Study on Control Strategy of Optimal Power Tracking of Multi-MW Wind Generating Set

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Abstract: - Recently, an increasing number of multi-MW (1MW and up) wind generating set are being developed with a variable speed-variable pitch (VS-VP) control strategy to improve the fast response speed and get optimal energy. But the power generated by wind turbine changes rapidly because of the continuous fluctuation of wind speed and direction, and wind energy conversion systems are of strong nonlinear characteristics because of many uncertain factors. By analyzing the mathematical model of doubly-fed induction generator (DFIG), this paper presents a kind of control strategy of optimal power tracking. Fuzzy adaptive PID controller (FAPIDC) is adopted, and simulation results show that the controller can compensate the nonlinearity and have excellent robustness.

Key-Words: - Doubly-fed induction generator (DFIG), Fuzzy, Adaptive, Variable speed-variable pitch (VS-VP), Wind turbine, Simulation

1 Introduction

Compared with fossil fuel and nuclear power generation, wind power is of cost competitive, environmentally clean and safe renewable power sources, and is being paid more attention recently [1], [2]. An actual turbine cannot extract more than 59.3 percent of the air kinetic energy according to Betz theory. In practice, this factor is less because of mechanical imperfections, but we also hope get maximum energy by adopting various methods.

On the other hand, in a renewable energy system, power quality and reliability are two most vulnerable issues. The ordinary linear constant gain controller will cause overshoot or even loss of system stability, at the same time the adaptive control method is not applicable in this case due to the complexity of the algorithm and the fast response characteristic of a multi-MW variable speed-variable pitch wind turbine. When the wind speed range varies from cut-in wind speed to rated wind speed, variable speed control method is adopted. Objectives for variable speed control system are summarized by the following general goals: to regulate and smooth the power generated, to maximize the energy capture, to alleviate the transient loads; When the wind speed range varies from rated wind speed to cut-out wind speed, variable pitch control method is adopted. Objectives for the pitch--angle control are similar to the variable speed ones but only can be match a rotational power by regulating pitch angle [3].

The conventional PID control has been used in industry for many years because of its simpler structure and good robust performance. However, the performance of a PID controller fully depends on the tuning of its parameters. It has been a problem to tune properly these parameters because many industrial plants are often burdened with problems such as high order, time delays, and nonlinearities [4], [5]. The fuzzy control can overcome uncertain parameters and unknown models of nonlinear systems and has a fast response characteristic. The ideas of full order feedback and membership function are used in the design of the controller, which we call fuzzy adaptive PID Control (FAPIDC).This paper describes a 1.5 MW variable speed-variable pitch wind turbine with doubly-fed induction generator (DFIG) where fuzzy adaptive PID Control (FAPIDC) has been used extensively to optimize the power output and enhance system performance [6-8].

2 Wind Turbine System

A simplified variable speed-variable pitch wind power conversion system is show in Fig.1, and can be divided into seven parts briefly, such as wind turbine, gear box, doubly-fed induction generator (DFIG), power grid, variable pitch mechanism, converter, controller, etc.

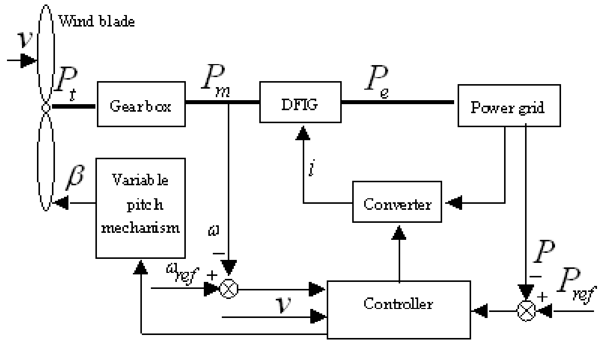

Fig.1 A simplified variable speed-variable pitch wind power conversion system

2.1 Wind Turbine

The main objective of using a variable speed-variable pitch control strategy is to improve the fast response speed and get maximum energy. The aerodynamic power captured by the multi-MW variable speed – variable pitch wind turbine is calculated by nonlinear expression

$$P_t = \frac{1}{2}\rho\pi R^2 C_P(\lambda,\beta)v^3 \tag{1}$$

The wind turbine torque is given by

$$T_t = \frac{1}{2}\rho\pi R^3 C_q(\lambda,\beta)v^2 \tag{2}$$

There is an expression between power coefficient $C_P(\lambda,\beta)$ and torque coefficient $C_q(\lambda,\beta)$

$$C_P(\lambda,\beta) = \lambda C_q(\lambda,\beta) \tag{3}$$

where $\lambda = \omega_t R / v$ is the tip speed ratio, ω_t is the turbine angular velocity, v is the wind speed, ρ is the air density, R is the rotor radius and β is the pitch angle. The power coefficient $C_p(\lambda,\beta)$ and $C_q(\lambda,\beta)$ are two nonlinear function of λ and β.

