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The Control Strategy and Simulation of the Yaw System for MW Rated Wind Turbine

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***Abstract*—As an important component of renewable energy, wind energy is a kind of power generation method with the most mature, most developed conditions and broad commercial prospects in renewable energy technology. The development of wind power has continuously exceeded its expected development speed and has maintained the status of the world's fastest-growing energy source. To ensure the stable and efficient conversion of wind energy by wind turbines, not only depends on the reliability of the wind power generation equipment itself, but also the wind turbine control system is also an important factor for the wind energy conversion system, or even become a long-term safe and reliable operation of the wind farm. Therefore, the control system has become a research hotspot. The key to the efficient and stable operation of the entire wind energy conversion system is control technology, including yaw control, pitch angle control, and maximum power point tracking control. The active yaw control system is one of the important components of the horizontal axis wind turbine control system. To eliminate the uncertainty of the influence of wind direction on turbine power, this paper verifies a composite yaw control system. Through an active yaw system and maximum power point tracking system, the turbine position and rotation speed are adjusted to enable the wind turbine to accurately track the wind direction, capture wind energy to the greatest extent. The results show that the active yaw system can accurately track the wind direction, effectively use wind energy, and meet the control requirements of the yaw system.**

Keywords—wind energy conversion system, yaw system, motor, Matlab/Simulink,

I. Introduction

With global warming and the increasing scarcity of non-renewable resources such as international crude oil, governments, especially developed countries, are paying more attention to the development and utilization of emerging green and environmentally friendly energy sources [1]. Wind energy is an exploitable energy source that is valued for its non-polluting, renewable nature. The key to the efficient and stable operation of the whole wind energy conversion system (WECS) is the control technologies [2]. When the wind speed is unstable in the natural environment, the control strategy used in the WECS can be divided into three types according to different types of control components: generator/converter control, pitch control, and yaw control. Compared with the first two control strategies, the purpose of studying yaw control is to implement the self-correction of wind and wind deviation in the engine room safely and efficiently [3].

Statistics show that there are two problems with wind turbines, one is fatigue damage to the root of the blades and the other is yaw characteristics [4]. The aerodynamic and dynamical characteristics of the yawing units are the least understood area at present, and there are problems with both free yawing units and yawing motor-driven units. For further research of WECS, it is necessary to build mathematical models of the yaw system and analyze them quantitatively [5].

The yaw control system is a part of the WECS [6]. The yaw drive keeps rotating surface of the wind turbine perpendicular to wind direction for making sure that the turbine blades capture the maximum sweep area. In wind energy conversion systems, the role of yaw control system is to align the wind direction quickly and smoothly when the direction of the wind velocity vector changes, in this way the turbine can get the maximum amount of wind [7]. Small and medium-sized wind energy conversion systems using passive yaw of the rudder or rudder wheel; large grid-connected wind energy generation systems use wind sensors and yaw motors to actively yaw [8].

Yaw error (angle between rotor horizontal axis and wind direction) is one reason that makes the WECS can not generate maximum output energy [9]. The yaw error reduces the wind velocity component acting perpendicularly to the rotor plane which lead to decrease of the effective swept area [10]. According to the statistics, the annual energy loss caused by yaw error starts from 2.7% to 11% when the average yaw error is 20° [11]. Thus, it's important to make sure the yaw error is 0, which means the rotating surface is oriented to wind direction. Fig. 1 shows the influence of yaw error on WECS [12].

