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An Active Disturbance Rejection Control of Large Wind Turbine Pitch Angle Based on Extremum-Seeking Algorithm

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Abstract: This paper proposes the analysis and design of the linear active disturbance rejection controller (LADRC) for the pitch angle model of a large wind turbine generator (WTG). Since the transfer function of the pitch control system exhibits nonminimum-phase characteristics, the parameters of LADRC are difficult to tune using the conventional bandwidth method. On the basis of PI controller parameters to first-order LADRC parameters, an optimization problem is proposed in this paper to find the parameters of an LADRC for the pitch control system under the constraint of robustness measure, and the extremum-seeking (ES) algorithm is used to solve the problem. Simulation results show that LADRC can achieve better tracking and disturbance rejection performance than traditional PI control without loss of robustness against time delay.

Keywords: pitch angle control; wind turbine; time delay; linear active disturbance rejection controller; PI control; extremum-seeking algorithm

1. Introduction

In the past few decades, renewable wind energy has received much attention, and wind power generation technology has developed rapidly [1–3]. As the power demand of wind turbines continues to increase, the size of wind turbine blades also increases with it. It is crucial to develop a feasible and reliable wind power system control strategy that matches it.

The PID controller has become an important strategy of wind turbine pitch angle control because of its simplicity and robustness. In [4], a graphical method is proposed to determine the stable boundary value of the pitch angle PI controller, but its complexity increases exponentially with the increase in the system order. In [5], an expert PID controller based on a track-differentiator is proposed, but the controller has difficulties in reasonably extracting the required differential signals. In [6], gain and phase margins (GPMs) are introduced and effective graphical methods are used to determine the stable range of PI controller, but the optimal dynamic response cannot be achieved. In [7], an accurate analysis method for correlation stability of a fractional order PID controller with a certain time delay is proposed. In [8,9], a delay margin calculation method is proposed that considers both the stability of a large wind turbine and GPMs in the frequency domain, but it is too complex to calculate. In [10], a two-degree-of-freedom linearized model was constructed to capture the coupled effects of blade flap and tower fore-aft motions. In [11], a novel PID controller was proposed, which considered PI parameter settings, unknown delay estimation and actual output delay compensation of a blade pitch angle control system. In general, the wind turbine pitch system can be described with a mathematical model, which is usually a high-order oscillating system with time delay. It increases the complexity of designing a PID controller. For this type of system, conventional PID cannot overcome various disturbances well, and its rapidity and tracking are not satisfactory.
With the emergence and rapid development of advanced control technologies, in order to achieve better control performance, they are gradually applied to the wind turbine pitch angle control system. The authors of [12] proposed an adaptive fuzzy controller with self-tuning fuzzy sliding film compensation, but the additional noise of the fuzzy controller cannot be completely eliminated, and the expected control effect may not be achieved due to the influence of the pitch rate limitation. In [13–15], a pitch angle control system based on a hydraulic valve control motor was proposed, but this system has too low of an operating efficiency and is unlikely to be used in practice. In [16], the linear quadratic Gaussian (LQG) technique was proposed. The controller has good performance in terms of phase and gain margin, but it cannot adapt to the characteristics of nonlinear wind turbines. In [17,18], a collective pitch angle controller based on the Radial Basis Function Neural Network (RBFNN) was designed, and particle swarm optimization was used to optimize RBNFF. However, due to the complexity of the structure, it is hard to apply. The authors of [19] proposed PSO-RBF algorithms that were successfully effective in wind turbine generator systems with and without time delay. These advanced control techniques cannot be immediately applied to practice due to the limitations of reality.

Considering the unsatisfactory performance of PI controllers and the complicated structure of advanced controllers, this paper proposes to apply the active disturbance rejection controller in wind turbine pitch control. Active disturbance rejection control (ADRC) technology is a simple and practical new control technology proposed by Han [20]. It is independent of the system model and can better compensate the external disturbances and internal uncertainties of the system. Gao later proposed a linear active disturbance rejection controller (LADRC) [21,22], and the structure and parameters of LADRC have been greatly simplified. Because of its strong disturbance rejection ability and its simple structure, it has become a potential substitute for PID control [23]. However, because the wind turbine pitch angle transfer function is a non-minimum phase, the traditional bandwidth method is difficult to use to tune its parameters; thus, this paper proposes to optimize the LADRC parameters under the robustness constraint.

