Power dispatching tracking control of wind turbine considering maximum and limited power generation below rated wind speed

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Abstract. Wind turbines should respond to power dispatching of power grid at all times. According to this demand, this paper puts forward a set of feasible power control strategies below rated wind speed. Firstly, the operation state of wind turbine is divided into two working modes: maximum power generation and wind power curtailment generation. Different control strategies are adopted in different working conditions. Under the mode of maximum power generation, the model predictive control (MPC) algorithm is used to give a torque compensation gain. The MPC controller not only improves the utilization efficiency of wind energy, but also reduces the mechanical load. Under the mode of wind curtailment, a hybrid tracking control strategy of giving priority to torque control than pitch regulation is adopted. It reduces the frequency and amplitude of the pitch mechanism greatly. By comparing the simulation results under various wind speeds, it is found that the proposed power control strategy can adapt to different power dispatching scenes, and can respond to power dispatching with greater performance. It is very significant for the improvement of wind power generation system.

1. Introduction

With the increasing prominence of global energy and environment problems, the development and utilization of renewable energy has been paid more attention. Among them, wind energy is the most mature and has the most commercial development prospects [1]. Wind power generation has developed rapidly in recent years, but there are still many problems. There is high uncertainty and fluctuation in natural wind speed, which is in contradiction with the stability and reliability of power grid. Therefore, modern wind turbines do not always work in the maximum power point tracking (MPPT) mode. This requires the wind power generation system to have an efficient control strategy that can generate corresponding power in real time according to power grid dispatching.

At present, a great deal of research on wind power control technology has been carried out at home and abroad. The literature [2] divided the power control system of wind turbine into two levels: wind farm level and unit level. The upper wind farm level received power dispatching instructions from power grid and distributed them to each unit. The variable speed variable pitch wind turbine unit includes two control loops: rotational speed control based on electromagnetic torque control and power control based on pitch angle control. This paper mainly studies the unit-level power control
strategy. Under the condition of maximum power generation, literature [3] proposed a flexible MPPT strategy for large inertia wind turbines, which balanced the contradiction between generation efficiency and power fluctuation. The literature [4] gave a relatively complete control strategy for 5MW wind turbine, but the classical optimal torque control (OTC) strategy was still used below rated wind speed. When the wind speed changed rapidly, the wind energy utilization coefficient was low. There are also some references which provide a good solution to the control strategy in wind curtailment condition. With the minimum comprehensive adjustment of speed and pitch angle as the objective function, Mi et al. [5] proposed an active power control strategy based on the optimal transfer trajectory model of the unit operating point. The experimental results showed that the strategy greatly reduced the fatigue load caused by frequent action of rotor speed and pitch angle. In [6, 7], power limitation control was realized by increasing generator speed to make it deviate from the optimal value. However, limited by the maximum speed of the unit, this control strategy could only curtail part of the power and had limited regulating ability. The output power of the unit was adjusted by variable pitch control in [8], but the variable speed circuit was not considered. The control strategy required the unit to adjust the pitch angle frequently, which led to excessive load of the unit and reduced the service life of the unit. Wind turbine is a complex and strongly coupled nonlinear system, so the uncertainties of parameters and nonlinearity of system should be taken into account when designing control algorithms for such systems [11]. This will bring a lot of trouble to the design of the controller.

In this paper, according to the subsystem models of wind turbine, the local linearization of the nonlinear system is carried out near steady wind speed, and the simplified local linear model is obtained. Using predictive control algorithm, MPC torque compensation controller is designed. A practical active power control strategy is proposed for unit power dispatching instructions below rated wind speed. The experimental results show that the strategy can respond well to the power setting instructions of the unit and adapt to the power dispatching control under different wind speeds. Under the condition of maximum power generation, it can greatly improve the utilization efficiency of wind energy and the generation capacity. Under the condition of wind curtailment, it can reduce the frequent action of the pitch mechanism and the mechanical load of the unit. This strategy can effectively solve the power dispatching tracking control problem for grid-connected single wind turbine below rated wind speed.

2. Subsystem models of wind turbine
According to the principle of hydrodynamics, the mechanical energy captured by wind turbines can be expressed as follows:

\[
\begin{align*}
    P_m &= \frac{1}{2} \rho \pi R^2 v^3 C_p(\lambda, \beta) \\
    T_m &= \frac{P_m}{\omega_i}
\end{align*}
\]  

(1)

where \( \rho \) is the air density, \( R \) is the rotor radius, \( v \) is the wind speed, \( C_p \) is the utilization coefficient of wind energy, \( T_m \) is the mechanical torque of wind turbine, \( \omega_i \) is the rotor speed, \( \beta \) is the blade pitch angle, \( \lambda = \omega_i R / v \) is the tip speed ratio.

