The design of compound pitch controller for wind turbines

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Abstract. As an important renewable energy source, wind energy has been highly valued by countries. In recent years, the mainstream of wind turbines in the world is the pitch control units. Based on the joint simulation of 1.5 MW doubly-fed wind turbine, a feed-forward and an adaptive PI pitch controller are combined, they are both designed by fuzzy theory. Through the simulation, it can be seen that the power of the unit can be controlled constant when the wind speed is higher than the rated value. The fuzzy compound pitch controller proposed in this paper can timely compensate the power fluctuation caused by the wind speed disturbance, it has better control effect than traditional PI and fuzzy PI controller with shorter adjustment time and less power overshoot.

1. Introduction

Wind power has been rapidly developed during recent years as a clean, safe and renewable energy. The research on wind turbines control strategy has always been an important topic in the field of wind power [1]. Generally speaking, the control of wind turbine is to regulate the power of the generator to adapt the changes of wind speed. It mainly focuses on two aspects [2]: One is the maximum power points track (MPPT) to achieve maximum output power when the unit is under the rated wind speed. The other is variable pitch control to keep the power of the unit near the rated power when the wind speed is higher than the rated. How to design a good pitch controller for the wind turbine is a hot spot for many scholars.

At present, the classical proportional integral (PI) variable pitch controller based on linear model is mostly used in practice. However, the wind turbines are complex systems with time-varying and multi-coupling, and it is not easy to establish an accurate mathematical model for the whole unit due to the serious non-linearity and big random disturbance. A set of fixed PI parameters can only guarantee the control effect near the linear working point, which cannot meet the control demand when wind speed fluctuates, and the adaptive ability of the controller is poor. Therefore, many scholars have made efforts to investigate new control methods. For example, in literature [3], variable pitch controller designed by MLP and RBF neural network was studied, the effectiveness was verified through experiments. In literature [4], the multivariable sliding mode controller was designed. The pitch angle and the torque of the generator can be adjusted at the same time, so not only the stable power of the generator was ensured, but also the torque change of the drive system and the change frequency of pitch angle were restrained; In literature [5], a fuzzy adaptive pitch controller with variable universe was proposed, taking the speed difference as the input, the pitch angle as the output. Constant power control was realized according to the variable universe of pitch angle. The strengths and weaknesses of
the intelligent control algorithms frequently used in wind turbines were listed in literature [6]. All of them, fuzzy control is an intelligent method that often used, it can overcome the disturbance of non-linear factors and has strong robustness. It can give the control amount within a large deviation range using fuzzy reasoning. However, due to the large rotating inertia of wind turbine, the system cannot respond quickly to compensate the disturbance of wind speed. Therefore, in this paper, a compound fuzzy variable pitch controller composed of feed-forward and adaptive PI controller is put forward to complete the constant power control of the unit at the high wind speed stage. The simulation results show that the fuzzy compound variable pitch controller has good characteristics in dynamic state. It enables the unit to respond quickly with the wind speed and to maintain the output power stable. The control effect is better than that of traditional PI and fuzzy PI controller.

2. Design of compound variable pitch controller
Due to the limitations of the unit's mechanical structure & electrical characteristics and the requirements of power quality to the grid, the method of regulating the pitch angle is used to control the wind energy utilization coefficient, $C_p$, under high wind speed conditions in this paper, so that the power of the generator is maintained near the rated value, achieving the goal of constant power control [2]. The specific control strategy is: increase the pitch angle and release some wind energy with the wind speed increasing; reduce the pitch angle and increase the unit’s output with the wind speed decreasing.

To make up for the shortcomings of classical PI and take advantage of fuzzy control, in this paper, a new compound pitch controller composed of a feed-forward and an adaptive PI pitch controller based on fuzzy theory are proposed. The feed-forward controller can pre-specify a certain pitch angle $\beta_f$ according to the wind speed disturbance, which was added to the output pitch angle $\beta_r$ of the adaptive fuzzy PI controller as the input $\beta_r$ of the pitch actuator. The structure is shown in figure 1.

![Diagram of compound pitch controller](image)

**Figure 1.** Structure of compound pitch controller.

2.1. The design of adaptive controller by fuzzy algorithm
The designed fuzzy adaptive controller is a regulator with two inputs and two outputs. The inputs are the unit's power error $e$ and its change rate $e_c$. After fuzzy reasoning and gravity defuzzification, the outputs $\Delta K_r$ and $\Delta K_p$ of the fuzzy controller is obtained.
In this paper, a 1.5 MW wind turbine is studied. According to the previous operational characteristics analysis and the experience accumulated from practice, the basic domain of the power error $e$ is [-0.6, 0.6] MW; the power error change rate $e'_c$’s is [-120,120] MW/s; the output PI parameter $\Delta K_p$’s is [-6,6], $\Delta K_i$’s is [-60,60].