The rest of this paper is arranged as follows: Section 2 introduces the transfer function models of the pitch angle control system under different working conditions, and the frequency characteristics are analyzed. Section 3 introduces the active disturbance rejection control technology, and under the given robustness, the parameters of the active disturbance rejection controller designed for the pitch angle control system are optimized by ES algorithm. Section 4 simulates and compares the control performance and robustness of the designed LADRC and PI controllers, and shows that the LADRCs have better performance. Section 5 summarizes and prospects the effects of the control method proposed in this paper.

2. System Model

Figure 1 is a block diagram of the entire wind turbine control system. First, the wind meter measures the speed and the direction information from the wind as an input signal and transmits it to the controller. The controller calculates the reference value of the pitch angle of the wind turbine according to the wind speed and direction information, and the pitch angle controller drives the actuator to change the pitch angle of the wind turbine according to the deviation between the actual pitch angle and the reference value of the pitch angle. The torque signal of the rotor affects the output power of the generator. There are delays in the wind speed measurement and in the pitch angle signal from the hydraulic drive unit. This brings great difficulties to the analysis and design of the pitch control strategy [4,17].
Anemometer

Pitch Angle Reference Generator

Generator Power

Pitch Controller

Hydraulic Pressure Unit

Figure 1. Control architecture of a large wind turbine.

In order to make better use of control theory to design LADRC, the wind turbine pitch angle model can be identified. At some operation point, the transfer function from pitch to tower fore-aft deflection is as follows:

\[ G_p(s) = \frac{a_2s^2 + a_1s + a_0}{b_4s^4 + b_3s^3 + b_2s^2 + b_1s + b_0} e^{-\tau s}. \]  

(1)

Here, \( a_2, a_1, a_0, b_4, b_3, b_2, b_1 \) and \( b_0 \) represent the time constant of the wind power model, and its value depends on the configuration of the wind power model. \( \tau \) is the overall delay in signal measurement.

The above transfer function was evaluated for various turbine configurations and operating conditions.

WT1: Rotor diameter = 70 m, tower height = 90 m, rated power = 1.5 MW, operating conditions: wind speed = 15 m/s, pitch angle = 0.

\[ G_1(s) = \frac{2.426s^2 - 4.6345s - 147.3}{s^4 + 4.857s^3 + 126.2s^2 + 266.4s + 3659} e^{-0.25s}. \]  

(2)

WT2: Rotor diameter = 15 m, tower height = 25 m, rated power = 50 kW, operating conditions: wind speed = 15 m/s, pitch angle = 0.75.

\[ G_2(s) = -\frac{0.2545s^2 - 0.0647s + 0.9384}{s^4 + 2.28s^3 + 878.5s^2 + 437.7s + 7.7 \times 10^4} e^{-0.25s}. \]  

(3)

WT3: Rotor diameter = 27 m, tower height = 42 m, rated power = 275 kW, operating conditions: wind speed = 15 m/s, pitch angle = 0.

\[ G_3(s) = -\frac{0.6219s^2 - 8.7165s - 2911}{s^4 + 5.018s^3 + 691.3s^2 + 1949s + 1.15 \times 10^5} e^{-0.25s}. \]  

(4)

These wind turbine parameters are obtained from [4]. The three transfer functions obtained are compared with the non-linear simulation prediction in the aeroelastic wind turbine simulator FAST [24], and it is found that the responses are consistent.