\( C_p \) is usually obtained by looking up table in practical engineering. For a fixed wind turbine object, there is a relatively stable \( C_p(\lambda, \beta) \) table. For a given \( \lambda \) and \( \beta \) in actual calculation, the corresponding \( C_p \) value can be obtained by looking up the \( C_p(\lambda, \beta) \) table.

For the drive-train system with gearbox, it can be divided into three parts: low-speed shaft, gearbox and high-speed shaft. If the low-speed shaft is assumed to be rigid, that is, the friction and torsion of the low-speed shaft are considered, the two-mass model is obtained as follows:
\begin{equation}
\begin{aligned}
J_i \dot{\omega}_i &= T_{in} - T_{shaft} \\
T_{shaft} &= K_{dil} \left( \theta_i - \frac{\theta_g}{N_{gear}} \right) + B_{damp} \left( \omega_r - \frac{\omega_g}{N_{gear}} \right) \\
J_{g\theta} \dot{\theta}_g &= \frac{T_{shaft}}{N_{gear}} - T_e
\end{aligned}
\end{equation}

where \( J_i \) is the rotational inertia of rotor, \( J_g \) is the rotational inertia of generator, \( T_e \) is the electromagnetic torque of generator, \( N_{gear} \) is the gearbox ratio, \( \omega_g \) is the generator speed, \( T_{shaft} \) is the equivalent mechanical torque of gearbox, \( K_{dil} \) is the stiffness coefficient of low speed shaft, \( B_{damp} \) is the damping coefficient of low speed shaft, \( \theta_i \) is the rotor angular position, \( \theta_g \) is the generator angular position.

Considering the fast dynamic response characteristics of the generator, it is simplified as a first-order inertial dynamic model:

\begin{equation}
\dot{T_e} = \frac{1}{\tau_e} (T_{e}^* - T_e)
\end{equation}

where \( T_{e}^* \) is the electromagnetic torque reference value of generator, \( \tau_e \) is the equivalent time constant.

3. Power dispatching tracking control below rated wind speed

For modern grid-connected large-scale wind turbines, the power control system not only needs to ensure the reliable operation of units and absorb maximum wind energy, but also adopts efficient control strategy to achieve accurate and fast dynamic response to power dispatching of power grid. Under this background, this section proposes a power dispatching tracking control strategy for wind turbine below rated wind speed. The strategy can flexibly switch between the modes of maximum wind energy tracking and power limitation tracking according to the real-time power dispatching instructions distributed by the power grid. In addition, it achieves the optimization of control performance in a single state based on predictive control algorithm.

According to the wind power characteristic curve of wind turbine and the known wind speed measurement value and power setting value, the operation mode of wind turbine can be judged. Under a certain wind speed, if the power setting value is greater than or equal to the maximum power generation value, the wind turbine is in the maximum output state. On the contrary, the wind turbine is in the wind curtailment state.

Under the condition of maximum power generation, the classical OTC strategy below rated wind speed has some shortcomings. Because of the large rotational inertia, the speed of rotor changes slowly so that it cannot follow the change of wind speed quickly, which leads to the long transient process of control system. In view of this shortcoming, this paper designs a torque compensator by using predictive control algorithm, which can make the system quickly transit to the steady-state operating point when the wind speed fluctuates, and improve the capture efficiency of wind energy.

Under the condition of wind curtailment, because the power setting value is less than the maximum power generation value, actual wind turbine usually uses a single control loop with variable speed or variable pitch to limit the power. However, the power regulation range of single variable speed control loop is limited, and the power regulation response time of single variable pitch control loop is long. Therefore, considering the randomness of wind speed and the uncertainty of power dispatching instructions, a hybrid tracking control strategy of variable speed and variable pitch is proposed in this paper. According to the power dispatching instructions, variable speed control is given priority. If it cannot meet the requirements, the strategy is switched to variable pitch control.

Firstly, it is necessary to set the speed limit of the rotor. The theoretical wind energy utilization coefficient \( C_p \) is calculated by substituting the power setting value into equation (1). According to the \( C_p(\lambda, \beta) \) table, the theoretical tip speed ratio \( \lambda \) is obtained when the blade pitch angle is equal to 0°, and
then the theoretical rotor speed $\omega_r$ is calculated. When the theoretical rotor speed $\omega_r$ is lower than the maximum speed, the power is limited only through the variable speed link, and the wind energy utilization coefficient is reduced by increasing the rotor speed of wind turbine to deviate from the optimal value. At this time, the given value of generator torque is $T_e = k \omega_g^2$, $k=0.5 \rho \pi R^3 C_p / (N_{gear}^3 \lambda^3)$, where $C_p$ and $\lambda$ are the theoretical wind energy utilization coefficient and the theoretical tip speed ratio, and the given value of generator power is $P_e = T_e \omega_g$.

