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The Application of Fuzzy PID Control in Pitch Wind Turbine

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Abstract

The theory of fuzzy control and PID control were applied to the control of generator speed and blade pitch angle. During the early period the fuzzy controller was used to improve system responsiveness and reduce the overshoot. When entering to steady-state regulation period, the PID controller was used, by regulating the ratio, differential, integral parameters of the system steady-state error was kept the minimum. Based on variable pitch wind turbine mathematical model we do a MATLAB simulation, results show that, the method can make the generator work at maximum power operation before Grid-connection, and with rated power after the run.

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Keywords:Wind turbine; fuzzy control; PID control; MATLAB simulation

1. Introduction

Wind energy is an inexhaustible supply of clean energy, in promoting low carbon economy and to strengthen environmental protection today, the wind power is becoming one of the fastest growing new energy. As of 2009, China's total installed capacity of wind power reached 263 million kilowatts. The total installed capacity in 2020 is expected to reach 800 million kilowatts or more [1].

With the development of control theory and algorithms and the people continuous deepen understanding to wind power, wind power control technology has evolved. Wind turbine control technologies went through a fixed pitch, whole leaf variable pitch, and variable speed constant frequency three stages. Now moving towards large-scale wind turbine development [2], variable pitch control technology advantages is standing out, Pitch wind turbine can keep the rated power output through the adjustment of blade pitch angle and generator speed. Compared with the fixed pitch control, pitch control can catch greater wind and make the output power smoother. This paper, fuzzy control technique was applied to the pitch control and generator speed control. In MATLAB, wind turbine model was set up and the simulation is done in Simulink to verify the feasibility of this method.

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2. Variable pitch wind turbine model

From the control point of view, the wind turbine model consists of four components [3]: aerodynamic model, transmission model, generator model, pitch execution model.

A. rodynamics System

Principles of wind power are that. First wind energy is converted to kinetic energy of the blades, and then drive power generators through the gear box. Known by the aerodynamics, the limited [4] actual wind energy can be calculated by following equation.

$$p_r = 0.5\rho S C_p(\lambda, \beta) v^3 \tag{1}$$

In the above equation, we definite p_r as the absorption of power. ρ as the air density. S as the swept area. $C_p(\lambda, \beta)$ as the wind energy utilization coefficient. v as wind speed, λ as the tip speed ratio ($\lambda = \frac{\omega R}{v}$). β as the blade pitch angle.

B. Transmission System

Wind turbine with gear box can change the generator's speed in proportion, assuming a rigid structure and ignore the resistance outside the spindle, and then transmission characteristics between wind rotor and the spindle are:

$$J_r \frac{d\omega}{dr} = T_r - T_D - nT_m \tag{2}$$

In the above equation, we definite Jr as wind rotor's moment of inertia. ω as angular velocity. Tr as pull-in torque. TD as main spindle's resistance, n as speed ratio, ωg as asynchronous generator's angular velocity, Tm as torque that high speed shaft transmitted to rigid gear. And

$$T_r = \frac{C_p(\lambda, \beta)}{2\lambda} \rho S R v^2 \tag{3}$$

Considering the linear relationship between resistance of main spindle and wind rotor's angular velocity then T_D is,

$$T_D = c_1\omega + c_2 \quad (c_1,\ c_2 \text{ are constants}) \tag{4}$$

If ignore mechanical resistance from the generator itself, only consider the generator anti-torque caused by load, then there is:

$$J_g \frac{d\omega_g}{dt} = T_m - T_e \tag{5}$$

In the above equation, Jg is definited as asynchronous generator's moment of inertia; Te is definited as anti-torque caused by load. By ordering (1) to (5), we can established (6) and (7) taking wind rotor speed and motor speed as variables respectively :

$$(J_r + n^2 J_g)\frac{d\omega}{dt} = T_r - T_D - nT_e \tag{6}$$

$$(\frac{1}{n} J_r + nJ_g)\frac{d\omega_g}{dt} = T_r - T_D - nT_e \tag{7}$$

C. Generator

From the Electric Machinery Theories [5], the ideal wound three-phase asynchronous generator model [4] is as follows:

$$T_e = \frac{pm_1 U_1^2 r_2^{'}}{(p\omega_g - \omega_1)\left[\left[r_1 - \frac{C_1 r_2^{'} \omega_1}{p\omega_g - \omega_1}\right]^2 + (x_1 + C_1 x_2^{'})^2\right]} \tag{8}$$

Where: p is definited as the generator pole number, m_1 as the number of phases, U_1 as the grid voltage, C_1 as the correction factor, ω_1 as the generator synchronous speed, r_1 、 x_1 as the stator winding resistance and leakage reactance, $r_2^{'}$ 、 x_2 as the resistance and leakage reactance when rotor winding are attributed to the side of the stator windings.