All transfer functions have oscillatory modes with small damping ratios. The Bode diagrams of the three transfer functions are shown in Figure 2. It is found that \( G_1 \) has an oscillatory mode around 7 rad/s. \( G_3 \) is similar to \( G_1 \), but its oscillation mode is higher (around 11 rad/s). \( G_2 \) is different from \( G_1 \) and \( G_3 \). It has two oscillation modes with smaller magnitude at 10 and 12 rad/s, respectively; thus, it will be more difficult to control \( G_2 \) than \( G_1 \) and \( G_3 \).
where $n$ represents the (relative) order of the controlled plant, $b$ represents the high-frequency gain of the controlled plant, and $f$ is the combination of unknown system dynamics and external disturbances, called “total disturbance”. An extended state observer can be used to estimate the total disturbance. Let

$$z_1 = y, z_2 = \dot{y}, \ldots, z_n = y^{(n-1)}, z_{n+1} = f.$$  

(6)

Suppose $f$ is differentiable and $\dot{f} = p$. Then, the system model (6) can be written as

$$\begin{cases} \dot{z} = A_sz + B_su + E_sp, \\ y = C_sz, \end{cases}$$  

(7)
where \( z = [z_1 \ z_2 \ \cdots \ z_n \ \hat{z}_{n+1}]^T \),

\[
A_c = \begin{bmatrix}
0 & 1 & 0 & \cdots & 0 \\
0 & 0 & 1 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & 1 \\
0 & 0 & 0 & \cdots & 0
\end{bmatrix}_{(n+1) \times (n+1)}
\]

\[
B_c = \begin{bmatrix}
0 & 0 & \cdots & b & 0
\end{bmatrix}_T^{(n+1) \times 1^n}
\]

\[
E_c = \begin{bmatrix}
0 & 0 & \cdots & 0 & 1
\end{bmatrix}_T^{(n+1) \times 1^n}
\]

\[
C_c = [1 \ 0 \ 0 \ \cdots \ 0]_1 \times (n+1)
\]

Design a full-order linear extended state observer (ESO):

\[
\hat{\dot{z}} = A_c \hat{z} + B_c u + L_o (y - C_c \hat{z}). \tag{8}
\]

where \( \hat{\dot{z}} \) represents the estimated value of \( z \), \( L_o \) represents the observer gain:

\[
L_o = [\beta_1 \ \beta_2 \ \cdots \ \beta_n \ \beta_{n+1}]^T. \tag{9}
\]

When \( A_c - L_o C_c \) is asymptotically stable, \( \hat{z}_1(t), \cdots, \hat{z}_n(t) \) approaches the output \( y(t) \) and its derivatives, respectively, and \( \hat{z}_{n+1}(t) \) approaches \( \hat{f} \). The disturbance rejection control law can be selected as follows:

\[
u(t) = \frac{k_1 (\hat{f}(t) - \hat{z}_1(t)) + \cdots + k_n (\hat{f}^{(n-1)}(t) - \hat{z}_n(t)) - \hat{z}_{n+1}(t)}{b} = K_o (\hat{f}(t) - \hat{\dot{z}}(t)). \tag{10}
\]

where \( K_o \) represents the feedback control gain, which is defined as:

\[
K_o = [k_1 \ k_2 \ \cdots \ k_n \ 1]/b, \tag{11}
\]

\( \hat{f}(t) \) represents the generalized reference input signal:

\[
\hat{f}(t) = [r(t) \ \dot{r}(t) \ \cdots \ \dot{r}^{(n-1)}(t) \ 0]T. \tag{12}
\]

Taking the first-order LADRC as an example, its structural block diagram is shown in Figure 3, where \( P \) is the controlled plant.

![Figure 3](image)

**Figure 3.** Structure of first-order LADRC.

The performance of LADRC can be adjusted by two gains: \( L_o \), the observer gain of ESO, and \( K_o \), the controller gain. For practical reasons, the adjustment of these two gains
is reduced to two tuning parameters as suggested in [22]: $\omega_c$, the controller bandwidth, and $\omega_o$, the observer bandwidth. The idea is to place all the poles of the ESO at the same location $-\omega_0$ and all the poles of the state-feedback control at $-\omega_c$.