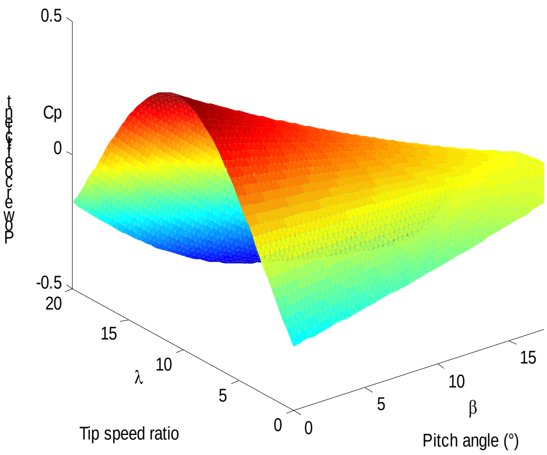

Fig.2 Coefficient curve of wind turbine power

At $\lambda = 10$, $\beta = 0$, the optimum power coefficient can be got, and its characteristic is shown in Fig.2.

2.2 Gear Box

In the mechanical model, the torque of high speed shaft T_m is calculated by the expression

$$J_t \frac{d\omega_t}{dt} = T_t - n_t T_m \tag{4}$$

where T_t is wind turbine torque, J_t is wind turbine rotor inertia, ω_t is the turbine angular velocity, n_t the gear drive train ratio. The gear drive train is considered because it has the most significant influence on the power fluctuations. Doubly-fed asynchronous generator (DFIG) is adopted mostly in a multi-MW variable speed-variable pitch wind turbine, and its characteristic is that the stator windings directly connected to the three-phase grid and the rotor windings connected to a frequency converter, which control the rotor voltage's phase and magnitude and are therefore used for active power and reactive power control [9].

The relation between the electrical torque T_e and mechanical torque T_m is shown below

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

where J_g is DFIG inertia, ω_g is the DFIG angular velocity.

2.3 Variable Pitch Mechanism

Hydraulic system is used in a process requiring large driving forces and torques. A fast accurate response with small overshot is also desirable in such system. The variable pitch mechanism is usually operated using hydraulics. In this paper the electro-hydraulic control technology is used for a 1.5 MW variable speed-variable pitch wind turbine to achieve accurate servo tracking in the presence of load disturbance and plant parameter variation [10]. The variable pitch mechanism may be simplified by the first-order inertia system:

$$\dot{\beta} = \frac{1}{\tau_\beta}(\beta_v - \beta) \tag{6}$$

where τ_β is time constant.

3 Control Strategies

The conventional PID controller output $u(t)$ is given by expression

$$u(t) = k_P \left\{ e(t) + \frac{1}{T_I}\int_0^t e(\tau)d\tau + T_D \frac{de(t)}{dt} \right\}$$
$$= k_P e(t) + k_I \int_0^t e(\tau)d\tau + k_D \frac{de(t)}{dt} \qquad (7)$$

where $e(t)$ is error input, T_I is the integral time constant, T_D is the derivative time constant, k_P is the proportional gain, $k_I = k_P / T_I$ is the integral gain, $k_D = k_P T_D$ is the derivative gain. The role of each separate part of a PID controller can be described as follows: The proportional part reduces the error responses of the system to disturbances, the integral part eliminates the steady-state error of the system, and the derivative part dampens the dynamic response and thereby improves the stability of the system. From the perspective of time, the proportional part estimates the system at present, the integral part takes the past into account, and the derivative part estimates what will happen in the future, which yields a much more stable control than the control with only one or two of these features [10]. The fuzzy controller may adjust on-line the proportional, integral and derivative gain of a conventional PID controller according to value of input $e(t)$. The modification gain is expressed as:

$$k_P = k_P^* + \Delta k_P \cdot k_{\Delta k_P} \qquad (8)$$

$$k_I = k_I^* + \Delta k_I \cdot k_{\Delta k_I} \qquad (9)$$

$$k_D = k_D^* + \Delta k_D \cdot k_{\Delta k_D} \qquad (10)$$

where k_P^*, k_I^*, k_D^* is initial value of the proportional, integral and derivative gain , Δk_P , Δk_I , Δk_D is given by expression

$$\Delta k_P = \{e \times \dot{e}\} \circ R_{\Delta k_P} \qquad (11)$$

$$\Delta k_I = \{e \times \dot{e}\} \circ R_{\Delta k_I} \qquad (12)$$

$$\Delta k_D = \{e \times \dot{e}\} \circ R_{\Delta k_D} \qquad (13)$$

where $R_{\Delta k_P}$, $R_{\Delta k_I}$, $R_{\Delta k_D}$ is fuzzy decision relation matrix. The fuzzy rules and membership functions have been designed to optimize the captured power at low wind speed and to limit the captured power at high wind speed [11],[12]. The two inputs are the DFIG rotor angular velocity error and its differential error at variable speed control; the two inputs are the DFIG power error and its differential error at variable pitch control; Two scaling factors are used to put the resulting error values to achieve a smooth control input, as shown in Fig.3. The rules of fuzzy adaptive PID Control (FAPIDC) modification gain Δk_P, Δk_I, Δk_D is produced based on the rules summarized in Table 1, Table 2, Table 3.

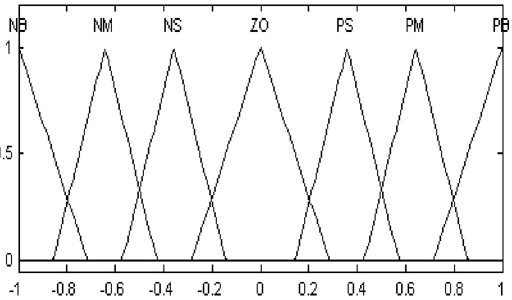

Fig.3 Membership functions for input and output variables

Table 1

Rules for Proportional Modification Gain

Δk \ $\dot{e}$ / e	NB	NM	NS	ZO	PS	PM	PB
NB					PM	PS	ZO
NM		PB		PM	PS	ZO	NS
NS			PM	PS	ZO	NS	NM
ZO		PM	PS	ZO	NS	NM	
PS	PM	PS	ZO	NS	NM		
PM	PS	ZO	NS	NM		NB	
PB	ZO	NS	NM				

Table 2

Rules for Integral Modification Gain

Δk_I \ $\dot{e}$ / e	NB	NM	NS	ZO	PS	PM	PB
NB					NS	ZO	ZO
NM		ZO		NS	NS	ZO	ZO
NS	NS	NM	NS	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PS	PM	PS
PM	ZO	ZO	PS	PS		ZO	
PB	ZO	ZO	PS				

Table 3
Rules for Derivative Modification Gain

Δk_D $\dot{e}$ / e	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NM	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	PS
NS	ZO	NS	NM	NS	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PM	PS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

Each input and output variable has its own control surface, which consists of fuzzy region. These regions overlap each other to give a smooth control response. The area in which membership functions are dense is where accurate control is crucial. The input and output regions are related by a set of rules. Once the fuzzy controller is activated, rule evaluation is performed and all the rules that are true are fired. The rules and membership functions have been designed and adjusted based on simulations, testing and knowledge of the characteristics and response for the wind turbine system. Where: e stands for error, $\dot{e}$ stands for differential error, P means Positive, N means Negative, B means Big and S means small.

4 Simulation

Simulation study is made for a 1.5 MW wind turbine with DFIG. Wind turbine start to provide power from 4m/s wind speed (cut-in wind speed). Maximum power is given for nearly wind speed to 12.2m/s (rated wind speed). Wind speed higher than 25m/s (cut-out wind speed) is recommended to brake wind turbine.

A. When the wind speed range varies from 4 m/s to 12.2 m/s, fuzzy adaptive PID variable speed control method is adopted by adjusting the rotor speed in order to get optimal value of λ. So, through changing the tip speed ration induced by rotor speed or wind speed, can leading to get the optimal power coefficient $C_{p-opt}(\lambda,\beta)$, namely get maximum power by adjusting value of λ. As shown in Fig.2, $C_{p-opt}(\lambda,\beta)$ is about 0.44, where $\lambda=10$, $\beta=0$.

