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Design of Rated Power Control Strategy of Wind Turbine Based on Particle Swarm Optimization

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Abstract. In view of the reduction of wind turbine operating efficiency caused by wind speed measurement errors, this paper proposes a rated power control strategy for wind turbines for practical applications; in order to solve the problem that the pitch PI controller parameters of wind turbines are not easy to calculate and tune in the process of design and optimization, this paper proposes a complete set of methods for parameter tuning of pitch control PI controllers for wind turbines. This paper establishes a Bladed-Matlab co-simulation platform, uses Bladed software to build a complete model of a 2MW wind turbine, and designs a rated power control strategy for wind turbines. After the wind turbine model is linearized at different wind speed points by applying Bladed software, the linearized model for PI parameter tuning is obtained, and then the optimal PI parameters for each wind speed point are set by using particle swarm algorithm. According to the variation law between the PI parameters and the pitch angle obtained before, the PI parameters are adjusted adaptively by variable gain PI control. The simulation results show the superiority of the control strategy and parameter tuning method used in this paper.

1. Introduction

Precise pitch control is essential to ensure a stable power rating of mechanical structures and electrical components when wind turbines operating above the rated wind speed. The current control strategy for wind turbines working on rated power stage is mostly variable pitch PI control. The "quickness, accuracy, and stability" of variable pitch control are directly related to the stability of the output power of wind turbines, which means, the rated power control of wind turbines directly affects the stability of power grid frequency under the trend of large-scale access to wind power. Although pitch control has many advantages, a corresponding pitch actuator is heavily required which structure and controlling are quite complex, requiring the blade pitch angle control system to be sufficiently responsive at different wind speeds [1]. The accuracy of pitch PI controller parameters is directly related to the reliability of the unit, and serious overshoot or delay will directly threaten the safety and stability of the unit.

Due to the characteristics of nonlinearity and time-varying parameters of the wind power generation system, the unit linear model is not easy to obtain and the linearized model parameters at each wind speed operating point vary greatly. The PI parameters based on a certain wind speed point model cannot achieve the optimal control effect in the whole working range. Meng designed the PI controller to pitch the wind turbine, but its control was not good in real time and the system was unstable [2]. Cui designed the PID controller to pitch the wind turbine, which has fast response and good adjustment characteristics, but poor robustness [3]. Conventional PI control is a linear control method based on a certain operating point cannot automatically identify and adjust the parameters, which is not suitable for a wind power generation system with strong nonlinearity because of the difficulty to establish an accurate model. At the same time, the precision of wind speed measurement in actual production hardly meet the design requirements, so the wind turbine works in a non-optimal condition in most cases.

This paper proposes a strategy for rated power control of wind turbines based on practical requirements, and presents a complete method for parameter tuning of pitch PI controllers. This paper establishes a Bladed-Matlab co-simulation platform and uses Bladed software to build a complete machine model for a 2MW wind turbine. After the wind turbine model is linearized at different wind speed points by applying Bladed software, the linearized model for PI parameter tuning is obtained, and then the optimal PI parameters for each wind speed point are set by using particle swarm algorithm. According to the variation law between the PI parameters and the pitch angle obtained before, the PI parameters are adjusted adaptively by variable gain PI control. Based on this, the rated power control strategy for wind turbines is designed. The simulation results show the superiority of the control strategy and parameter tuning method used in this paper.

2. Wind turbine rated power control strategy

The wind energy utilization factor represents the ratio of the wind energy obtained by the wind turbine to the original wind energy applied to the wind turbine per unit of time, denoted by C_p, which represents the conversion efficiency of the wind turbine to convert wind energy into electrical energy [4].

$$C_p = \frac{P}{\frac{1}{2}\rho S v^3} \tag{1}$$

Where: P is the actual shaft power obtained by the wind turbine, ρ is the air density, S is the swept area of the rotor, and v is the actual wind speed.

The wind energy utilization factor C_p is simultaneously affected by the tip speed ratio λ and the pitch angle β. The tip speed ratio is an important parameter used to describe the characteristics of a wind turbine. It is equal to the line speed at the tip of the blade to wind speed, denoted by λ, which reflects the wind turbine rotor speed at a certain wind speed.

$$\lambda = \frac{\omega_0 R}{v} = \frac{\omega R}{G v} \tag{2}$$

Where: ω_0 is the wind wheel rotation angular velocity, R is the wind wheel radius, v is the wind speed, ω is the generator rotation speed, and G is the generator box gear ratio.