Since the pitch control plant is a fourth-order model with delay and weak under-damped oscillation modes, the existing LADRC tuning is not suitable for this kind of dynamics; that is, the LADRC tuning based on the bandwidth method cannot achieve good results.

In order to obtain better LADRC parameters, the existing PI controller parameters can be converted into first-order LADRC parameters. First-order LADRC can be equivalent to a dual-free controller system, and we can obtain a transmission from control signal $u$ to output $y$:

$$K_c(s) = K_o(sI - A_e + B_eK_o + L_oC_e)^{-1}L_o$$

$$= \frac{(k_1\beta_1 + \beta_2)s + k_1\beta_2}{b_5(s + k_1 + \beta_1)} \times \frac{1}{s + 1}$$

(13)

where $k'_p$ and $k'_i$ are generalized proportional and integral gain, respectively.

According to [25], the Equation (14) can be obtained:

$$\begin{cases} 
  k'_i = \frac{b}{\varphi_2}k_i \\
  \frac{1}{\varphi_2}\left(k'_i + \varphi_2k'_p\right) = k_p'
\end{cases}$$

(14)

where $\varphi_2 = \beta_2/\beta_1$, $k_p$ and $k_i$ are the parameters of the proportional and integral of PI controller, respectively.

The above equation can be further reduced to polynomials of $b$ and $\varphi_2$

$$\varphi_2^2 - bk_p\varphi_2 + bk_i = 0$$

(15)

By fixing the parameter $b$, this equation can be solved and the parameters of first-order LADRC can be obtained.

### 3.2. Robust LADRC Design

Since there are uncertainties in the model of the pitch control system, the designed controller must possess a certain degree of robustness with respect to uncertainties, and we propose to solve the following optimization problem to obtain the “optimal” parameters for LADRC. The general idea is to optimize the disturbance rejection ability of the closed-loop system under a certain robustness constraint.

$$\min_{b, K_o, L_o} \int_0^{\infty} t e(t)^2 dt$$

s.t. $\varepsilon < \eta$

(16)

where $e(t)$ is the error between the output of the system and the reference input for step disturbance at the input of the controlled plant, and the cost function is the integral time squared error (ITSE). $\varepsilon$ is the robustness of the system [26], and $\eta$ is the expected closed-loop robustness $\eta = 2.5$ in the paper. For single variable systems:

$$\varepsilon = \sup_{\omega} (\|S\|_{\infty} + \|T\|_{\infty})$$

(17)

where $S$ and $T$ are the sensitivity function and complementary sensitivity function of the closed-loop system, respectively. The larger the value of $\varepsilon$ is, the weaker the robustness is and the better the disturbance rejection is. Similarly, the smaller $\varepsilon$ is, the better the robustness is, and the worse the disturbance rejection performance is.
3.3. Extremum-Seeking Algorithm

In order to obtain a better control effect, this paper proposes a LADRC parameter optimization based on ES algorithm. The extremum-seeking algorithm is a kind of adaptive control algorithm that can search and keep the controlled object in the extreme value working state [27–29]. ES is a nonmodel-based method that iteratively modifies the arguments of a cost function (in this application, the LADRC parameters) such that the output of the cost function reaches a local minimum or local maximum. Figure 4 shows a block diagram of multi-parameter extremum seeking. Equations (18)–(20) show the ES principle formula.

\[
\xi(k) = -h\xi(k-1) + f(\theta(k-1)) \tag{18}
\]

\[
\hat{\theta}_i(k+1) = \hat{\theta}_i(k) - \gamma_i \alpha_i \cos(\omega_i k) [f(\theta(k)) - (1 + h)\xi(k)] \tag{19}
\]

\[
\theta_i(k+1) = \hat{\theta}_i(k+1) + \alpha_i \cos(\omega_i k + 1) \tag{20}
\]

where, \(\xi(k)\) is a scalar; subscript \(i\) represents the \(i\)th entry of the vector; \(\gamma_i\) is adaptive gain; \(\alpha_i\) is perturbation amplitude. Stability and convergence are affected by the value of \(\gamma_i, \alpha\) and the shape of the cost function \(f(\theta)\) near the extreme value. The modulation frequency \(\omega_i\) is selected to enable \(\omega_i = a^i \pi\), where \(a\) meets \(0 < a < 1\). In addition, a high pass filter \((z - 1)/(z + h)\) is designed to \(0 < h < 1\). In the paper, \(a = 0.5\) and \(h = 0.8\). The cutoff frequency is much lower than the modulation frequency \(\omega_i\).