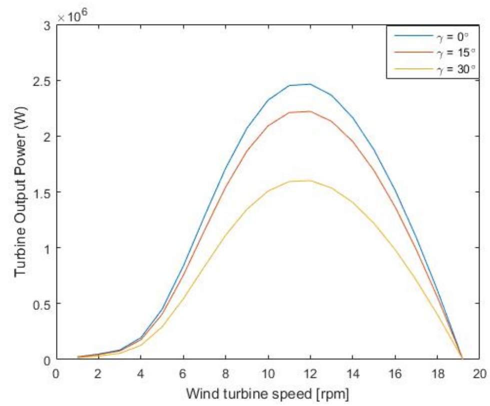

Fig. 1. Turbine output power affected by the yaw angle

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According to Fig. 1, it can be seen that the yaw angle has a big influence on the WECS. When the wind speed is constant at 9 m/s with 15 ° yaw angle, this is a considerable part of the generated power of the turbine has been reduced by about 10.53%; at an angle of 30 °, the output power is reduced by approximately 36.84%, which is extremely unfavorable for wind power plants, so we need a yaw system to avoid these losses and improve power generation efficiency, which requires us to study stability, reliability and efficient yaw control system.

At present, the mainstream wind turbines in the world all use horizontal axis wind power generation. The yaw system is indispensable as its unique mechanism. The stability of the yaw system operation determines the benefit of the WECS and its service life [13]. To ensure that the yaw system can operate as stably as possible and improve the power generation and economic benefits of wind turbines, in recent years, people have done a lot of research and analysis on active yaw control algorithms mainly used in large wind turbines. The aviation system has completed the wind strategy and algorithm, and the representative research results are:

Reference [14] proposed a combined control strategy insists of yaw control and maximum power point tracking (MPPT) strategy for WECS. As the MPPT control, input is the rotor speed, and in the yaw control system, input is the wind speed measured by wind speed sensor, in this system, doesn't need wind vane, because the yaw angle can be estimated by the parameters of WECS, the required parameters are the shaft's real and optimum mechanical power, and simulation experiments show that the controller can effectively reduce the number of yaw actions when the wind direction does not change much. Reference [15] proposed a strategy which uses the indirect estimation of the yaw error. In this strategy, yaw error is calculated by the error between the optimal speed of the MPPT algorithm and the actual rotor speed. This yaw estimation strategy is cost-effective, also it can be installed at any power rated of wind turbines. Reference [16] provided a new yaw control method based on rotational speed, and the rotor speed control is based on the wind measurement data of LIDAR. The results show that the method can effectively reduce wind error when the wind speed is lower than the rated wind speed. Reference [17] used LIDAR to detect the wind speed and wind direction 150 m directly in front of the impeller and optimized the pitch control and yaw control scheme based on this data. However, owing to the high price of LIDAR wind measurement technology, the application in wind turbine control is still in the experimental stage.

At present, in practical applications, the control method of setting the "yaw tolerance angle" is generally adopted for the yaw system of WECS. To avoid frequent movement of the cabin, when the cabin wind error exceeds the yaw tolerance only when the angle is set, the unit will yaw the wind. This method has low control accuracy and directly affects the wind energy utilization rate of the unit. Because of this situation, this paper starts with the perference of the WECS, model, and simulate the control system of the wind turbine yaw system, using the proposed yaw control strategy.

Based on the typical yaw system and MPPT system, this paper studies the control method of the WECS and establishes the corresponding control model in the Matlab/Simulink, which is practical to the Siemens 3.6-120. By establishing the model of the WECS and conducting experiments, it is promising to verify the influence of the application of the yaw system on improving the efficiency of power generation.

II. WIND TURBINE CHARACTERISTICS

The wind turbine can change wind energy into turbine mechanical energy. But the wind can't be fully conversered, which means only a part number of the wind energy can be absorbed and change into the mechanical energy of turbine. This process can be expressed by the following equation [2]:

$$\mathrm{P} = \frac{1}{2}\rho \mathrm{A} v^3 \cdot \mathrm{C}_p(\lambda, \theta, \gamma) \tag{1}$$

In this equation:

ρ - the air density;

v - the wind speed;

A - the swept area of the wind turbine;

C_p - the power coefficient.