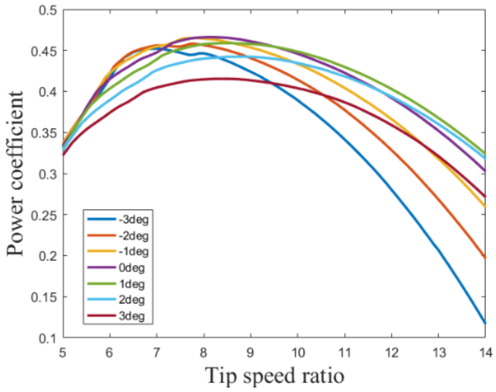
The pitch angle is the angle between the rotation plane of the wind wheel and the chord line of the blade, denoted by β. Wind energy utilization curve under different pitch angles is shown in Figure 1.

The wind turbine needs to limit the power output when it reaches the rated power. And the mechanical power captured by the wind turbine from the wind is shown in formula (3):

$$P_W = \frac{1}{2}\rho S C_p v^3 \tag{3}$$

Where: P_W is the mechanical power captured by the wind turbine from the wind, ρ is the air density, S is the swept area of the wind wheel, C_p is the wind energy utilization factor, and v is the actual wind speed.

As shown in formula (3), for wind turbines operating below the rated wind speed, higher output power can be obtained at the same wind speed by selecting the larger possible wind energy utilization factor; and for wind turbines operating at rated wind speeds and above, the pitch angle can be controlled to change the wind energy utilization factor, as shown in Figure 1, in order to maintain the unit's mechanical power P_W stabilized at rated power. Variable pitch control means that when the unit reaches rated power and the wind speed continues to increase, the pitch angle is changed and the wind energy utilization factor is reduced to maintain the constant power operation of the wind turbine. The specific control logic is shown in Figure 2.



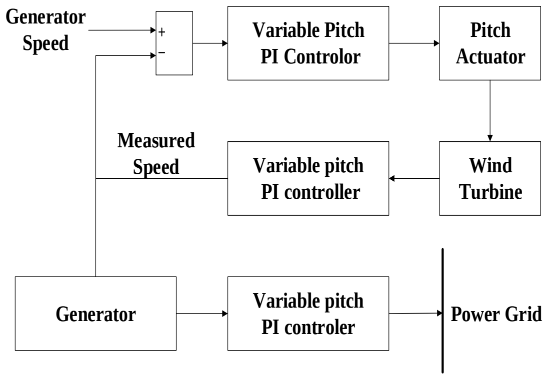
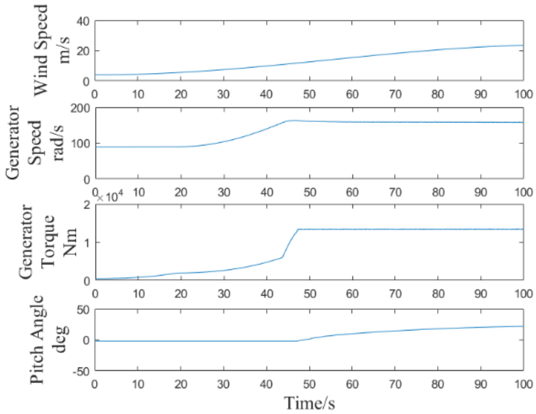


Figure 1. Curve of wind energy utilization at different pitch angles, **Figure 2.** Wind Turbine Control System Structure



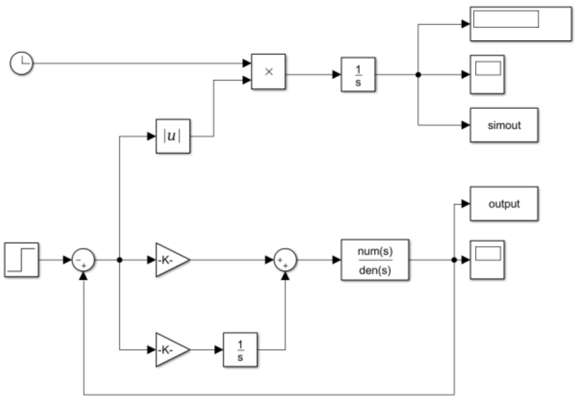


Figure 3. Generator speed, torque, and pitch angle with wind speed curve; **Figure 4.** Simulink model diagram

There is an upper limit of the generator speed called the rated speed; and the electromagnetic torque of the generator is limited by the inverter and electrical design, there is also an upper limit called rated torque. When the generator speed is increased to the upper limit and the torque reaches the rated torque (at this time, the unit is in: rated speed, rated torque, rated power), the wind speed continues to increase, variable pitch PI control can be adopted. Through the pitch actuator, the pitch angle is changed to reduce the wind energy utilization factor of the wind wheel to ensure that the unit will continue to work at rated speed, rated torque and rated power. Generator speed, torque and pitch angle with wind speed curve shown in Figure 3.