After a reasonable selection of the quantization and the scale factor, the variables are transformed from the basic domain to the fuzzy domain. The fuzzy domains of the inputs $E$, $EC$ and the outputs $\Delta K_p$, $\Delta K_i$ are all \{-6,-4,-2,0,2,4,6\}. The fuzzy sets are all \{NB, NM, NS, ZO, PS, PM, PB\}[2].

The membership of the variables $E$, $EC$, $\Delta K_p$ and $\Delta K_i$ are all triangular functions.

According to the previous control experience of the pitch angle and the tuning experience of the PI parameters, the rules of designing fuzzy adaptive controller are shown in table 1 [2] and table 2 [7].

**Table 1. Control rules of $\Delta K_p$.**

| $E$ | NB | NM | NS | ZO | PS | PM | PB |
|-----|----|----|----|----|----|----|----|
| NB  | PB | PS | PM | PM | PS | ZO | ZO |
| NM  | PB | PB | PM | PS | PS | ZO | NS |
| NS  | PM | PM | PM | PS | ZO | NS | NS |
| ZO  | PM | PM | PM | ZO | NS | NM | NM |
| PS  | PS | PS | ZP | NS | NS | NM | NM |
| PM  | PS | ZO | NS | NM | NB | NM | NB |
| PB  | ZO | ZO | NM | NM | NM | NB | NB |

**Table 2. Control rules of $\Delta K_i$.**

| $E$ | NB | NM | NS | ZO | PS | PM | PB |
|-----|----|----|----|----|----|----|----|
| NB  | NB | NB | NM | NM | NS | ZO | ZO |
| NM  | NB | PB | NM | NS | NS | ZO | ZO |
| NS  | NB | NM | NS | NS | ZO | PS | PS |
| ZO  | NM | NM | NS | ZO | PS | PM | PM |
| PS  | NM | NS | ZO | PS | PS | PM | PM |
| PM  | ZO | ZO | PS | PS | PM | PB | PB |
| PB  | ZO | ZO | PS | PM | PM | PB | PB |

2.2. *The design of feed-forward controller by fuzzy algorithm*

The fuzzy feed-forward controller proposed in this paper has two inputs and single output. One input is the last moment wind speed $v(k-1)$, the other is the wind speed difference $\Delta v = v(k) - v(k-1)$; the output is the pitch angle $\beta_f$ [7].

The rated wind speed of the wind turbine studied in this paper is 10 m/s, and the cut-out wind speed is 25 m/s. The basic domain of the input variable $v(k-1)$ of the fuzzy feed-forward controller is [10 m/s, 25 m/s], the fuzzy domain is \{10, 13.75, 17.5, 21.25, 25\}, and the corresponding fuzzy set is \{LH, RH, H, VH, EH\} [7]. The basic domain of the input $\Delta v$ is [-3 m/s, 3 m/s], the fuzzy domain is \{-3, -2, -1, 0, 1, 2, 3\}, and the corresponding fuzzy set is \{NB, NM, NS, Z, PS, PM, PB\} [7]. The basic domain of the output variable $\beta_f$ is \[-4^\circ, 4^\circ\] [7], the fuzzy domain is \{-4, -3, -2, -1, 0, 1, 2, 3, 4\}, and the corresponding fuzzy sets are \{NB, NM1, NM2, NS, Z, PS, PM1, PM2, PB\}[7].

The membership of the inputs and output of the fuzzy feed-forward controller are all triangular
functions.

When the wind speed increases above the rated [7], the feed-forward controller outputs a positive value, that is, increases the pitch angle in advance to reduce the wind energy absorption; otherwise, the controller outputs a negative value, reduces the pitch angle in advance to increases the wind energy absorption. So that constant power output can be maintained. According to the experience and the blade characteristics of the wind turbine, the aerodynamic torque is more sensitive to the pitch angle at high wind speed than at low wind speed. That is, when $\Delta v$ is a constant value, a larger feed-forward pitch angle $\beta_f$ will be output if $v(k-1)$ is near the rated wind speed [7]; a smaller feed-forward pitch angle will be output if $v(k-1)$ is near the cut-out wind speed [7]. Therefore, the fuzzy feed-forward control rules are shown in table 3 [7].

| $\Delta v$ | NB | NM | NS | Z | PS | PM | PB |
|------------|----|----|----|---|----|----|----|
| LH         | NB | NB | NM1| Z | PM1| PB | PB |
| RH         | NB | NM2| NS | Z | PM1| PM2| PB |
| H          | NM2| NM1| NS | Z | PS | PM1| PM2|
| VH         | NM1| NS | NS | Z | PS | PS | PM1|
| EH         | NS | NS | NS | Z | PS | PS | PS |

### 3. Simulation analysis

Set the parameters of the wind turbine in the joint simulation model (The model was discussed in another paper): wind turbine radius $R=41.38$ m, rated wind speed $v_r=10$ m/s, cut-out wind speed $v_{out}=25$ m/s, air density $\rho=1.225$ kg/m$^3$, rated power $P_r=1.5$ MW. In order to obtain the control results under different wind speed, the step and the natural wind speed near the rated and cut-out are used as the inputs, the performance of the designed pitch controller is tested.