According to the Betz's law [2], the WECS only can absorb a maximum number of 16/27 of the energy from wind. And the equation (2) shows a generic method to calculate power coefficient:

$$\begin{cases} C_p = (C_1\left(C_2\frac{1}{\lambda_i} - C_3\theta - C_4\right)e^{-C_5\frac{1}{\lambda_i}} + C_6\lambda) * \cos^3\gamma \\ \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{1+\theta^3} \\ \lambda = \frac{\omega R}{v} \end{cases} \tag{2}$$

In this equation:

$C_1 \sim C_6$ are defined by specific turbines, in this paper: $C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_{6=}0.0068$;

θ - pitch angle,

λ - tip speed ratio,

γ - yaw error.

In this paper uses the Siemens SWT-3.6-120 onshore wind turbine as research object. The basic parameters are shown in Table 1.

TABLE I. MAIN PARAMETERS OF 3.6MW WIND TURBINE

Variable	Value
Blade number	3
Turbine radius (m)	60
Gearbox ratio	1:119
Rated power (Mw)	3.6
Rated wind speed (m/s)	12.5
Maximum power coefficient (C_p)	0.44

At a specific wind speed, there must be an optimal speed for the wind turbine to output maximum mechanical power. At this optimal speed, the association between the maximum output mechanical power and the wind speed forms the optimal tip speed ratio relationship. Therefore, to make the turbine output the maximum mechanical power, the wind turbine needs to keep the optimal tip speed ratio. The goal of yaw system control is to adopt corresponding control strategies and methods when the yaw error occurs, and use the yaw motor to effectively change the position of the fan in time to capture the maximum power.

III. Yaw Control System

As the most important structure, the yaw control system, also known as the wind control device, has two main functions: one is to cooperate with the main controller, when the direction of the wind speed vector changes, the yaw control system can be stable and quickly align the wind direction, thus the WECS can get the maximum energy from wind [18]. The second is to ensure that the turbine cable will not be broken due to excessive unidirectional winding. When the cable is entangled in the engine room, it can automatically unwind the cable to make sure the safe perfemance of the WECS [8].

There are two main types of yaw systems: active yaw and passive yaw [9]. The action process of the passive yaw system is mechanical convection. The passive wind method is adopted through the rudder and engine room. The maximum efficiency of wind energy cannot be used, so the power generation efficiency is relatively low, so it is generally used for small wind turbines. Active yaw usually uses electric or hydraulic drag to perform the wind action, and WECS connect to grid usually use the form of the gear drive [19]. The active yaw system is an automatic control system. It needs to measure the wind speed and direction, and then adjust nacelle direction according to the magnitude of the strong wind and the angle of the wind direction and the normal of wind turbine to realize the windward control of the WECS. The yaw system is a servo system, and its composition and working principle are shown in Fig. 2.

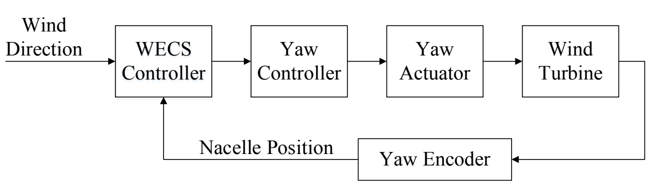

Fig. 2. The typical yaw system

The typical yaw system is shown in Fig. 2. The turbine adopts active yaw to the wind. The wind direction sensor element converts the changed wind direction signal into an electrical signal and transmits it to the yaw control subroutine of the main control system. After comparison, the controller sends a clockwise or counterclockwise signals to the yaw control system.

For getting more energy from the wind, the WECS in this paper uses a composite control method which includes two control strategies, namely yaw control and MPPT. The yaw system is applied to eliminate the influence of the yaw error on the output power, and the MPPT is used to keep the turbine blade TSR at the optimal state, thereby outputting the maximum power. The process of the control strategy is shown in Fig. 3.