The existing control strategy usually uses the wind speed as input to judge the working status of the wind turbine, and based on this, control strategy designed will inevitably be affected by the wind speed measurement error. Therefore, this paper proposes a variable pitch PI control strategy for wind turbines for practical applications.

When the wind turbine is operating above the rated wind speed, the nonlinearity between the pitch angle and the generator speed is particularly obvious, then the PI parameters based on a working point model cannot achieve optimal control effects over the entire working range. Therefore, this paper obtains wind turbine models at different wind speeds by model linearization, and then sets corresponding PI controller parameters. At the same time, it determines the optimal pitch angle for the corresponding wind speed, and finds out the variation of PI parameters with the pitch angle. The control strategy of adaptively adjusting the PI parameters based on the pitch angle is implemented to eliminate the influence of the wind speed measurement error on the pitch control to the greatest extent.

3. Model linearization and its processing

Wind turbine is a complex system with the characteristics of nonlinear and time-varying parameters. Taking into account the complex environmental factors, changing operating conditions, the application of nonlinear control and other advanced control algorithms is not ideal, so consider the model linearization.

3.1 Bladed model linearization

The authoritative wind turbine simulation software Bladed, developed by GH, can use a large number of detailed equipment parameters to create a mathematical unit simulation model. Due to the accurate simulation calculation of the software and the high precision of the model, it has become one of the recognized industry standards which has already been certified by German classification society and IEC. The Model Linearization function is used for the unit model established by Bladed, and then the Linear Model module is used for post-processing the result of the operation. The MIMO linearized model data file shaped as Equation (4) can be obtained [5].

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{4}$$

In the formula: The coefficient matrix A, B, C, D is a three-dimensional array based on wind speed. The input of the state space equation obtained by the linearization of Bladed model is wind speed, pitch angle demand and generator torque demand. In this paper, the generator speed is selected as the output.

3.2 Matlab data processing

The MIMO state space equation is imported into MATLAB and converted to a SISO transfer function model at any wind speed. At 16 m/s wind speed, the transfer function of the pitch angle-generator speed model is as follows:

$$G_\beta(s) = \frac{\begin{aligned}&-137.63s(s+640.1)(s+3.333)^2(s^2-0.1216s+8.193)\\&(s^2+0.08863s+8.76)(s^2+4.308s+48.81)(s^2+4.435s+49.7)\\&(s^2-0.763s+51.15)(s^2+0.2918s+82.95)(s^2+0.3031s+85.27)\\&(s^2+0.1575s+266.7)(s^2+9.724s+378.4)(s^2+0.371s+366.6)\\&(s^2+5.798s+629.3)\end{aligned}}{\begin{aligned}&(s+3.333)^3(s+0.1287)(s+0.01822)\\&(s^2+0.04482s+8.387)(s^2+0.3168s+8.6)(s^2+4.376s+48.74)\\&(s^2+4.433s+49.6)(s^2+4.129s+50.9)(s^2+0.2919s+82.95)\\&(s^2+0.3044s+85.26)(s^2+1.75s+204.4)(s^2+0.5883s+280.6)\\&(s^2+0.3615s+366.5)(s^2+5.081s+408.8)(s^2+3.653s+661.2)\end{aligned}} \tag{5}$$

4. PID parameter tuning based on particle swarm optimization

4.1 The basic concept of PSO algorithm

Suppose a group consists of M particles, each particle is in the D-dimensional search space, the velocity of the i-th particle can be represented as the vector $v_i = (v_{i1}, v_{i2}, \ldots, v_{iD})$, and the position is represented as the vector $x_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$, the particles update their positions and velocities according to the fitness value [6]-[8], and the updated basis is based on two extreme values—the individual extremum and the global extremum. The individual extremum is the best position currently found by the i-th particle, denoted as $p_{best} = (p_{i1}, p_{i2}, \ldots, p_{iD})$. The global extremum is the best position for all particles in the population, and is denoted as $g_{best} = (p_{g1}, p_{g2}, \ldots, p_{gD})$. For the k-th iteration, the particle velocity and position update rules in the PSO are:

$$\begin{cases} v_{id}^{k+1} = \omega v_{id}^{k} + c_1 r_1 (p_{id} - x_{id}^{k}) + c_2 r_2 (p_{gd} - x_{id}^{k}) \\ x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \end{cases} \tag{6}$$