![Figure 4](image_url)

**Figure 4.** Diagram of the multi-parameter extremum-seeking algorithm.

First-order ADRC can be equivalent to a two-degree-of-freedom system, in which \(C_1(s)\) softens the feed quantity and \(C_2(s)\) compensates for the feedback quantity. For a normal simulation, it is necessary to add a pole to \(C_1(s)\), and to set the frequency \(f_p\) of the pole several orders of magnitude higher than the original pole, without affecting the control effect. The overall extreme value search algorithm LADRC setting scheme is shown in Figure 5.

![Figure 5](image_url)

**Figure 5.** Diagram of overall extremum-seeking algorithm LADRC tuning.
In the figure,

\[ C_1(s) = \frac{K_p s^2 + \beta_1 K_p s + \beta_2 K_p}{(\beta_2 + \beta_1 K_p) s^2 / f_p + (\beta_2 + \beta_1 K_p + \beta_2 K_p / f_p) s + \beta_2 K_p} \]  
\[ C_2(s) = \frac{(\beta_2 + \beta_1 K_p) s + \beta_2 K_p}{\beta s^2 + (b \beta_1 + b K_p) s} \]

The core idea of the paper is to minimize the ITSE index to obtain the optimal value of the LADRC parameters \( k_1, \beta_1, \beta_2, b \) under a certain robustness measure and to obtain the transfer function of the LADRC feedback controller. The specific step is shown in Figure 6, where the robustness measure is chosen between 2 and 2.5. ITSE* represents the upper bound of the expected ITSE value.

**Figure 6.** The process of optimizing the parameters of first-order LADRC by ES.

### 3.4. Design Results

According to the parameters transformed by PI and optimized by the ES algorithm, the parameters for first-order LADRC are shown in Table 1. It is noted that the parameters are not “optimal” since problem (16) is noncovex and the algorithm may not reach the global optimum. Nevertheless, the locally optimal parameters can achieve better performance compared with the robust PI controllers designed in [4], as shown in the following section.
Table 1. Parameters and performance of designed controllers.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Controller</th>
<th>$k_1$</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>$b$</th>
<th>ITSE</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_1$</td>
<td>PI ($K_p = 0.5; K_i = -15$)</td>
<td>−21.0977</td>
<td>120</td>
<td>$7.1098 \times 10^3$</td>
<td>100</td>
<td>0.1148</td>
<td>2.67</td>
</tr>
<tr>
<td></td>
<td>1st order LADRC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1st order LADRC (ES)</td>
<td>−22.6061</td>
<td>24.8238</td>
<td>149.2546</td>
<td>90.94</td>
<td>0.1127</td>
<td>2.04</td>
</tr>
<tr>
<td>$G_2$</td>
<td>PI ($K_p = 250; K_i = 10000$)</td>
<td>45.6371</td>
<td>−30</td>
<td>$6.7106 \times 10^4$</td>
<td>17.5</td>
<td>1.0387</td>
<td>5.16</td>
</tr>
<tr>
<td></td>
<td>1st order LADRC</td>
<td>9.51</td>
<td>−7.7</td>
<td>8080</td>
<td>1.75</td>
<td>0.8737</td>
<td>2.59</td>
</tr>
<tr>
<td></td>
<td>1st order LADRC (ES)</td>
<td>45.6371</td>
<td>−30</td>
<td>$6.7106 \times 10^4$</td>
<td>17.5</td>
<td>1.0387</td>
<td>5.16</td>
</tr>
<tr>
<td>$G_3$</td>
<td>PI ($K_p = 1; K_i = -9$)</td>
<td>−6.7</td>
<td>20</td>
<td>534.66</td>
<td>20</td>
<td>0.3872</td>
<td>2.82</td>
</tr>
<tr>
<td></td>
<td>1st order LADRC</td>
<td>−5.1966</td>
<td>12.8487</td>
<td>103.7111</td>
<td>2.4125</td>
<td>0.0827</td>
<td>2.07</td>
</tr>
<tr>
<td></td>
<td>1st order LADRC (ES)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

