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Моделирование системы управления рысканием ветротурбины

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Энергия ветра — важный компонент возобновляемой энергетики, представляющий собой метод производства электроэнергии с наиболее тщательно продуманными, высокоразвитыми технологиями и широкими коммерческими перспективами. Обеспечение стабильного и эффективного преобразования энергии ветра с помощью ветряных турбин зависит не только от надежности самого оборудования, но и от системы управления турбинами, что, в свою очередь, способствует долгосрочной безопасной и надежной работе ветропарка. Таким образом, система управления ветряными турбинами — главный предмет исследования настоящей работы. Ключом к эффективной и стабильной работе всей системы преобразования энергии ветра является технология управления, включающая в себя регулирование рыскания, управление углом наклона лопастей и отслеживание точки максимальной мощности. Система активного рыскания — один из главных компонентов системы управления ветрогенератором с горизонтальной осью. С целью устранения неопределенности влияния направления ветра на мощность турбины проверена комбинированная система управления рысканием. Посредством активной системы рыскания и системы слежения за точкой максимальной мощности положение турбины и скорость вращения ротора регулируются таким образом, что позволяют ветровой турбине точно отслеживать направление ветра и, в наибольшей степени, улавливать энергию ветра.

Ключевые слова: системы преобразования энергии ветра и рыскания, ветрогенератор с горизонтальной осью.

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Simulation of the Wind Turbine Yaw Control System

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Owing to its being an important component of renewable energy, wind energy is a kind of power generation method with the most mature, highly developed technologies and broad commercial prospects. The stable and efficient conversion of wind energy by wind turbines depends not only on the reliability of the wind power generation equipment itself, but also on the wind turbine control system, which, in turn, contributes to long-term safe and reliable operation of the wind farm fleet. It is exactly the wind turbine control system that is the main subject of this study. The key to efficient and stable operation of the entire wind energy conversion system is the control technology, which includes yaw control, pitch angle control, and maximum power point tracking control. The active yaw control system is one of the important components of a horizontal axis wind turbine's control system. To eliminate the uncertainty of wind direction influence on the turbine power output, a composite yaw control system has been checked. By using an active yaw system and maximum power point tracking system, the turbine position and its rotation speed are adjusted to enable the wind turbine to accurately track the wind direction and capture the wind energy to the fullest extent.

Key words: wind energy conversion system, yaw system, horizontal axis wind turbine.

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I. Introduction

With global warming and the increasing scarcity of non-renewable resources such as international crude oil, governments, especially developed countries, are paying increasing 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 technology [2]. When the wind speed is unstable in the natural environment, the control strategy of the wind turbine 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 system is a unique system for wind turbines [6]. The yaw drive keeps the rotating surface of the wind turbine perpendicular to the wind direction to ensure that the blades capture the maximum sweep area. In wind energy conversion systems, the function of the yaw control system is to align the wind direction quickly and smoothly when the direction of the wind velocity vector changes, so that the wind turbine gets the maximum amount of wind [7]. Among the existing yaw control systems, there are mainly passive yaw systems and active yaw systems. 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 misalignment (deviation between rotor axis and wind direction) is one of the reasons that a wind turbine does not provide maximum output energy [9]. It reduces the wind velocity component acting perpendicularly to the rotor plane and thus, reduces the effective swept area to the wind direction [10]. The energy loss depends on the yaw error and wind speed. The average annual energy loss due to yaw error starts from 2.7% and can reach up to 11% for the average yaw error of 20°[11]. Therefore, if the turbine is to fully capture the power of the wind, it should be correctly oriented to the inflow of the wind. Fig. 1 shows the effect of the yaw angle on wind turbine output power [12].

According to Fig. 1, it can be seen that the yaw angle has a great influence on the output power of the wind turbine. When the wind speed is constant at 9 m/s and the yaw angle is 15°, this is a considerable part of the output 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 wind turbine and also determines the wind turbine 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.

