Self-optimizing Pitch Control for Large Scale Wind Turbine Based on ADRC

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Abstract. Since wind turbine is a complex nonlinear and strong coupling system, traditional PI control method can hardly achieve good control performance. A self-optimizing pitch control method based on the active-disturbance-rejection control theory is proposed in this paper. A linear model of the wind turbine is derived by linearizing the aerodynamic torque equation and the dynamic response of wind turbine is transformed into a first-order linear system. An expert system is designed to optimize the amplification coefficient according to the pitch rate and the speed deviation. The purpose of the proposed control method is to regulate the amplification coefficient automatically and keep the variations of pitch rate and rotor speed in proper ranges. Simulation results show that the proposed pitch control method has the ability to modify the amplification coefficient effectively, when it is not suitable, and keep the variations of pitch rate and rotor speed in proper ranges.

Keywords: Wind Turbine; Pitch Control; Self-optimizing Control; Tracking Differentiator; ADRC

1. Introduction
Wind power is a clean and renewable energy, and has become more and more important for modern industrial civilization. Today’s leading products of wind-power market in the world are variable pitch and variable speed wind turbines, due to the significant control performances of rotor speed and electric power. Wind turbine is a complex nonlinear and strong coupling system, so effective control methods are needed to ensure safe and reliable operation of the unit. Pitch control system is an important part of large scale variable pitch wind turbine to limit the aerodynamic power in above-rated wind speeds, and keep it’s rotor speed under control[1] [2].

Pitch control method is the key to achieve high control efficiency, and conventional PI control method, which is normally used in power or speed regulation, can hardly achieve excellent control performance when wind speed changes.

Recently, plenty of pitch control methods for wind turbine have been proposed, such as fuzzy PID control [3], variable gain PID control [4], sliding mode control [5] and LQR control [6]. Fuzzy PID control, which usually uses a fuzzy controller to adjust the PID gains, is suitable for the high-order nonlinear system. Sliding mode control has the drawback of chattering. Variable gain PID control and LQR control both need to set up the accurate model of wind turbine, which is difficult to implement in practice.
In this paper, a self-optimizing pitch control method is designed for variable pitch and variable speed wind turbine, which is based on active-disturbance-rejection control (ADRC).

The linear model of the wind turbine is derived by linearizing the aerodynamic torque equation and a linear extended-state observer based on the feedback of rotor speed is used to estimate the disturbance which can be counteracted through the feedforward compensation. Then the dynamic response of wind turbine is transformed into a first-order linear system. An expert system is design to optimize the amplification coefficient which is the key control parameter of ADRC system. The control performances of the proposed pitch control method have been simulated, and results show that the self-optimizing pitch control based on ADRC results in good rotor speed regulation and has the ability to self-adjust parameters.

2. Wind Turbine Model

The aerodynamic power $P_{\text{mech}}$ extracted by wind turbine is proportional to the cube of wind speed, power coefficient, area swept and air density, which can be described as:

$$P_{\text{mech}} = \frac{1}{2} C_p(\lambda, \beta) A \rho v^3$$  \hspace{1cm} (1)

Where $C_p(\lambda, \beta)$ is the power coefficient, $\lambda$ is the tip speed ratio, $\beta$ is the pitch angle, $A$ is the area swept by blades. The relations among $C_p(\lambda, \beta)$, $\lambda$ and $\beta$ can be approximated as:

$$C_p(\lambda, \beta) = c_1(c_2 / \lambda - c_3 \beta - c_4)e^{-c_5 / \lambda}$$  \hspace{1cm} (2)

Where $\lambda = \frac{1}{\lambda + 0.08 \beta} - \frac{0.035}{\beta^3 + 1}$, $c_1 = 0.22$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 0.5$, $c_5 = 12.5$.

The aerodynamic torque on the rotor, which is produced by the blades of wind turbine, can be mathematically written as:

$$Q_a = P_{\text{mech}} / \Omega = \frac{1}{2} C_p(\lambda, \beta) A \rho v^3 / \Omega$$  \hspace{1cm} (3)

With $\lambda = \frac{\Omega^* R}{v}$, then equation (3) can be written as:

$$Q_a = \frac{1}{2} C_p(\lambda, \beta) A \rho \frac{\Omega^* R^3}{\lambda^3}$$  \hspace{1cm} (4)

Where $\Omega$ is the rotor speed, $R$ is the rotor-plane radius.

The dynamic response of the drive train for wind turbine is shown to be

$$J \frac{\dot{\Omega}}{\Omega} = \frac{1}{2} C_p(\lambda, \beta) A \rho \frac{\Omega^* R^3}{\lambda^3} - G \times Q_g - k \Omega$$  \hspace{1cm} (5)

Where $J$ is the total rotor inertia, $G$ is the ratio of the gearbox, $Q_g$ is the electromagnetic torque of the generator, $k$ is the rotor friction coefficient.

