. 17 that the linear ADRC regulates the grid currents to their references.

Figure 18: Active power injected to the grid.
The control of the active and reactive powers is also achieved as shown in Fig. 18, Fig. 19, and Fig. 20 where the extracted power from the wind turbine was injected into the grid and the reactive power was set to zero to ensure a unit power factor.

![Fig. 19: Reactive power injected to the grid.](image)

![Fig. 20: Grid voltage V_a and Grid Current I_a.](image)

In order to test the robustness of the proposed control strategy, another test was carried out in which we have changed the internal parameter of the PMSG, the stator inductance $L_s$, by an increase of 50 % of the nominal value. The results obtained by LADRC are compared with the classical PI controller. The utilized wind speed profile is given in Fig. 21.

![Fig. 21: Wind speed profile.](image)

So as a closing statement, the simulation results have demonstrated that the proposed strategy is efficient in terms of stability, rapidity, accuracy and for the robustness regarding the variation of the parameters of the machine.

7. Conclusion

This paper deals with the modelling and control of a wind energy conversion system based on a permanent magnet synchronous generator. A new control...
strategy has been proposed to operate the wind turbine with the aim to extract the maximum power from the wind energy and deliver it to the utility grid. This control strategy is known as the Active Disturbance Rejection Control. It has been presented and applied to the machine and the grid side converters. The objective consists in controlling the stator currents for adapting the PMSG rotational speed with the wind speed by acting on the electromagnetic torque of the generator (MPPT). The control of the active and the reactive powers was obtained by regulating the DC bus voltage and by controlling the grid currents according to their references.

The results have demonstrated that the suggested control strategy is efficient in terms of fast tracking and robustness for internal and external disturbances compared to the classical PI controller.

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Appendix A

PMSG Wind Turbine Parameters

- Radius: \( R = 24 \) m,
- Nominal wind speed: \( V_v = 12 \) m\( \cdot \)s\(^{-1} \),
- Total inertia of the mechanical transmission: \( J_T = 10^5 \) kg\( \cdot \)m\(^2\),
- \( C_{P_{max}} = 0.48 \),
- \( \lambda_{optimal} = 8.1 \),
- Nominal power: \( P_n = 750 \) kW,
- Stator resistance: \( R_s = 6.52 \cdot 10^{-3} \) Ω,
- Stator inductance: \( L_s = L_d = L_q = 3.85 \cdot 10^{-3} \) H,
- Flux: \( \Psi = 8.53 \),
- Pair poles: \( P = 26 \),
- DC bus voltage: \( V_{dc} = 1500 \) V,
- DC bus capacitor: \( C = 5000 \cdot 10^{-6} \) F,
- Filter Resistance: \( R_f = 0.1 \) Ω,
- Filter Inductance: \( L_f = 2 \cdot 10^{-3} \) H.