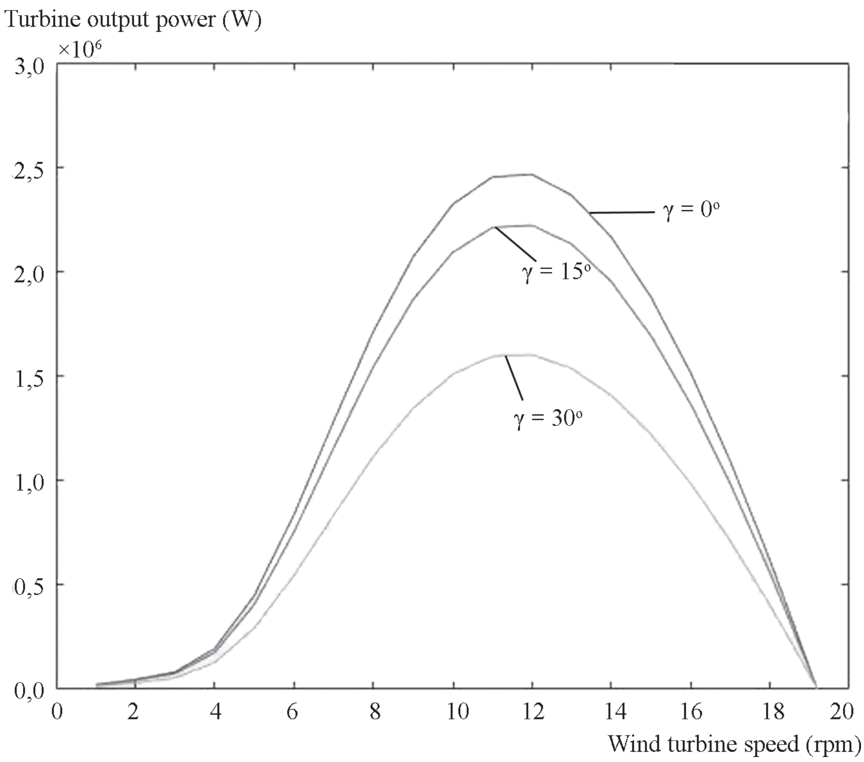

Fig. 1. Turbine output power affected by the yaw angle

The aviation system has completed the wind strategy and algorithm, and the representative research results are:

Reference [14] proposed a combined maximum power point tracking (MPPT) and active yaw control strategy for a wind energy conversion system. For the implementation of the MPPT control, the rotor speed is required, while for the implementation of the yaw control, only the measurement of the wind speed is needed because the wind direction, and therefore the yaw angle, can be estimated from the error between the optimum and the real mechanical power at the shaft, 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 method for the indirect estimation of the yaw-angle misalignment, the yaw angle is indirectly determined by the error between the actual rotor speed and that obtained by the optimal tip-speed ratio of the MPPT algorithm. the proposed yaw error estimation method is cost-effective, it can be applied at any power range of wind turbines. Reference [16] proposed a yaw control strategy based on rotational speed control based on the wind measurement data of LIDAR. The experimental results show that this 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, due to the high cost 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 control of wind turbines. 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 operation of the wind turbine, 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 analyzes the control strategy of the wind energy conversion system and establishes the corresponding control model in the Matlab/Simulink, which is applied to the Siemens 3.6-120. By establishing a simulation model of the system and conducting simulation experiments, it is possible 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 is used to convert wind energy into mechanical energy. Because the wind speed passing through the wind turbine cannot be zero, the energy possessed by the wind cannot be fully utilized. In other words, only a part of the energy of the wind may be absorbed and become the mechanical energy of the blade. The equation of mechanical power obtained from the wind turbine is indicated in the following equation [2]:

$$P = \frac{1}{2}\rho A v^3 C_p\left(\lambda, \theta, \gamma\right). \quad (1)$$

Where: ρ is the air density; v is the wind speed; A is the swept area of the wind turbine; C_p is the power coefficient.

Based on Betz's law [2], the turbine only can extract a maximum of 16/27 (59.3%) of the kinetic energy from the wind. So it's important to make the coefficient as big as possible, the following equation is a generic equation to calculate wind turbine coefficient:

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

In this equation:

The coefficient C_1 — C_6 and x are defined by specific turbines, in this turbine set: $C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$; θ is pitch angle, λ is the tip-speed ratio, γ is the yaw angle.

This paper intends to select the feasibility of a Siemens SWT-3.6-120 onshore wind turbine test for the WECS. The basic parameters of the wind turbine are as follows.

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 relationship between the maximum mechanical power output and the wind speed forms the optimal tip speed ratio relationship. Therefore, to make the wind turbine output the maximum mechanical power, the wind turbine needs to maintain the optimal tip speed ratio. The goal of yaw system control is to adopt corresponding control strategies and methods when the wind direction changes, and use the yaw motor to effectively change the position of the fan in time to capture the maximum power (Table I).

Table I

Main parameters of 3.6 Mw 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

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 unit control system, when the direction of the wind speed vector changes, the yaw control system can be stable and quickly align the wind direction, so that the wind turbine can get the maximum wind energy [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 ensure the safe operation of the turbine [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 grid-connected wind turbines 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 in real-time, and then adjust the direction according to the magnitude of the strong wind and the angle of the wind direction and the normal of the wind wheel to realize the windward control of the wind turbine. The yaw system is a servo system, and its composition and working principle are shown in Fig. 2.

The typical principle of the yaw system is shown in Fig. 2. The wind 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 motor control subroutine of the main control system. After comparison, the controller sends a clockwise or counterclockwise yaw command to the yaw control system.

To get more energy from the wind, the wind energy conversion system in this paper uses a composite control method which includes two control strategies, namely yaw control and MPPT. The yaw control system is used to eliminate the influence of the yaw angle on the output power, and the MPPT is used to maintain the turbine blade tip speed ratio at the optimal state, thereby outputting the maximum power. The block diagram of the control strategy is shown in Fig. 3.