D. Pitch Execution system

Pitch actuator includes Hydraulic pitch actuators and electric pitch. The advantages of hydraulic pitch are positioning accuracy, fast dynamic response; electric pitch can adjust each of blades individually by a servo motor. Hydraulic pitch actuator dynamic model can be described as a first-order time-delay system：

$$G(s) = \frac{\beta(s)}{\beta_{ref}(s)} = \frac{e^{-\tau s}}{T_\beta s + 1} \tag{9}$$

Where： β is definited as the actual pitch angle, β ref as the pitch angle for the reference, T β as the time constant , τ as the delay time.

E. Establishment of Control Strategy

Wind energy utilization coefficient CP is a nonlinear function of parameter λ and β , CP can be approximately expressed [6] as：

$$C_p = (0.44 - 0.0167\beta)\sin\left|\frac{\pi(\lambda-3)}{15-0.3\beta}\right| - 0.00184(\lambda-3)\beta \tag{10}$$

From (10), we know that for any λ , the smaller β , the greater CP. So when the pitch angle is very small (the actual paddle generally transferred to 3 °) [7], tip speed ratio is 9, the power coefficient CP reaches the maximum value (about 0.44). therefore, at the low speed, the target is to find the largest wind energy utilization coefficient CP.Below the rated wind speed, the blade angle is set to 3 ° , when the wind changes, change the speed of the wind rotor to ensure constant tip speed ratio of 9. at high wind speed, based on power control ,the target is to find a constant power. So keep power close to rated power by controlling the blade pitch angle.

Fuzzy controller can summarize the experiences to form fuzzy relations, through fuzzy reasoning and fuzzy decision, drive implementing agencies to implement the corresponding action. Have the advantage of fast dynamic response, robustness etc. and so is suitable to nonlinear multivariable systems. But on the whole fuzzy controller is equivalent to a nonlinear PD controller, the lack of integral action, will cause the system steady-state error. Therefore, fuzzy controller and PID controller can be used together. Early in the control fuzzy controller is selected to achieve system's rapid response. When the error reaches a certain level (error<10%), the PID control system is cut in quickly to reduce the steady-state error. Improve overall system performance. So when the control start in the low wind speed zone, speed fuzzy controller is used, when the error between generator voltage and the reference voltage is less than 10% PID controller is switched to. Similarly, when the control start in the high wind speed zone, power fuzzy controller is used, when the error between the Pitch angle and the reference value is less than 10% the PID controller is switched to.

3. Establishment of Fuzzy Controller and Simulation

F. Fuzzy Controller Design

Two-dimensional fuzzy controller [8] with error and the changing rate as its inputs and the controlled variable as output is widely used. System block diagram of two-dimensional fuzzy controller is shown in Figure 1:

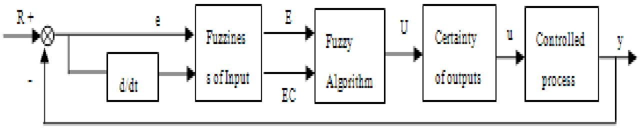

Fig. 1 Block diagram of two-dimensional fuzzy controller

Here，using this two-dimensional fuzzy controller, in Low wind speed region，using wind rotor speed error and its changing rate as inputs and voltage of generator stator as its outputs. When Lower than the rated speed, the block diagram of control system is shown in Figure 2：

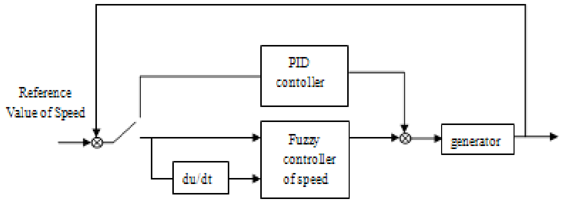

Fig. 2. The control block diagram when lower than the rated speed

Two inputs(error and error rate)both use PB (CP), PM (middle), PS (positive small), ZE (zero), NS (negative small), NM (negative middle), NB (negative big)) as 7 linguistic variables, the selected universe is {-6，-5，-4，-3，-1，-1，0，1，2，3，4，5，6}。 Use Gaussian type function as Membership Function (shown in Figure 3). Get the solutions of fuzzy by the method of weighted average.