The pitch servo actuator can be approximated as a first-order lag equation with time constant $\tau$, which depends on the pitch servo actuator [7]. The equation is shown as

$$\beta = \frac{1}{\tau s + 1} \beta_{\text{ref}}$$  \hspace{1cm} (6)
Where $\beta$ is the pitch angle, $\beta_{\text{ref}}$ is the pitch angle reference which is usually given by the main control system of the wind turbine.

It is clear that the pitch angle $\beta$ from equation (2) has an effect on the power coefficient $C_p(\lambda, \beta)$. If the pitch angle $\beta$ increases, the power coefficient $C_p(\lambda, \beta)$ will decrease, and the aerodynamic torque will reduce to a lower value. So the rotorspeed and the power wind turbine captured can be controlled by the pitch control system.

3. Pitch Control System

The purpose of the pitch control method proposed in this paper is to keep the rotor speed of wind turbine at rated value in high winds.

By linearizing the aerodynamic torque equation (4) around the rated operation point ($\beta_0$, $\Omega_{\text{rated}}$), a linear model of the wind turbine can be obtained

$$ Q_a = Q_{ao} + \alpha(\beta - \beta_0) + \xi(\Omega - \Omega_{\text{rated}}) + \sigma $$

(7)

Where $\beta_0 = 0$, $\Omega_{\text{rated}}$ is the rated rotor speed of wind turbine, $\sigma$ is the high order term, $\alpha = \frac{\partial Q_a}{\partial \beta}$, $\xi = \frac{\partial Q_a}{\partial \Omega}$.

Then the dynamic response of the drive train (5) can be written as

$$ \dot{\Omega} = (\alpha* \beta) / J + \eta $$

(8)

Where $\eta = (Q_{ao} - \alpha* \beta_0 + \xi(\Omega - \Omega_{\text{rated}}) + \sigma - G \times Q_g - k\Omega) / J$.

Here, the variable $\eta$ is regarded as the disturbance which is estimated by the extended-state observer and eliminated by the method of feedforward compensation.

The linear extended-state observer which is utilized in the proposed pitch control system is described as:

$$ \begin{cases} 
  e = z_1(t) - \Omega \\
  z_1(t + h) = z_1(t) + h* (z_2(t) - \xi \xi e + b_0 \beta) \\
  z_2(t + h) = z_2(t) + h* (z_2(t) - \xi \xi e) 
\end{cases} $$

(9)

Where $b_0$ is the amplification coefficient, $b_0 = \alpha / J$, $z_1(t)$ is the state variable and $z_2(t)$ is the extended-state variable which is used to estimate the disturbance $\eta$, the gains $\xi_1$ and $\xi_2$ determine the convergence speed of the extended-state observer, $h$ is the integral step size.

To eliminate the disturbance $\eta$ of the system, the pitch angle set point $\beta^{**}$ can be taken as $[k \times (\Omega^* - \Omega) - z_2(t)] / b_0$, which is the output of the pitch controller. That is to say, the estimated value $z_2(t)$ is added in the output of the pitch controller to dispel the influence of the disturbance $\eta$.

Hence, the equation (8) may be expressed as:

$$ \dot{\Omega} = b_0 \times [k \times (\Omega^* - \Omega) - z_2(t)] / b_0 + \eta $$

(10)

Simplifying:

$$ \dot{\Omega} = k \times (\Omega^* - \Omega) $$

(11)
That is, the dynamic response of the drive train equation (8) is transformed into a first-order linear system. So the pitch angle set point may be written as
\[ \beta^* = \frac{k \times (\Omega^* - \Omega) - z_2(t)}{b_0} \]. It is easy to select an appropriate gain \( k \) to minimize the rotor speed deviation from the set point \( \Omega^* \) without causing any instabilities.

From equation (7) and (9), it is obvious that the amplification coefficient \( b_0 \) is hard to be obtained, which is related to \( Q_a, \beta \) and \( J \). If the amplification coefficient is larger than the actual value, the rate of pitch angle will become large, which may cause extra mechanical fatigue of pitch servo actuator. If the amplification coefficient is smaller, the rate of pitch angle will be lower and a larger speed deviation may be occurred.

So an expert system is designed to regulate the amplification coefficient automatically, according to the rate of pitch angle and the speed deviation. That means the inputs of the expert system are the rate of pitch angle \( \frac{d\beta}{dt} \) and the speed deviation \( \varepsilon \). According to the inputs, the expert system can be divided into two conditions:

1) If \( |\frac{d\beta}{dt}| > M_\beta \), it means that the absolute value of the rate of pitch angle is larger than the set point \( M_\beta \). In this situation, the amplification coefficient which is used in the pitch controller is larger and it is needed to be brought down.