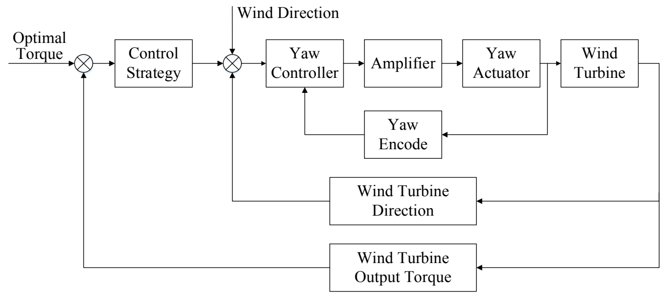

Fig. 3. The proposed control strategy

Working process of control system: the outer loop of the control system firstly calculates the real-time output torque of turbine through the measured real-time wind speed, and then compares with the optimal torque of the turbine to determine the control strategy to regulate the working state of the wind turbine. The inner loop of the control system compares the detected wind direction signal with the nacelle position and sends a control signal to the yaw motor through the controller to adjust the wind angle to achieve the best wind energy capture of the turbine.

According to the proposed control method, the corresponding model is built in Matlab / Simulink, which are shown in Fig. 4, mainly including wind turbine, MPPT, yaw control system.

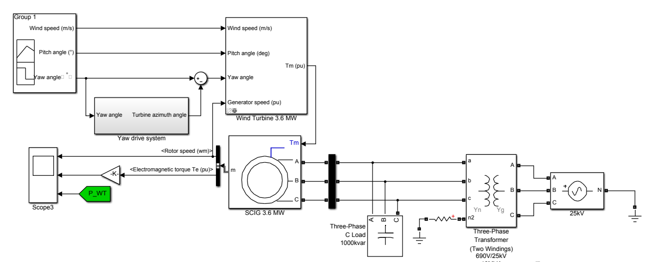

Fig. 4. Simulation modeling of the wind energy conversion system

IV. Yaw Motor And Controller

The yaw system is composed of the control part and actutor mechanism. The control part includes wind vane, controller, unwinding sensor, and other parts, and actutor mechanism includes yaw bearing, motor, brake (or yaw damping device) and other parts. This paper studies the demonstrating and simulation of the yaw system of wind power generation. The yaw motor is an asynchronous AC motor, and the vector control strategy is applied to control the motor [20]. The electrical system modules in MATLAB / SIMULINK (Power System) are used to construct an asynchronous motor vector control simulation model, and the dynamic operation of the whole wind power generation system is simulated [21].

The so-called vector control is to use the rotor magnetic field orientation and the vector transformation method to achieve complete decoupling of the AC motor speed and flux control and achieve the same speed control performance as the DC motor [22], [23]. The overall design scheme is shown in Fig. 5.

The system uses a double closed-loop control strategy: the speed control loop is composed of a PI regulator, and the current control loop is composed of a current hysteresis regulator. It mainly includes: AC motor, vector control part, Parker transformation part, coordinate transformation part, current hysteresis controller, speed controller, torque calculation part, and voltage inverter [24].

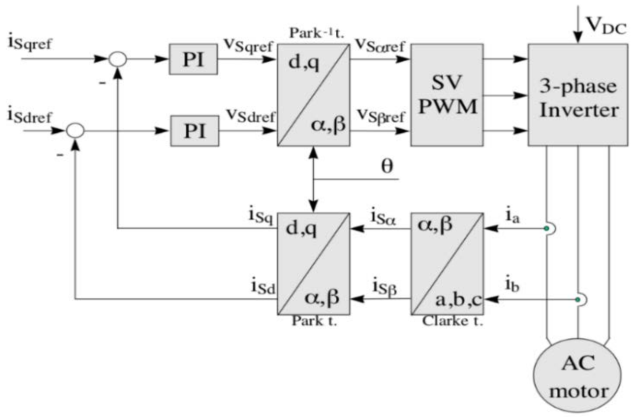

Fig. 5. Vector control of AC motor

Now from the above figure, the Simulink model for vector control strategy can be developed in Simulink which is shown in fig. 6.