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

According to the proposed control strategy and the selected wind turbine, the corresponding model is established in Matlab/Simulink, as shown in Fig. 4, mainly including wind turbine, MPPT, yaw control system.

IV. Yaw motor and controller

The yaw system is composed of the yaw control mechanism and the yaw drive mechanism. The yaw control

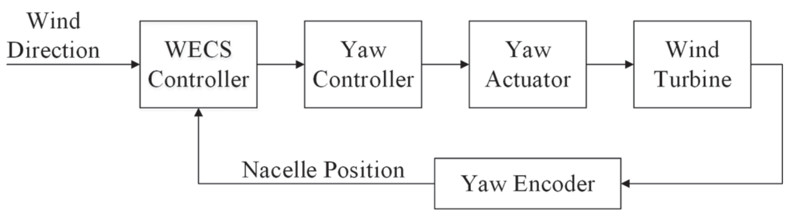

Fig. 2. The typical yaw control strategy

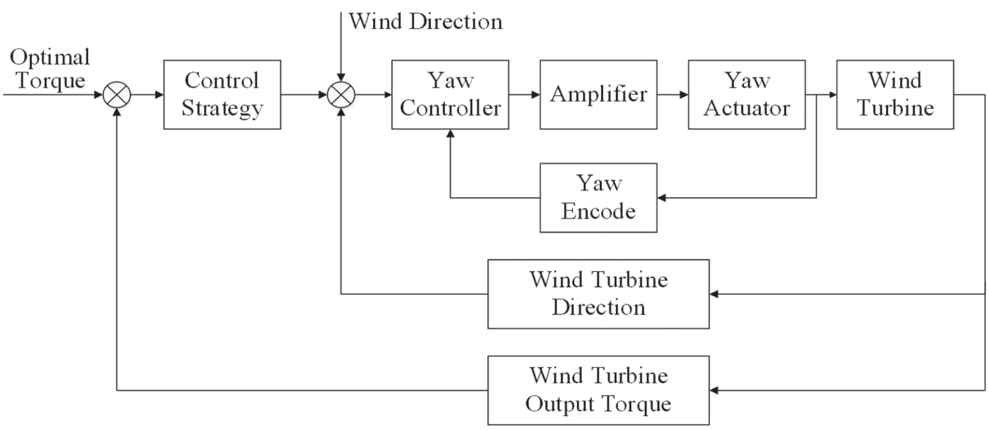

Fig. 3. The proposed yaw control strategy

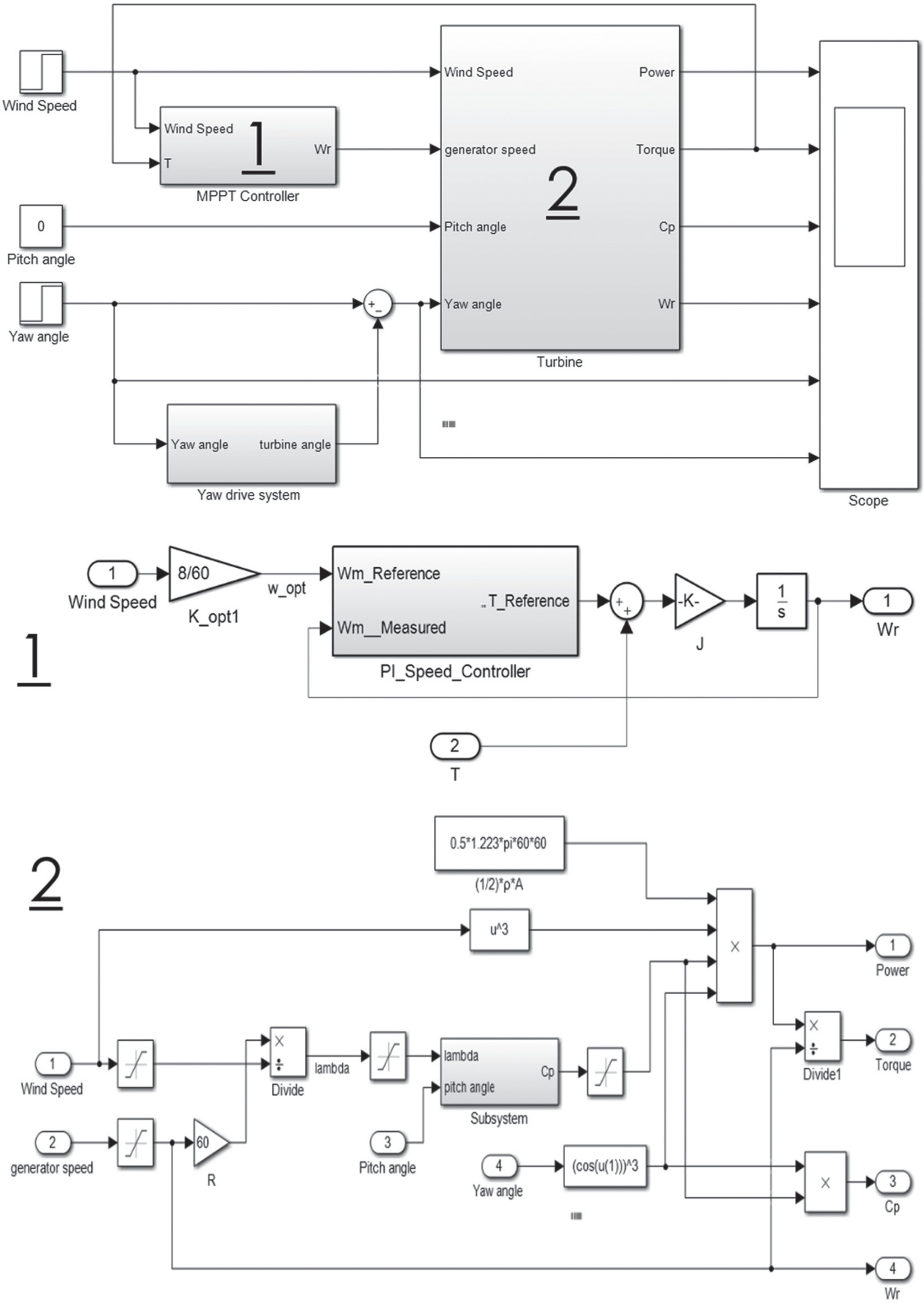

Fig. 4. Simulation modeling of the wind energy conversion system with contents of MPPT Controller (1) and Turbine (2)

mechanism includes wind direction sensor, yaw controller, unwinding sensor, and other parts, and the yaw drive mechanism includes yaw bearing, yaw drive device, yaw brake (or yaw damping device) and other parts. This paper studies the modeling and simulation of the yaw system of wind power generation. The yaw motor is an asynchronous AC motor, and the vector control method is used to control the operation of 