B. When the wind speed range varies from 12.2 to 25m/s, fuzzy adaptive PID variable pitch control method is adopted by adjusting the pitch angle β in order to make generator work in the case of rated power.The following system parameters are considered.

A. Rotor speed range (rpm): 11.1-22.2, Diameter (m)=70.5, Cut in wind speed (m/s)=4, Rated wind speed (m/s)=12.2, Cut out wind speed (m/s)=25, Gearbox ratio=1: 90, Optimum tip speed ratio=10, Optimum power coefficient=0.44, Turbine rotor inertia (kg • m^2)=320000.

B. Generator pole=4, Rated power (KW)=1500, Rated frequency (Hz)=50, Stator rated voltage (V)=690, Rotor rated voltage (V)=690, Stator resistance (pu)=0.0076, Rotor resistance (pu)=0.0073, Stator leakage inductance (pu)=0.1248, Rotor leakage inductance (pu)=0.0884, Magnetizing inductance (pu)=1.8365, Generator rotor inertia (kg • m^2)= 60, Power factor =1.

Fig.4 shows that DFIG rotor speed changes with wind speed during 4 m/s to 25m/s. It can be seen that the rotor speed changes in order to get a $C_{p-opt}(\lambda,\beta)$ in variable speed control, but the rotor speed maintain rated value 2000 rpm in variable pitch control. Fig.5 shows the $C_{p-opt}(\lambda,\beta)$ changes in variable speed control and the $C_p(\lambda,\beta)$ value equals to 0.44 approximately. Meanwhile, Fig.6 shows the $C_p(\lambda,\beta)$ changes in variable pitch control, and also the pitch angle β changes in Fig.7. It can be seen that the $C_p(\lambda,\beta)$ change small along with pitch angle β change big. Fig.8 shows the DFIG power change in variable speed control. Fig.9 shows the DFIG power change in variable pitch control. So, the maximum power in variable speed control and rated power in variable pitch control can be got.