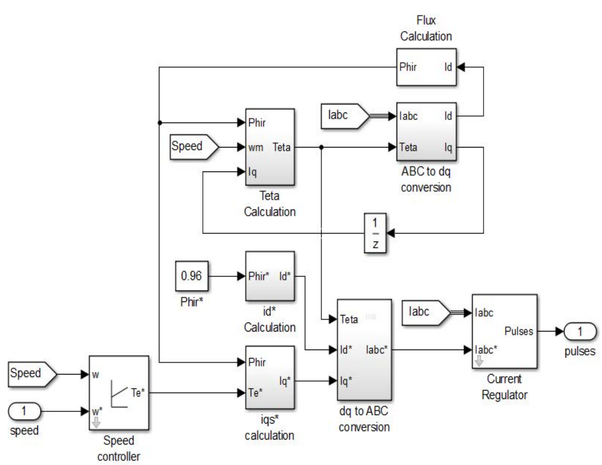

Fig. 6. Simulation model for vector control strategy

Next is the complete vector control model of AC motor, including DC source, inverter, vector controller, induction motor.

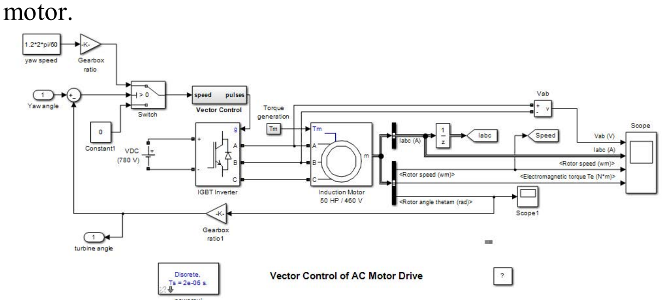

Fig. 7. Simulation model for yaw motor

V. Simulation Results

The suggested control strategy has been realized using Matlab/Simulink. A turbine with a blade radius of 60m has been simulated along with a gearbox with a gear ratio of 119. For yaw motor, a 3-phase, induction motor has been considered.

The system's initial conditions are: wind speed set as 8 m/s; pitch angle is 0; wind direction changes from 0 to 20° at 6s, then change to 10° at 14s. It is shown in Fig. 8.