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 performance of the entire 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 block diagram is shown in Fig. 5. The system uses a double closed-loop control scheme: the speed loop is composed of a PI regulator, and the current loop is composed of a current hysteresis regulator. According to the idea of modular modeling, the control system is divided into sub-modules with independent functions, which mainly include: AC motor module, vector control module, Parker transformation module, coordinate transformation module, current hysteresis control module, speed control Module, torque calculation module, and voltage inverter module [24]. Through the organic integration of these functional modules, a simulation model of the AC motor control system can be built-in Matlab/Simulink, and a double closed-loop control algorithm can be realized.

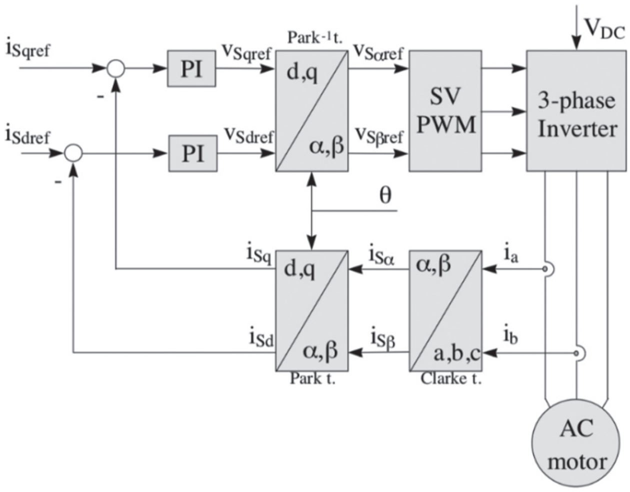

Fig. 5. Vector control of AC motor

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

Next is the complete vector control model of AC motor, including DC source, inverter, vector controller, induction motor, Fig. 7.