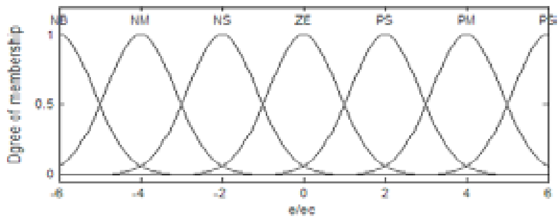

Fig. 3. The Membership function of inputs E,EC

Fuzzy control rules are a summary of expert knowledge and experience accumulated. Fuzzy control rules is expressed by the fuzzy conditional statement,

If E and EC then U

All the rules drawn into the table constitutes a fuzzy control rule table. At the low wind speed, there are 49 fuzzy control rules, shown as Table 1. For example, when the wind rotor's speed is far less than the reference speed (error is NB), and the changing rate is increasing constantly (NB), it will have to increase the generator's stator voltage(PB) rapidly to increase wind rotor's speed,similarly,when the wind rotor's speed is much greater than reference speed(error is PB), and the changing rate increasing constantly(PB),it will have to reduce the generator voltage (PB) rapidly to reduce the speed of the wind rotor. For the high-speed region, when the output power of generator is far less than the rated power (error is NB), and the changing rate is increasing constantly (NB), it have to change the pitch angle quickly(PB), so that pitch turn to the direction where more wind can be catched to increase the output power,similarly,when the generator's output power is far greater than the rated power (error is PB), and the changing rate is increasing constantly(PB), it will have to change the pitch angle quickly (NB),so that the pitch turn to the direction where less wind can be catched to reduce the generator output power.

TABLE 1. The fuzzy control rules AT THE LOW SPEED REGION

<table>
<tr><th>Ec \ U \ E</th><th>NB</th><th>NM</th><th>NS</th><th>ZE</th><th>PS</th><th>PM</th><th>PB</th></tr>
<tr><td>NB</td><td rowspan="3" colspan="2">PB</td><td rowspan="2">PM</td><td rowspan="2" colspan="2">PS</td><td rowspan="2" colspan="2">ZE</td></tr>
<tr><td>NM</td></tr>
<tr><td>ZS</td><td>PS</td><td colspan="2">ZE</td><td>NS</td><td>NM</td></tr>
<tr><td>ZE</td><td>PB</td><td>PM</td><td>PS</td><td>ZE</td><td>NS</td><td>NM</td><td>NB</td></tr>
<tr><td>PS</td><td>PM</td><td>PS</td><td>ZE</td><td>ZE</td><td>NS</td><td rowspan="3" colspan="2">NB</td></tr>
<tr><td>PM</td><td rowspan="2" colspan="2">ZE</td><td rowspan="2" colspan="2">NS</td><td rowspan="2">NM</td></tr>
<tr><td>PB</td></tr>
</table>

At the high wind speed areas, using power error and the changing rate as its inputs, and a reference pitch angle of Pitch control system as its output [9] [10].The establishment of the fuzzy controller is similar with the Low wind speed region, the only difference is selection of fuzzy rules. The system control block diagram when higher than the rated wind speed is shown in Figure 4, fuzzy rule table is shown in Table 2.