#### 3.1. Step wind speed

**3.1.1. Near the rated wind speed.** As shown in figure 2, the wind speed is 7 m/s before $t=0.5$ s and increases suddenly to 10 m/s at $t=0.5$ s. It remains at 10 m/s till at $t=1$ s, and increases suddenly to 13 m/s. Compared with the traditional PI and the fuzzy PI pitch controller, the simulation results of the pitch angle and the unit output power of the compound controller are shown in figures 3 and 4.

**Figure 2.** Step wind speed near the rated.

**Figure 3.** Pitch angle near the rated wind speed.
Figure 4. Output power near the rated wind speed.

It can be seen from figures 3 and 4 that when the wind speed is changed from 7 m/s to 10 m/s, the pitch controller starts to work. With the compensation of the feed-forward controller and the adjustment of the PI parameters by fuzzy adaptive controller, the pitch angle of the compound controller increases to 2.6°, which is about 1.4° larger than that of PI and fuzzy PI controller. The power overshoot of the unit is reduced by 3.8% and the adjustment time is shortened by 0.03 s. When the wind speed changes from 10 m/s to 13 m/s, the output of the compound pitch controller increases to about 14.4°, which is about 1° larger than that of PI and fuzzy PI controller. The power overshoot of the unit is reduced by about 2.6%, the adjustment time is shortened by about 0.02 s.

3.1.2. Near the cut-out wind speed. As shown in figure 5, the wind speed is 18 m/s before $t = 0.5$ s and increases suddenly to 21 m/s at $t = 0.5$ s. It remains at 21 m/s till at $t = 1$ s, it increases suddenly to 24 m/s. Compared with the traditional PI and fuzzy PI pitch controller, the simulation results of the pitch angle and the unit output power of the compound controller are shown in figures 6 and 7.

It can be seen from figures 6 and 7 that when the wind speed is changed from 7 m/s to 10 m/s, the output of the compound pitch controller increases to 31.8°, which is about 0.9° larger than that of the PI and fuzzy PI pitch controller. The power overshoot of the unit is reduced by approximately 11.54%, the adjustment time is reduced by approximately 0.03 s. When the wind speed changes from 21 m/s to 24 m/s, the output of the compound pitch controller increases to about 35.1°, which is about 0.7° larger than that of PI and fuzzy PI pitch controller. The overshoot of the power is reduced by about 6.41%, the adjustment time is shortened by about 0.03 s, and the power can be kept around 1.5 MW, which reduces the impact on the grid.

Figure 5. Step wind speed near the cut-out. Figure 6. Pitch angle near the cut-out wind speed.
Figure 7. Output power near the cut-out wind speed.

3.2. Natural wind speed

The natural wind speed is shown in figure 8. It varies from about 8 m/s to 20 m/s. Under the natural wind speed, the simulation results of the pitch angle and the output power of different controllers are shown in figures 9 and 10.

Figure 8. Natural wind speed.  
Figure 9. Pitch angle under natural wind speed.  
Figure 10. Output power under natural wind speed.

It can be seen from figures 9 and 10 that when the wind speed exceeds the rated value, the pitch controller starts to work. The compound controller outputs bigger pitch angle than that of the classical PI and fuzzy PI controllers, and its pitch angle also can be adjusted more quickly following the change.
of the wind speed. In addition, the compound pitch controller has more significant effect on the fluctuation of the output power. The overshoot is obviously smaller than that of the classical PI and fuzzy PI controller, and the adjustment time is also shorter.

4. Conclusion
In this paper, a compound fuzzy variable pitch controller is designed on the joint simulation model, which combined fuzzy adaptive PI controller with fuzzy feed-forward controller. It not only solves the problem that traditional PI parameters are difficult to set, but also realizes rapid compensation for the wind speed disturbance. The simulation of the compound pitch controller of the unit is carried out under the step and natural wind speed. The results show that the compound pitch controller has good dynamic performance of reducing the output power fluctuation caused by wind speed disturbance, and the control effect is better than that of the traditional classical PI and fuzzy PI controller.

Acknowledgments
This research was funded by National Natural Science Foundation of China (51577008).

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