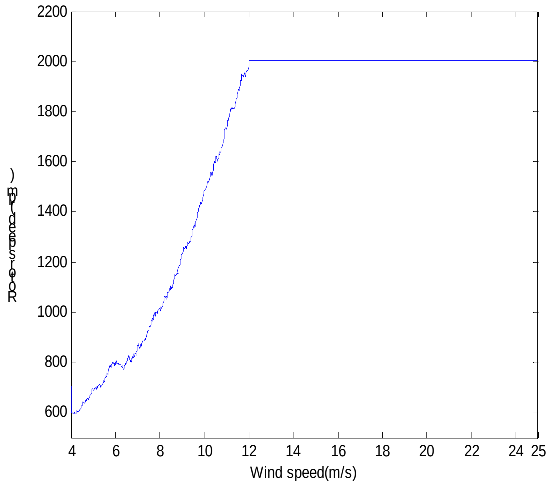

Fig.4 DFIG rotor speed change in wind speed from 4 m/s to 25 m/s

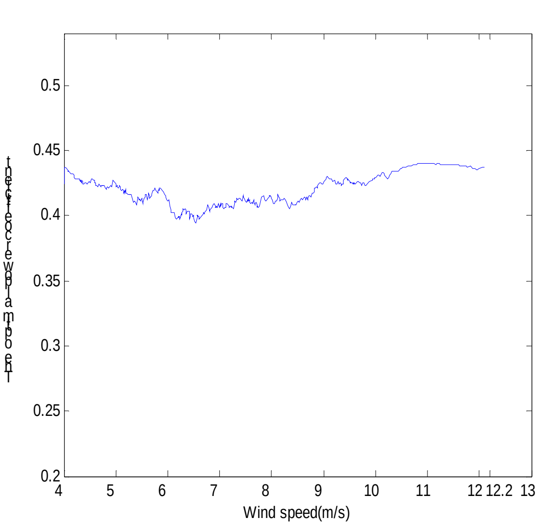

Fig.5 $C_{p-opt}(\lambda,\beta)$ change in variable speed control

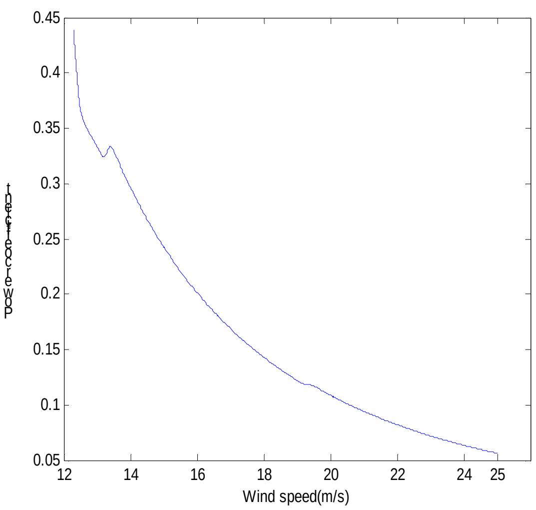

Fig.6 $C_p(\lambda,\beta)$ change in variable pitch control

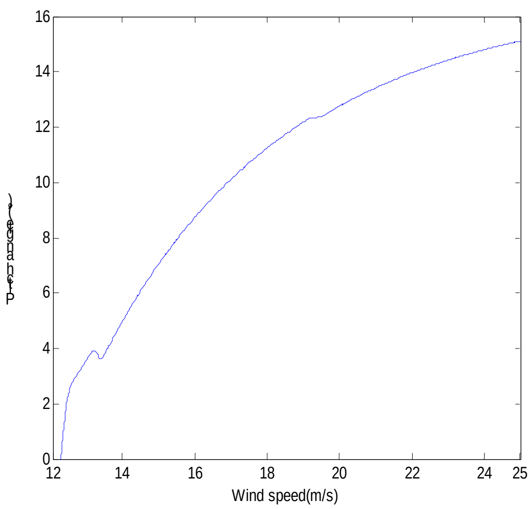

Fig.7 Pitch angle β change in variable pitch control

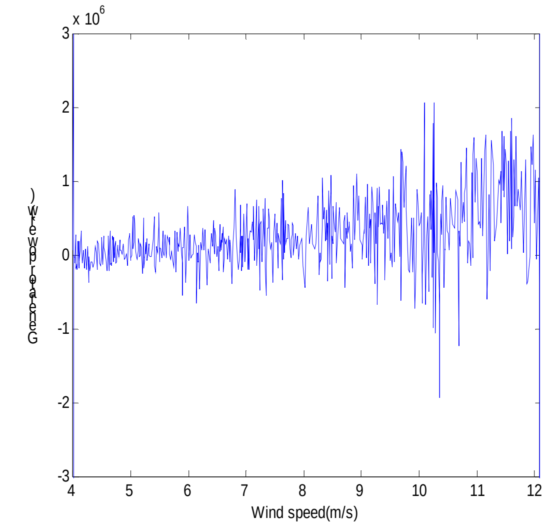

Fig.8 DFIG power change in variable speed control

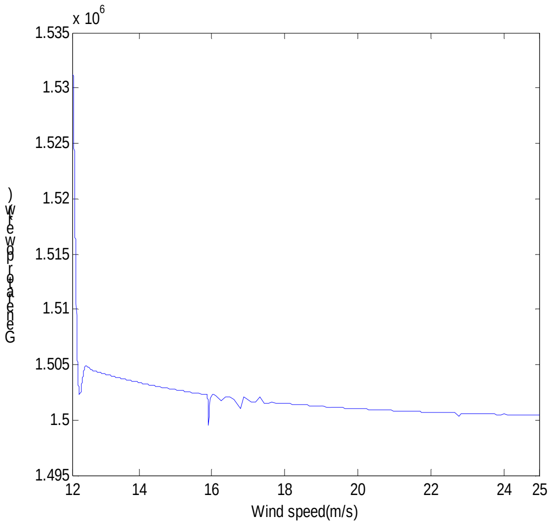

Fig.9 DFIG power change in variable pitch control

5 Conclusion

The paper presents a dynamic model for a 1.5 MW VS-VP wind generating set with DFIG. When the wind speed range varies from cut-in wind speed to rated wind speed, fuzzy adaptive PID variable speed control method is adopted by adjusting the rotor speed in order to get maximum power; When the wind speed range varies from rated wind speed to cut-out wind speed, fuzzy adaptive PID variable pitch control method is adopted by adjusting the pitch angle β in order to make generator work in the case of rated power..

A fuzzy adaptive PID controller (FAPIDC) has been used in this paper. This control method can shorten the system response time, compensate system nonlinearity and eliminate the steady state error due to the uncertain factor. Simulation results show that this method can improve the wind turbine performance at low, rated and high wind speed.

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