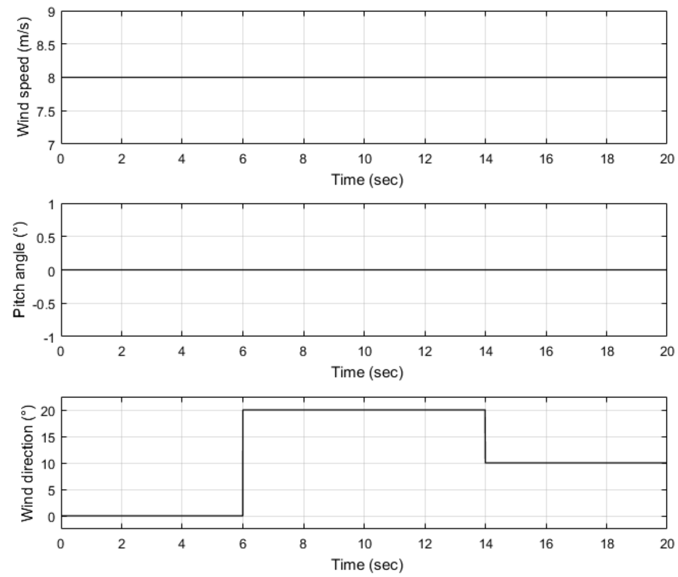

Fig. 8. The step input data of the WECS

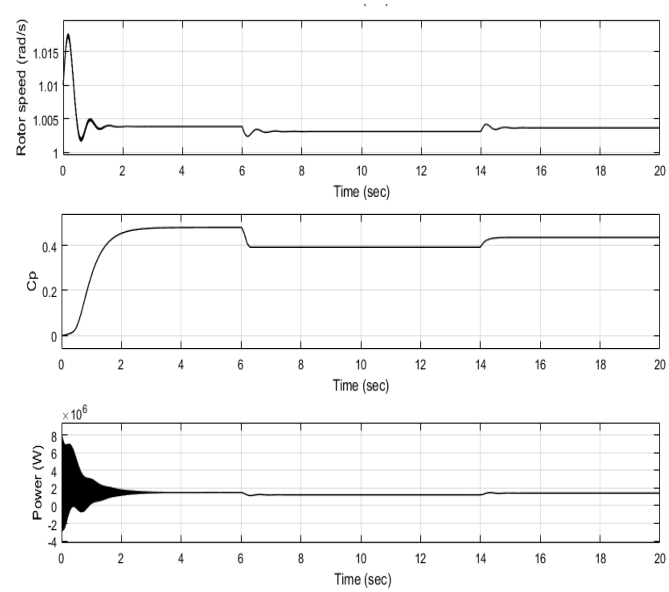

Fig. 9. The response of the WECS without yaw system

In Fig. 9, it can be seen that when wind direction changes, if there doesn't have yaw system, the power coefficient decreased, so the output power decreased, the detailed information is shown in Fig. 10.

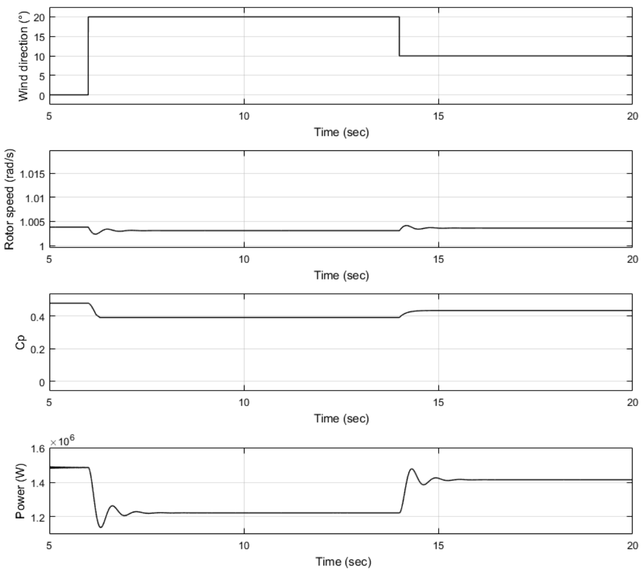

Fig. 10. The detailed simulation results of WECS without yaw system

The wind direction changes from 0 to 20° at 6 second, in this moment, rotor speed and power coefficient decreased, and the output power changed from $1.5 \times 10^6 W$ to $1.22 \times 10^6 W$, the conversion efficient decreased about 18.7% . At 14 second, wind direction changes to 10° , the yaw error is decreased, so the output power increased to $1.422 \times 10^6 W$, compared to the monment 5s, there still lost about 5.2% energy. When the wind energy conversion system uses the yaw system, it can reduce this loses, the simulation results in shown in Fig. 11.

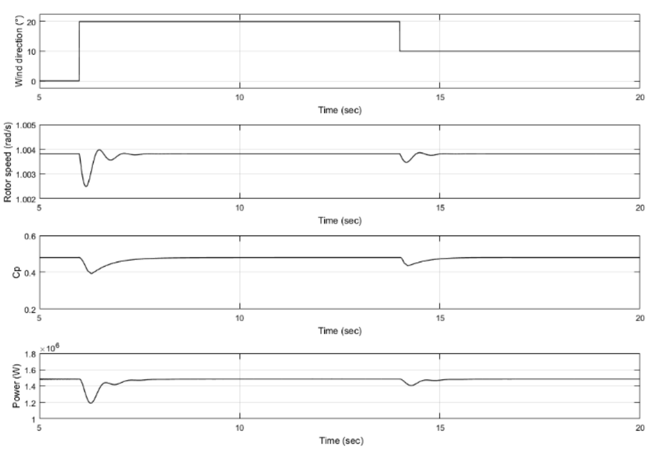

Fig. 11. The response of the WECS with yaw system

Fig. 11 shows when yaw error occurs, the output power is decreased, then yaw system started, the yaw motor drives the wind turbine (nacelle) to align with the wind direction to obtain the maximum energy from the wind until there no yaw error, this process can be seen in 6s to 10s and 14s to 16s. When wind direction changed, the turbine speed, power coefficient and output power all decreased, but after the yaw system regulated, there was no angle error between wind direction and nacelle, the wind energy conversion system can get the maximum power from wind, in this system is $1.5 \times 10^6 W$.