2) If \( |\varepsilon| > M_\varepsilon \), it means that the absolute value of the speed deviation is larger than the set point \( M_\varepsilon \). So the amplification coefficient should be increased to reduce the speed deviation.

Furthermore, in order to obtain the rate of pitch angle accurately, a discrete tracking-differentiator is adopted here.

The equations of the discrete tracking-differentiator are described as [8]:
\[
\begin{align*}
    x_1(t + h) &= x_1(t) + h \times x_2(t) \\
    x_2(t + h) &= x_2(t) + h \times u, |u| \leq r
\end{align*}
\]

In these equations:
\[
\begin{align*}
    u &= fst(x_1(t) - \varepsilon, x_2(t), r, h_0) \\
    d &= r \times h_0, \; d_0 = d \times h_0 \\
    y &= x_1(t) - \varepsilon + h_0 \times x_2(t) \\
    a_0 &= \sqrt{d^2 + 8 \times r \times |y|} \\
    a &= \begin{cases} 
        x_2(t) + (a_0 - d) \times \text{sgn}(y) / 2, & |y| > d_0 \\
        x_2(t) + y / h_0, & |y| \leq d_0 
    \end{cases} \\
    fst &= \begin{cases} 
        r \times a / d, & |a| \leq d \\
        r \times \text{sgn}(a), & |a| > d 
    \end{cases}
\end{align*}
\]

Where, \( h \) is the integral step size, \( r \) is the speed factor which determines the tracking speed of the differentiator, \( h_0 \) is the filter factor which strongly affects the filtering performance of the differentiator.

Fig. 1 shows the block diagram of the configuration for the self-optimizing pitch control system based on the ADRC.
Figure 1. The pitch control system configuration

Where, ES is the expert system which is used to regulate the amplification coefficient, TD is the discrete tracking-differentiator which is employed to acquire the rate of pitch angle, ESO is the extended-state observer which is used to obtain the disturbance $\eta$, $\Omega^*$ is the rotor speed set point, $\Omega$ is the measured rotor speed of wind turbine, $\beta^{**}$ is the output of the pitch control system, $\Delta h_0$ is correcting value of the amplification coefficient.

4. Simulation Results and Discussion
The pitch control system of the wind turbine is simulated using Matlab to verify the control performance. It’s focused on the above-rated wind speed region, and the purpose is to regulate the amplification coefficient automatically. The pitch control system is used to regulate the rotor speed to the rated value while the torque set point demanded by the torque controller is kept constant at $13.403\, \text{kNm}$.

The parameters of the wind turbine are given in the table 1. Fig. 2 shows the wind speed used in the simulations. The mean wind speed is 14 m/s.

Table 1. Wind turbine characteristics

| Parameters                  | Value       |
|-----------------------------|-------------|
| Rated power                 | 2MW         |
| Rated torque                | $13.403\, \text{kNm}$ |
| Gear box ratio              | 83.33       |
| Rated wind speed            | 12m/s       |
| Rotor diameter              | 80m         |
| Rated rotor speed           | 1500 rpm    |
| Maximum pitch rate          | 10 deg/s    |
Simulation 1: The initial value of amplification coefficient $b_0$ is -0.1, which is too larger than the actual value.

Fig.3 is the variation tendency of amplification coefficient $b_0$, which decreases gradually and finally stabilizes around -40.

Fig.4 is the variation tendency of pitch rate, which is very large at the beginning and the variation amplitude is smaller than the maximum pitch rate in the end.

Fig.5 is the variation tendency of rotor speed. The variation range of rotor speed is increasing slowly and at last is not over 10 rpm, which is acceptable.

Simulation 2: The initial value of amplification coefficient $b_0$ is -350, which is smaller than the actual value.

Fig.6 is the variation tendency of amplification coefficient $b_0$, which increases gradually and finally stabilizes around -50.

Fig.7 is the variation tendency of pitch rate, which increases slowly and finally was not over the maximum pitch rate.

Fig.8 is the variation tendency of rotor speed. The variation range of rotor speed is larger than 20 rpm, and is decreasing and at last is under 10 rpm, which is acceptable.
5. Conclusions
A self-optimizing pitch control system based on the ADRC theory is designed for variable pitch and variable speed wind turbines in this paper. The purpose of the proposed control method is to regulate the amplification coefficient automatically and keep the variation of pitch rate and rotor speed in proper ranges.

Simulations have been performed based on the Matlab software. Simulation results show that the pitch rate and the speed deviation are closely related with the amplification coefficient, and the performances of the pitch control method proposed in this paper are satisfactory. When the amplification coefficient is improper, self-optimizing pitch control system can modify it effectively according to the pitch rate and the speed deviation.

Thus, the self-optimizing pitch control based on ADRC is suitable for the high-order nonlinear wind turbine system, and also it is easy to implement in practice.

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