V. Simulation results

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

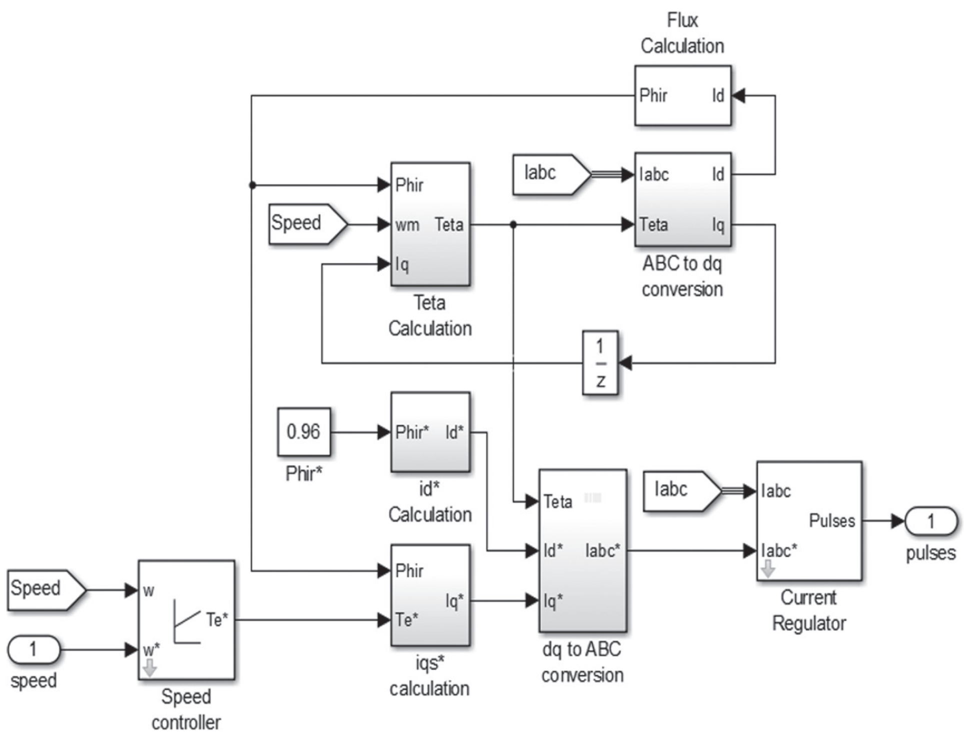

Fig. 6. Simulation model for vector control strategy

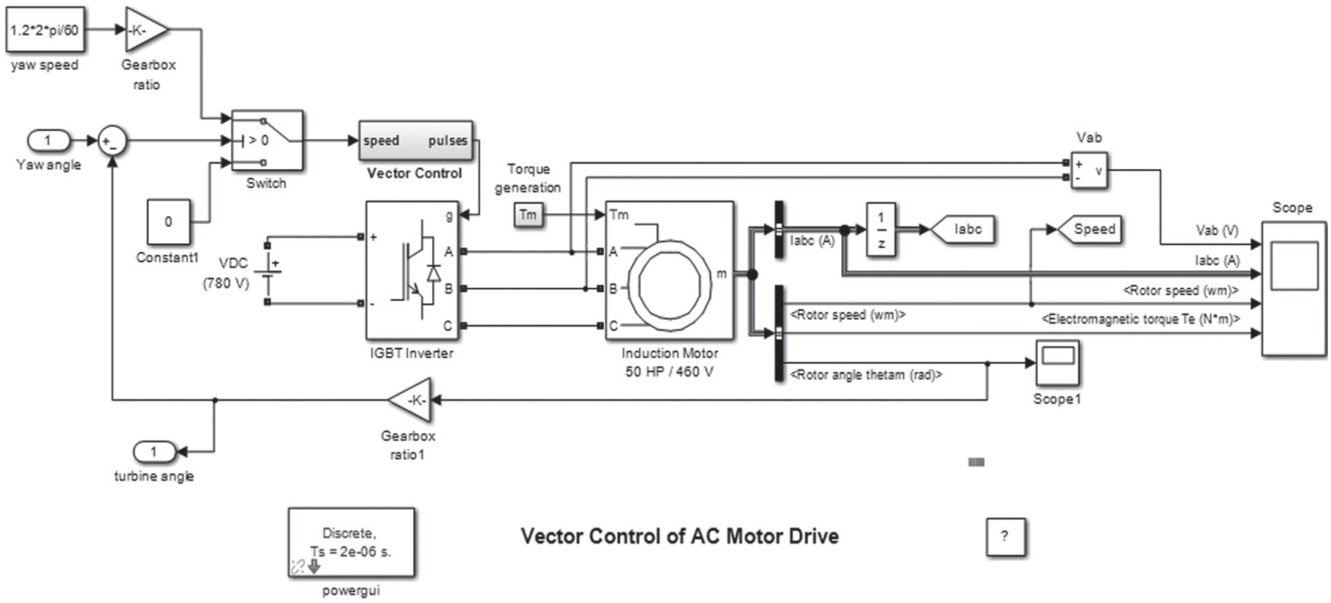

Fig. 7. Simulation model for yaw motor

The system's initial conditions are: wind speed set as 6 m/s, yaw angle is 0, according to the simulation results, it can be seen that tip speed ratio is 8, the output power is 0.71×10^6 W (Fig. 8).

The wind speed changes from 6 to 10 m/s at 1 second, there still no yaw angle changes. At the changing moment, the system data are: tip speed ratio decreases to 5, output power still is 0.71×10^6 W. After MPPT controller adjusting, the system goes back to steady-state, tip speed ratio goes back to 8, the output power reaches to 3.32×10^6 W, which is the optimal output power when wind speed is 10 m/s.