Among them, d represents the current search space dimension; i represents particles; k represents evolutionary algebra; x_{id}^{k} is the d-dimensional component of the position vector of particle i in the k-th iteration; v_{id}^{k} is the d-dimensional component of the velocity vector of particle i in the k-th iteration; p_{gd} is the d-dimensional component of the global extreme g_{best} of the population; p_{id} is the d-dimensional component of the particle extremum p_{best}; c1 and c2 are acceleration factors; ω is the inertia weight; r1 and r2 are random numbers between [0,1].

4.2 PSO parameter optimization

The PI parameters of each transfer function obtained by linearizing the model are adjusted by using the particle swarm algorithm. The specific parameters of the PSO algorithm are set as follows: particle swarm size M=100, maximum iteration number k=50, dimension D=2, inertia factor ω=0.6, acceleration constant c1=1, c2=1, and the fitness function is selected:

$$Q = \int |e(t)| t dt \tag{7}$$

Build a Simulink model, as shown in Figure 4. Under the unit step input, the optimal PI parameters of the pitch angle-generator rotational speed transfer function under different operating points are obtained through operation optimization. Taking the transfer function of pitch angle-generator speed at 16m/s wind speed as an example, see equation (10). The PI parameters obtained by particle swarm optimization are: Kp=0.0149 and Ki=0.0132.

4.3 Variable gain PI controller parameter setting

The particle swarm optimization algorithm is used to optimize the PI parameters for linear models under different wind speeds at 12-24 m/s. The changes of the blade pitch angle β and controller parameters Kp and Ki are shown in Table 1:

Table 1. Partial controller parameters and pitch angle at 12-24m/s wind speed

Wind(m/s)	Kp	Ki	β(deg)
12	0.033	0.0117	-0.03477
14	0.0179	0.0112	0.162199
16	0.0105	0.0049	0.177321
18	0.0149	0.0132	0.198041
20	0.0078	0.0016	0.220163
22	0.0077	0.002	0.24962
24	0.0056	0.0018	0.299954

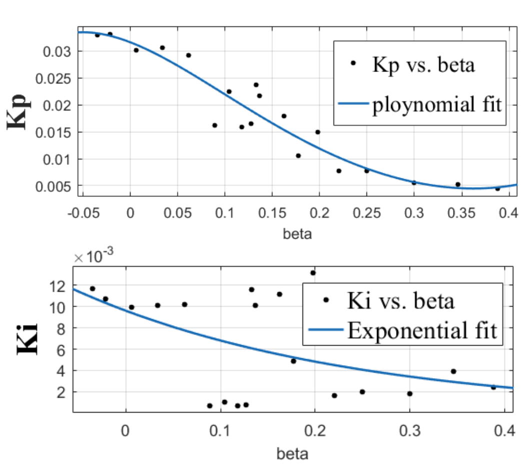


Figure 5. Kp and Ki fitting curves

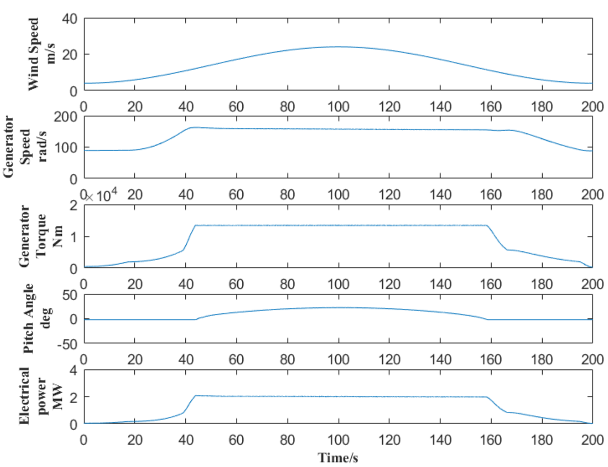


Figure 6. Generator speed, torque, pitch angle and

output power curve under 12-24m/s wind

Using the Matlab Curve Fitting Toolbox curve fitting, the obtained curve as follow, which shows the variation of controller parameters Kp, Ki with pitch angle β:
The rules of controller parameter Kp, Ki changing with pitch angle β are as follows:

$$Kp = -1.419\beta^4 + 1.619\beta^3 - 0.4155\beta^2 - 0.06288\beta + 0.03152 \quad (8)$$

$$Ki = 0.009622\exp(-3.456\beta) \quad (9)$$

5. Example analysis

5.1 Wind turbine modeling and control strategy implementation
Model the blades, airfoils, rotor, towers, power train, nacelle and other components of a 2MW wind turbine unit based on Bladed. The key parameters are shown in Table 2.