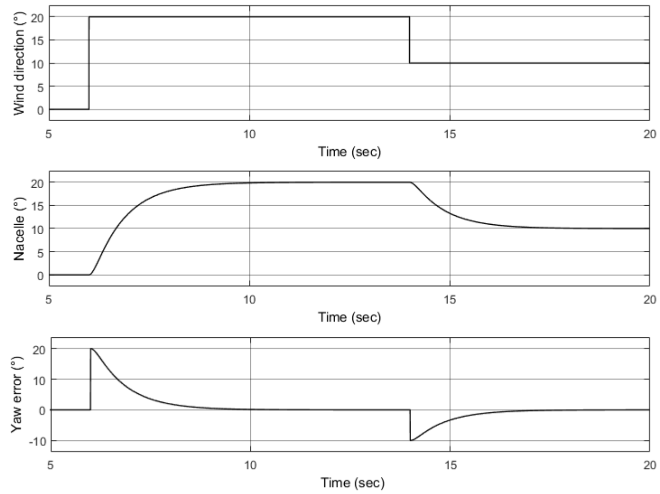

Fig. 12. Simulation results of yaw angle and turbine position

According to Fig. 12, it can be seen, when wind direction changes to 20° , the yaw error occurs, so the yaw control system starts to work until the yaw error is eliminated, after regulated, the nacelle azimuth angle is equal to wind direction, during this process, the yaw error is changing to 0, because the turbine is driven to align with the wind direction until the swept area of the turbine is perpendicular to the wind direction, and the yaw control system stop, the same process happed in 14s to 17s.

Fig. 13 shows the simulation results of generator's parameters in 6s to 8s, it just shows one phase of voltage and current. When the wind direction changes, the generator current is decreased to 1768 A, so the generated power is decreased, during regulation process, current is increasing, so the output power is increasing, when yaw error is 0, the regulation process stoped, the current back to 2170 A.

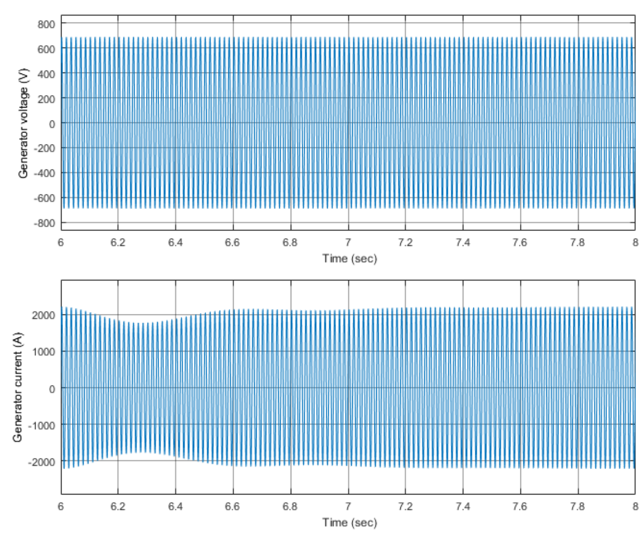

Fig. 13. Simulation results of the generator in 6s to 8s

VI. CONCLUSIONS

This paper model and simulate the yaw system of WECS, and controls the turbine based on the generator output power and the wind direction sensor. The experimental results show that the control strategy can effectively improve the power generation efficiency. This control strategy requires generator output power and wind direction as input data. Compared with other control strategies, it is easier to update the existing wind turbine control system, so it can be applied to various types of generator sets.

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