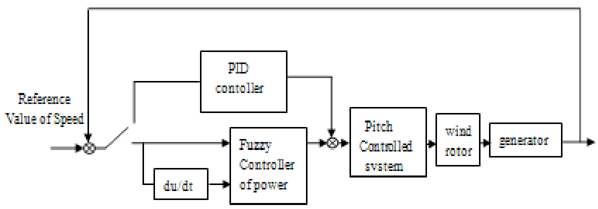

Fig. 4.The control block diagram when higher than the rated speed

TABLE 2. The fuzzy control rules AT THE HIGH SPEED REGION

<table>
<tr><th>Ec / E / U</th><th>NB</th><th>NM</th><th>NS</th><th>ZE</th><th>PS</th><th>PM</th><th>PB</th></tr>
<tr><td>NB</td><td colspan="2" rowspan="4">PB</td><td rowspan="4">PM</td><td rowspan="2">PM</td><td rowspan="2">PS</td><td colspan="2" rowspan="2">ZE</td></tr>
<tr><td>NM</td></tr>
<tr><td>ZS</td><td>PS</td><td>ZE</td><td>NS</td><td>NM</td></tr>
<tr><td>ZE</td><td>ZE</td><td>NM</td><td colspan="2" rowspan="4">NB</td></tr>
<tr><td>PS</td><td colspan="2">PM</td><td>PM</td><td>NS</td><td>NM</td></tr>
<tr><td>PM</td><td colspan="2" rowspan="2">ZE</td><td rowspan="2">NS</td><td colspan="2" rowspan="2">NM</td></tr>
<tr><td>PB</td></tr>
</table>

G. Experimental simulation

In MATLAB, set up the whole system model, the selection of parameters refers to existing data of a wind farm, parameters are as follows moment of inertia of Blade is 1.655×10^{6} Kg • m2, the moment of inertia of generator is 50 Kg • m2, Wind rotor diameter is 45m, rated wind speed is14m/generator rated power is 0.9MW, generator pole number is 2, stator phase is 3, air density is $1.225 \mathrm{kg/m}^{3}$, speed increasing ratio is 50.

When lower than the rated speed, maintain constant pitch angle of 3, to find the optimal tip speed ratio. The control of pitch angle is shown as figure 4.

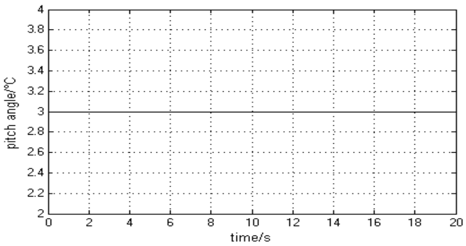

Fig. 5.The control of pitch angle at low wind speed region

Under different wind speed, simulation results of the output power are shown as Figure 5 and Figure 6.

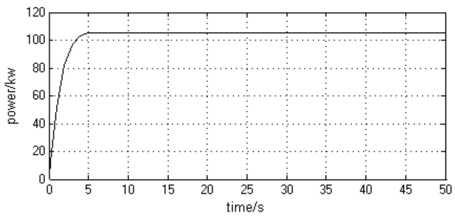

Fig. 6. The output power when lower than the rated speed (v = 5 m / s)

From Figure 4, Figure 5 we can see when lower than the rated speed, pitch angle is maintained at 3 °, generator speed changes by regulating the voltage of generator stator, and then drive blade speed change through the gear box, making wind turbine maintain optimum tip speed ratio when lower than the rated speed.

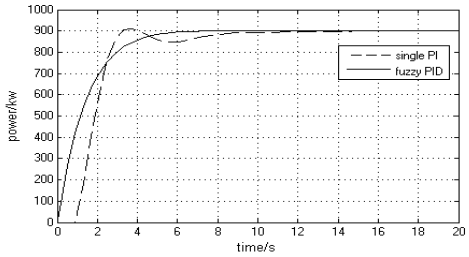

Fig. 7. The output power when higher than the rated speed (v = 18m / s)

Figure 6 gives the comparison between fuzzy PID controller and a simple PI controller, when the wind speed is above the rated wind speed, the generator's output power can be maintained constant near the rated power through the blade pitch angle adjustment. Besides, we also can see at the beginning of 4.3 seconds, by using the fuzzy controller, system response speed has been improved greatly, and the paranormal value has been reduced.at 4.3 seconds, steady state error is about 10%, the PID controller was switched to, by adjusting the parameters Kp,、Ki 、Kd ,the speed of the system to reach steady state has been accelerated, and the steady state accuracy of the system has been improved.

4. Conclusions

In this paper, fuzzy PID control theory was applied to wind turbine pitch control, through the stator voltage control at low speed and the blade pitch angle control at high speed the generators works in the best condition. By comparison with the traditional PI controller we can see, this method can accelerate system response speed, improve the accuracy and improve variable pitch wind turbine control effect.

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