As for the yaw control system, using a wind direction sensor to get the yaw angle, and using the vector control method to drive yaw motor. When the simulation begins,

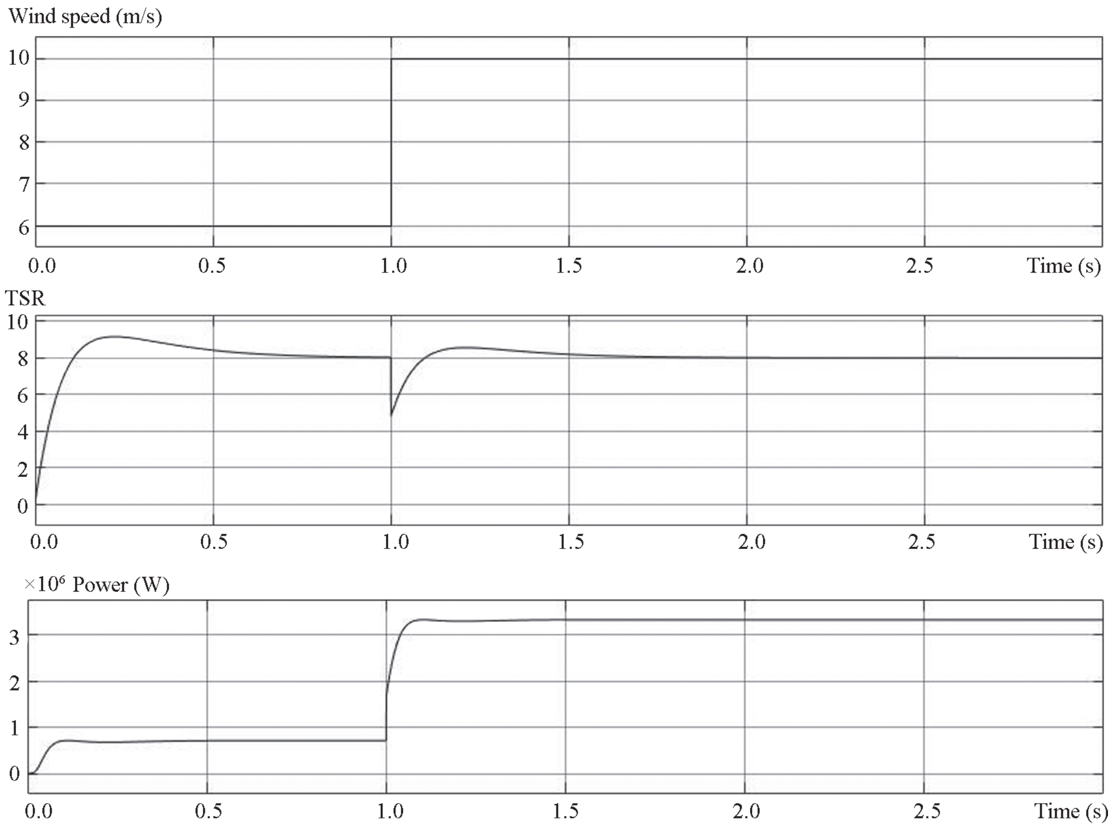

Fig. 8. The response of the WECS to a step change of the wind speed 6 to 10 m/s (just MPPT operate)

the wind speed set as 6 m/s, yaw angle is 0, but at 1 second, yaw angle changes to 12°, the simulation results are shown below.

Fig. 9 shows when yaw error occurs, the yaw motor drives the wind turbine to align with the wind direction to obtain the most energy from the wind until there no yaw error, thus the system goes back to steady-state, the turbine output power goes back to 0.71×10^6 W again. According to the simulation data, it can be seen if there no yaw control system, the output power reduced by 10% (yaw angle is 12°), after the yaw control system adjusting, the output power will go back to optimal value again.

According to Fig. 10, it can be seen, when wind direction changes, the yaw angle occurs, so the yaw control system starts to work until the yaw angle is eliminated. During this process, the yaw angle is decreasing 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.

Fig. 11 is showing the proposed control system simulation results, which verified the feasibility of the proposed control system. The wind speed and direction both changed during this process. It can be seen that the nacelle tracks the wind direction successfully, which means the control system is helpful to improve the efficiency of power generation.

From the simulation results, it can be seen that the wind speed changes from 6 to 10 m/s in 1 second, and the yaw angle changes 0 to 12° in 2 seconds. When that change happens, both cause a reduction in power generation efficiency, which is extremely unfriendly to wind power plants. Thus the control system is used to eliminate these bad effects and improve the efficiency of power generation. At 2 seconds, when the yaw angle occurs, the output power is decreased to 3.11×10^6 W, losing about 6.4% energy.

The data of several experiments are summarized in table 2.

VI. Conclusions

This paper model and simulate the yaw control system of the wind turbine, and controls the wind turbine based on the generator output power and the wind direction sensor. The simulation results show that the control strategy can effectively improve the wind turbine 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.