Table 2. Key parameters of wind turbines

Blade length(m)	38.75
Number of blades	3
Rotor diameter(m)	80
Tower height(m)	60
Gearbox ratio	83.3
Generator rated speed (rpm)	1500
Rated torque(T)	13403

Bladed allows external controllers to be designed from the dynamic link library (DLL). Compile the control strategy into a DLL file, select the external controller and invoke the DLL in the Control function module of Bladed to complete the controller design and implementation.

5.2 Analysis of simulation results
The generator speed, torque, pitch angle and electrical power under a 12-24m/s time varying wind are shown in Figure 6. Under 15m/s wind with a turbulence of 4%, the generator speed, torque, pitch angle, and electrical power are shown in Figure 7.

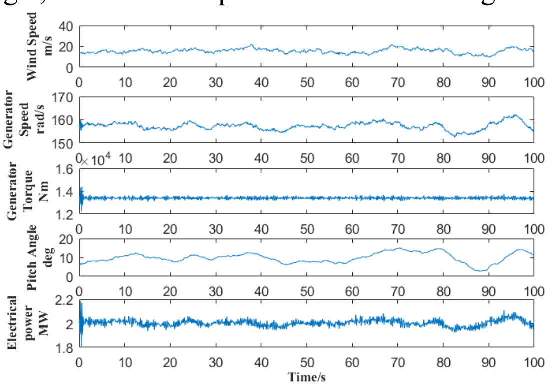


Figure 7. Generator speed, torque, pitch angle and electrical power under 15m/s turbulent wind

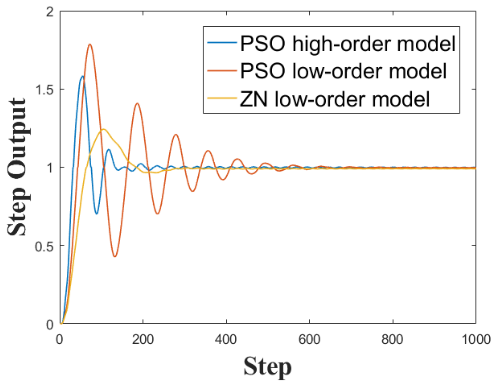


Figure 8. Unit step response under different PI parameters

As can be seen from the above figure, the rated power control strategy can effectively control the pitch angle to ensure the constant power operation of the unit.
The traditional PI controller parameter tuning is usually to use the least square method, Pade method or Routh method to reduce the order of high-order systems, and then through the Z-N, C-C and other empirical formulas or PSO and other intelligent algorithms for PI parameter tuning .The pitch angle-generator speed transfer function can be reduced to the first-order inertial delay link which in the form of formula (15) (FOLPD):

$$\mathrm{G}(s)=\frac{K}{Ts+1}e^{-Ls} \tag{10}$$

Taking the wind speed of 16m/s as an example, the FOLPD model obtained by reducing the formula (10) is as follows:

$$\mathrm{G}_{\beta}(s)=\frac{-112.2}{0.3548s+1}e^{-0.597s} \tag{11}$$

For formula (16), the PI parameters determined by the Z-N empirical formula are: Kp=0.0046，Ki= 0.0023

For formula (16), the PI parameters set by the PSO algorithm are: Kp= 0.0045, Ki=0.0086

For the pitch angle-generator speed model at 16m/s wind speed, as shown in equation (10), the corresponding unit step response for each group of PI parameters is shown in Figure 8.

As can be seen from the figure 8, the PI parameters obtained by optimizing the higher-order linearization model using the PSO algorithm have shorter rise time and shorter adjustment time, and have better control effect.

6. Conclusion

The main content of this article is:

A control strategy for rated power of wind turbines for practical production needs is proposed. Compared with traditional control strategies, the new strategy can minimize the impact of wind speed measurement errors on control strategies.

A method of parameter tuning of PI controller under full wind speed range is proposed. Compared with the traditional method of tuning the reduced-order model parameters, the new method has a better control effect. Relative to the enumeration method for a certain operating conditions for parameter tuning, the new method has a greater scope of application and faster setting speed.

7. Acknowledgement

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