When the theoretical rotor speed is higher than the maximum speed, that is, when the speed rises to the setting threshold and still cannot meet the power limitation requirements, the strategy is switched to variable pitch control. Through the strategy of increasing speed to curtail power, all or part of the curtailed wind energy can be converted into the kinetic energy of wind turbine, and the output power of the latter stage can be reduced. When the limited power condition is improved (wind speed drops or power setting value rises), the kinetic energy can be converted into electricity, which can properly improve utilization efficiency of wind energy.

The control strategy flow chart is shown in figure 1.

Figure 1. Flow chart of control strategy.

4. Torque compensation MPC controller

4.1. State space equation

Torque compensation controller is designed by predictive control algorithm to compensate the given torque value of classical OTC control strategy. The control principle is shown in figure 2, and the reference value of electromagnetic torque is expressed as the following equation:

$$T_e^* = T_{e\text{opt}} - T_{\text{comp}} = K_{\text{opt}} \omega_g^2 - K_w \dot{\omega}_g$$ (4)

where $K_{\text{opt}} = 0.5 \rho \pi R^3 C_{p\max} / (N_{gear} \lambda_{opt}^3)$, $K_w$ is the gain of torque compensation, which is given by MPC controller.

Since the pitch mechanism does not operate below rated wind speed, that is, $\beta = 0^\circ$, and then set up equations (1), (2), (3) simultaneously, the following equations can be obtained after local linearization:

$$\begin{align*}
J_c \delta \dot{\omega}_c &= \Gamma_w \delta \omega_r + \Gamma_v \delta v - \delta T_{\text{shaft}} \\
\delta T_{\text{shaft}} &= K_{\text{slip}} \left( \delta \omega_r - \frac{\delta \omega_c}{N_{\text{gear}}} \right) + B_{\text{damp}} \left( \delta \omega_r - \frac{\delta \omega_c}{N_{\text{gear}}} \right) \\
J_b \delta \dot{\omega}_b &= \frac{\delta T_{\text{shaft}}}{N_{\text{gear}}} - \delta T_e \\
\tau_e \delta \dot{T}_e &= \delta T_e^* - \delta T_e
\end{align*}$$ (5)

where $\Gamma_w = \frac{\partial T_m}{\partial \omega_r} |_{(\omega_c, v)}$, $\Gamma_v = \frac{\partial T_m}{\partial v} |_{(\omega_c, v)}$.  

Figure 2. Torque compensation principle.
According to MPPT principle, $T_k = \frac{1}{J} (\dot{J} + B \omega + \Gamma)$.

The state space equation can be expressed as:

$$
\delta \dot{x}(t) = \begin{bmatrix}
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
-\frac{K_{\text{stiff}}}{J_e} & -\frac{K_{\text{stiff}}}{J_g N_{\text{gear}}} & \Gamma_{\text{tw}} - B_{\text{damp}} & B_{\text{damp}} & 0 \\
-\frac{K_{\text{stiff}}}{J_e N_{\text{gear}}} & -\frac{K_{\text{stiff}}}{J_g N_{\text{gear}}} & B_{\text{damp}} & -B_{\text{damp}} & -1 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\delta x(t) + \begin{bmatrix}
0 \\
0 \\
1 \\
-1
\end{bmatrix}
\delta u(t) + \begin{bmatrix}
0 \\
0 \\
0 \\
0
\end{bmatrix}
\delta v(t)
$$

(6)

where $\delta x(t) = [\delta \theta, \delta \theta_c, \delta \omega, \delta \omega_c, \delta T_e]^T$, $\delta u(t) = \delta T_e^*$, $\delta y(t) = [\delta \omega_c, \delta T_{\text{shunt}}]^T$.

### 4.2. Cost function and constraints

The main control objective of the torque compensation controller is to improve the utilization efficiency of wind energy and reduce the mechanical load. According to MPPT principle, the maximum wind energy capture efficiency can be represented by the speed of rotor speed tracking the optimal speed. In the control horizon $N_e$, the square sum of the difference between the wind turbine speed and the optimal speed can be used as the evaluation index, and the cost function is obtained as follows:

$$
J = \min \sum_{i=1}^{N_e} \left[ Q_1 \left( \omega_i (k+i) - \omega_{\text{opt}} (k+i) \right)^2 + Q_2 \left( T_{\text{shunt}} (k+i) \right)^2 + Q_3 (K_w (k+i) - K_w (k+i-1)) \right]^2
$$

(7)

Constraints:

$$
\omega_i \min \leq \omega_i (k+i) \leq \omega_i \max
$$

(8)

$$
\omega_i (k+i) \leq \omega_i \max
$$

(9)

$$
0 \leq T_e (k+i) \leq T_e \max
$$

(10)

The first item in the cost function is the index of wind energy utilization efficiency, the second item is the mechanical load of drive-train shaft, and the third item is the incremental limitation of compensation gain $K_w$. $Q_1$, $Q_2$ and $Q_3$ are the weight coefficients of the control objectives. In the constraints, equation (8) is the speed limit. Equation (9) is the speed acceleration constraint to prevent the mechanical load of the drive-train system from being too high. Equation (10) is the generator electromagnetic torque amplitude constraint.