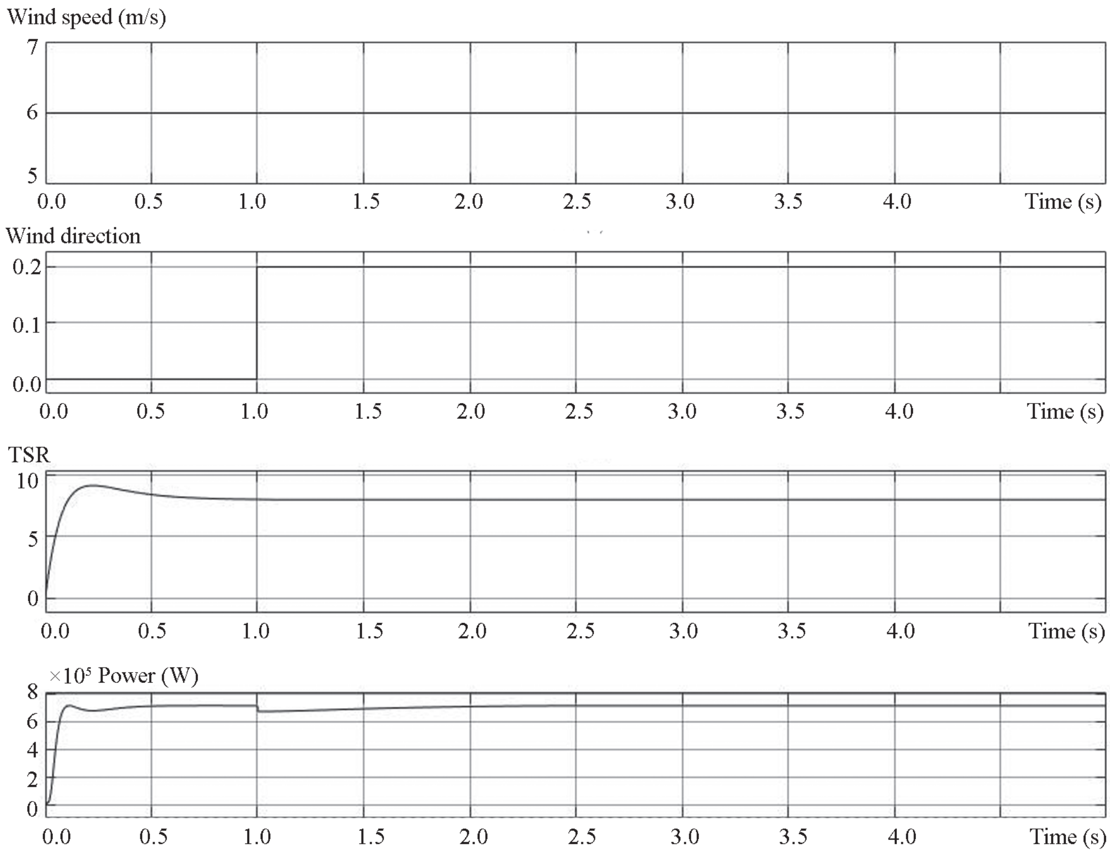

Fig. 9. The response of the WECS to a step change of the yaw angle 0 to 12° (just yaw system operate)