4. Discussion

This section compares the first-order LADRC based on PI transformation and ES optimization parameters and the traditional PI controller designed for three different wind turbines under specific working conditions to clarify the superiority of the LADRC control.

For tracking performance, a unit step setpoint is inserted at $t = 0$ s, and for disturbance rejection performance, a unit disturbance with an amplitude of $-1$ is inserted at 1 s. The setpoint responses and the disturbance responses of the three systems are shown in Figures 7–9. In addition, the robustness of each controller is analyzed.

**Figure 7.** (a) Evolution of the cost function; (b) robustness of the controllers; (c) output signal; (d) disturbance responses during experiments of a closed-loop system with $G_1$. 
For large wind turbine $G_1$, Figure 7a shows that ES minimizes the cost function (16) to LADRC parameters that produce a local minimum. In Figure 7b, the robustness of the system under the control of a PI controller and the first-order LADRC is close; both are around 2.63. The optimized first-order LADRC robustness is lower than them, only 2.04, which means stronger robustness. At the same time, the LADRC itself has strong disturbance rejection performance, which can make up for the disadvantages of low robustness. As shown in Figure 7c, the optimized first-order LADRC has reached a steady state in 5 s without overshoot, and the rise is stable. The first-order LADRC and PI controllers fluctuated greatly and slowed down during the rising process, and did not reach the steady state until 10 s. As shown in Figure 7d, when the system is disturbed, the oscillation amplitude of the PI controller and the first-order LADRC is large and the speed to steady state is slow. However, the maximum amplitude of the optimized first-order LADRC is only half of them, and the time to reach steady state is nearly twice as fast and only takes 5 s, which greatly improves the disturbance rejection ability of the system.

For small wind turbine $G_2$, Figure 8a shows that ES minimizes the cost function to produce a local minimum. It can be seen from Figure 8b that $G_2$ has the worst robustness under PI controller. The robustness of the system under the control of the first-order LADRC is about 2.59, and the optimized first-order LADRC is about 2.0, the robustness is lower than the value of 5.1 for the PI controller. The dynamic characteristics of $G_2$ are different from $G_1$. There are two oscillation modes, which will oscillate violently under the disturbance. As shown in Figure 8d, when the system is disturbed, the oscillation amplitude of the PI controller is the highest and the speed to the steady state is the slowest, while the oscillation amplitude of the first-order LADRC is only $2/3$ of that of the PI controller, and the steady state time is also reduced by half. It only takes 3.5 s. The performance of the first-order LADRC optimized by the ES algorithm is greatly increased, and the maximum oscillation
amplitude is only half of the original, which greatly improves the disturbance rejection ability of the system. In Figure 8c, the optimized first-order LADRC has reached a steady state at 10 s, and its response speed is significantly faster than that of PI and first-order LADRC. The unoptimized LADRC and PI controller rise slowly, and still have not reached steady state at 20 s.

![Figure 9a](image1.png)  ![Figure 9b](image2.png)  ![Figure 9c](image3.png)  ![Figure 9d](image4.png)

Figure 9. (a) Evolution of the cost function; (b) robustness of controllers; (c) output signal; (d) disturbance responses during experiments of a closed-loop system with $G_3$.