### 5. Simulation

In this paper, the FAST (Fatigue, Aerodynamic, Structure, Turbulence) simulation platform is used to build the simulation model of wind power system. The simulation parameters are as follows: $P_{\text{rated}}=5\text{MW}$, $\omega_{\text{rated}}=12.1\text{r/min}$, $R=63\text{m}$, $\rho=1.225\text{kg/m}^3$, $N_{\text{gear}}=97$, $\eta=94.4\%$, $J_i=115926\text{kg}\cdot\text{m}^2$, $J_g=534.116\text{kg}\cdot\text{m}^2$, $K_{\text{stiff}}=867637000\text{Nm/rad}$, $B_{\text{damp}}=621500\text{Nm}\cdot\text{s/rad}$, $C_{\text{opt}}=0.482$, $\lambda_{\text{opt}}=7.55$, $v_{\text{opt}}=7\text{m/s}$, $\omega_0=0.8302\text{rad/s}$. The $C_p(\lambda,\beta)$ table of 5MW wind turbine is exported by WT_perf software.

#### 5.1. Maximum power generation

The simulation results of step wind below rated wind speed are shown in figure 3. It can be seen from the figure that the wind speed rises from 6 m/s to 7 m/s at 70 s. At the moment when the wind speed changes, the rotor speed cannot change immediately because of the existence of the inertia of wind
turbine, which results in the decrease of wind energy utilization coefficient. Because of compensation gain $K_w$, the rotor speed with torque compensation increases faster than that without torque compensation. The wind turbine can reach the steady-state operating point faster, so the utilization efficiency of wind energy in the transition process is higher.

Figure 3. Simulation results of step wind under the condition of maximum power generation.

5.2. Wind power curtailment

Figure 4 is the simulation results of step wind under wind curtailment condition. The power setting value is 1.1MW and the wind speed is 7m/s in the first 100s. The theoretical rotor speed is 11.5r/min calculated by looking up the table, which is less than the maximum value of rotor speed. Therefore, variable speed control strategy is adopted to make rotor speed track the theoretical speed and the blade pitch angle does not act. When the wind speed rises from 7m/s to 8m/s at 100s, the theoretical rotor speed becomes 16.9r/min, which is higher than the maximum speed value, and the pitch adjustment starts. The pitch angle controller adopts PID controller. At 200s, the wind speed reduces to 7m/s, and then variable pitch control is switched to variable speed control. It can be seen from the figure that the final power of the generator is not accurately stabilized at 1.1MW when using variable speed control. The reason is that the $C_p(\lambda,\beta)$ table is derived by WT_perf software, which may be different from the internal aerodynamic characteristics of FAST, but the final error is small and acceptable.
5.3. Multiple operating conditions under turbulent wind speed

This section simulates the power dispatching when the average wind speed is 9m/s and the turbulent intensity is 19.2%. The power setting value is 2MW in the first 100s and the condition of the last 100s is maximum power generation. Because the wind speed fluctuates greatly in the first 100s, it is necessary to determine the operation conditions according to the wind speed, and adopt corresponding control strategies. It can be seen from figure 5 that there are three switching strategies in the first 100s: maximum power generation, variable speed control and variable pitch control in wind curtailment. The maximum power generation strategy is adopted in the latter 100s. The control strategy proposed in this paper can switch between maximum power generation and limited power generation very well, and the control target is still well achieved even in harsh wind conditions.

6. Conclusions

In this paper, a practical active power control strategy is proposed for the single wind turbine power dispatching problem below rated wind speed. The original control strategies are optimized for different operating modes, and controllers with better control performance are designed by using
predictive control algorithm. The simulation results show that the proposed control strategy is suitable for different power instructions under various wind speeds. It can judge the operation conditions in real time and adopt corresponding control strategies. Under the condition of maximum power generation, the utilization efficiency of wind energy is improved and the generation capacity is increased by using MPC torque compensation controller. Under the condition of wind curtailment, the hybrid tracking control strategy of variable speed and variable pitch is adopted. Priority is given to increasing speed, which can convert the curtailed wind energy into the kinetic energy of wind turbine. It can also reduce the frequent switching between variable speed and pitch, reduce the mechanical load and prolong the service life of the unit. In actual pitch angle control, gain scheduling PI or piecewise PI can be used to meet the requirements of fast and stable control of wind turbines with different aerodynamic characteristics under various operating conditions.

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