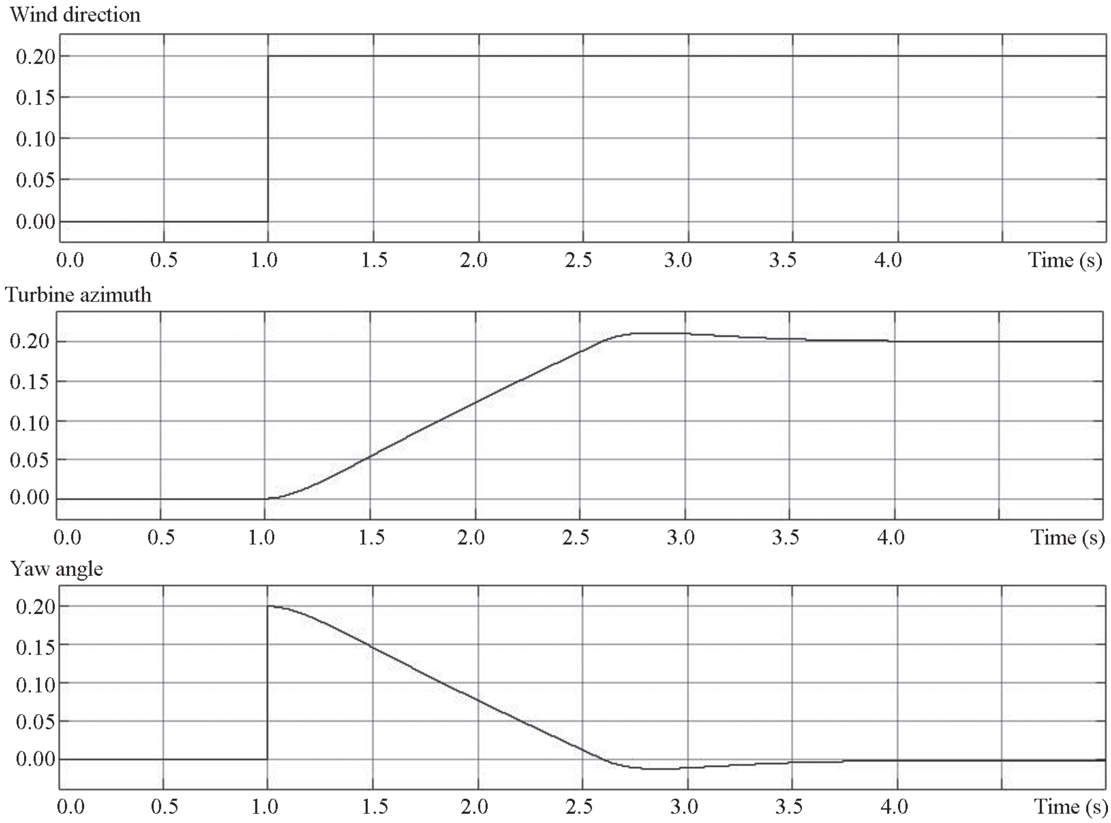

Fig. 10. Simulation results of yaw angle and turbine position

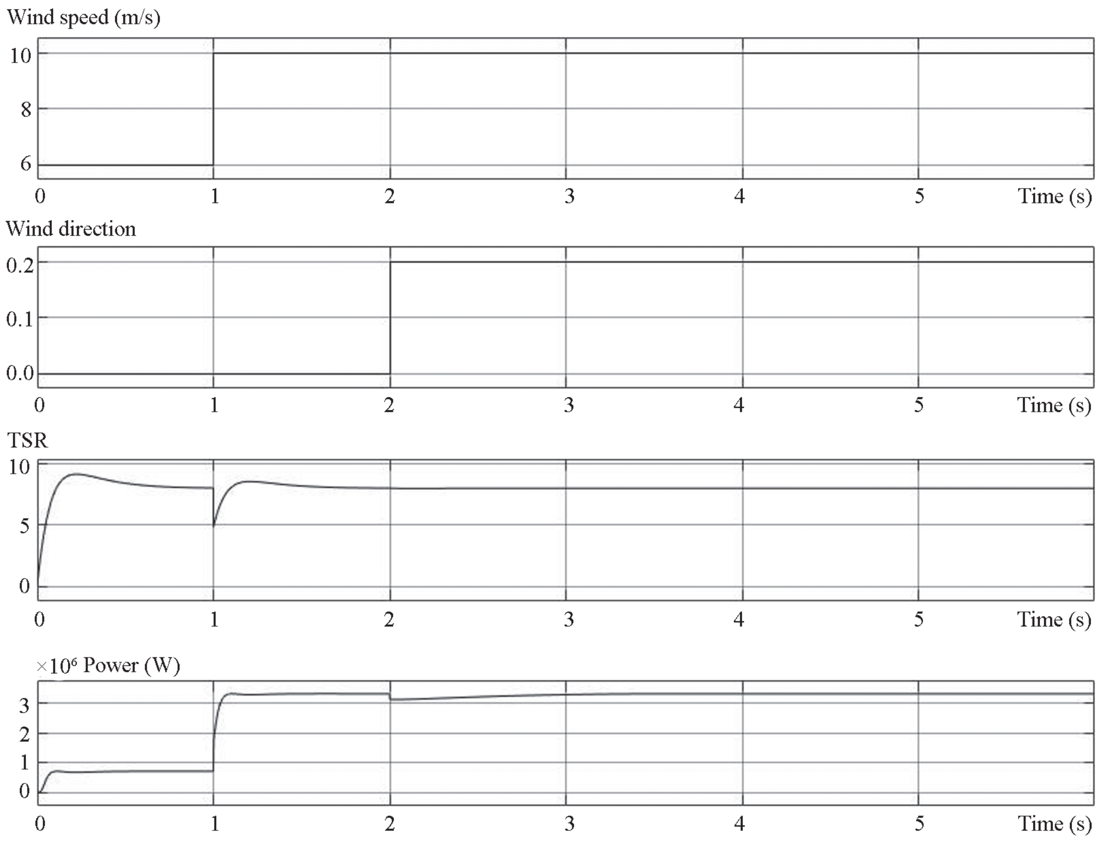

Fig. 11. Simulation results of the WECS operation with wind speed and direction change

Table II

Summarised results of simulations

Variable	Simulation 1			Simulation 2			Simulation 3		
	Initial value	Change moment	Steady moment	Initial value	Change moment	Steady moment	Initial value	Change moment	Steady moment
Wind speed, m/s	6	10	10	6	6	6	6	10	10
Wind direction, °	0	0	0	0	12	12	0	12	12
Tip speed ratio	8	5	8	8	8	8	8	5	8
Output power, Mw	0.71	1.70	3.32	0.71	0.65	0.71	0.71	3.11	3.32

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