For medium wind turbine $G_3$, the convergence curve of the cost function of $G_3$ is shown in Figure 9a. It can be seen from Figure 9b that, compared with the PI control, the robustness of the first-order LADRC is similar to that of the optimized first-order LADRC, which is much lower than that of PI controller around 2. The response is shown in Figure 9c. The response curves of the three controllers are compared. The optimized first-order LADRC is faster than the first-order LADRC and faster than the PI controller, and it only takes 3 s to reach the steady state. After the oscillation is caused by disturbance in Figure 9d, the oscillation amplitude under the control of LADRC is similar and small, reaching steady state faster, which reflects the strong disturbance rejection ability.

It can be seen from the above simulation results that LADRC can achieve better control effects than PI for the pitch angle system with large time delay. It can be seen that LADRC is more prominent than PI in terms of regulation speed and has a shorter rise time. For disturbance rejection, LADRC can significantly reduce the drop rate of the system setpoint, reflecting strong disturbance rejection ability. The ES algorithm parameters are simply optimized, and the effect is good. The optimized first-order LADRC has better control performance than the first-order LADRC. The above examples show that LADRC can be applied to oscillating systems with large time delays and can achieve satisfactory control results.
To further clearly demonstrate the robustness of the system, step and disturbance response experiments were performed with the time delay of the controlled object changed by 30%. The step and disturbance response curves are shown in Figures 10–12. For $G_1$ shown in Figure 10, the robustness of both the PI controller and the designed LADRC is acceptable, and the control effect is still ideal when the time delay changes. For $G_2$ shown in Figure 11, the robustness of the PI controller is weaker against the time delay. The closed-loop system under the PI controller is unstable and diverges seriously. The first-order LADRC also exhibits divergence characteristics when the time delay increases. In contrast, the optimized first-order LADRC has excellent robustness and can quickly and smoothly reach the setpoint regardless of the time parameter changes. For $G_3$ shown in Figure 12, the robustness of the PI controller is not desired. Although the closed-loop system is stable under PI when the delay time is increased by 30%, both the step and disturbance curves of the controlled system show a divergent trend when the delay time is decreased by 30%. As the delay time increases or decreases, the LADRC has a little overshoot, but the overall control effect is satisfactory, which shows that the designed LADRC has better robustness.

**Figure 10.** Response of $G_1$ under PI and LADRCs with different time delay. Step response curve when $\tau$ decreases by 30% (a) and increases by 30% (b). Disturbance response curve when $\tau$ decreases by 30% (c) and increases by 30% (d).
Figure 11. The response of $G_2$ under PI and LADRCs with different time delays. Step response curve when $\tau$ decreases by 30% (a) and increases by 30% (b). Disturbance response curve when $\tau$ decreases by 30% (c) and increases by 30% (d).

Figure 12. Cont.
Figure 12. The response of $G_3$ under PI and LADRCs with different time delays. Step response curve when $\tau$ decreases by 30% (a) and increases by 30% (b). Disturbance response curve when $\tau$ decreases by 30% (c) and increases by 30% (d).

5. Conclusions

This paper proposes and designs a linear active disturbance rejection controller (LADRC) based on an extremum-seeking algorithm for a large wind turbine pitch angle model with delay under certain robust conditions. In order to facilitate the study, the pitch angle model is considered as a fourth-order oscillation system with time delay, and a first-order LADRC is designed for this model. Under a certain robustness constraint, the ES algorithm is used to optimize the parameters of the LADRC. Finally, the designed LADRC is compared with the traditional PI controller. The simulation results show that the setpoint tracking performance of LADRC is better than that of the PI controller, the rise time is reduced by half, and the steady state can be quickly reached. When the system is disturbed, its oscillation amplitude is small, and the speed of recovery to steady state is fast. When the delay of the system changes, LADRC has a better control effect than the PI controller, and the system always converges, reflecting better robustness. In the actual industrial process, many controlled systems have many disturbance factors, which are greatly affected by time delay, and even lead to system divergence in severe cases. Compared with PID control, LADRC has a simple structure, concise parameters, and strong disturbance rejection, and can solve this problem well. At the same time, the optimization of LADRC parameters by ES algorithm is effective and satisfactory. It can be seen that LADRC is a good choice to replace PID in practical control.

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