Hybrid control of variable-speed variable-pitch system in wind power generation

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Abstract: A control model based on hybrid automata is proposed for the complex system of VSVP (Variable-Speed Variable-Pitch) wind power generation with big random disturbance, multi-state operation and time-varying structure, which takes the output power, rotor speed and pitch angle as the main study objects. With fully consideration of the coupling relationship between variable-speed control and variable-pitch control, the control process is divided into four stages and the control algorithm combined with the estimation control is given for the controller of each stage. The simulation model of a 1 300 kW VSVP wind power generation system is established with MATLAB/Simulink toolbox and the simulative results show that, with the proposed control model, higher wind power utilization efficiency and better power quality are achieved.

Key words: wind power; hybrid automata; variable-speed variable-pitch control; estimation control
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0 Introduction

VSVP (Variable-Speed Variable-Pitch) generation system will be the direction of large wind generator's development in the high volume wind power generation system. But adding VSVP devices to the system will complicate the control system, and traditional control models have been unable to get the ideal control effectiveness. In recent years, many scholars have done a lot of research to improve the control method such as variable structure control[1], adaptive control[2], predictive control[3-6], fuzzy control[7] and so on. In the cases of multiple loading conditions operation, heavy random disturbance, hided uncertain factors and time-varying structure, adopting above control structures and methods can make better control effectiveness, but it will cause serious fluctuation of the output power.

VSVP wind power generation system has the typical hybrid system's structure. In a certain work model, it's a continuous dynamic system driven by the time; while changing between diversified work models, it can be regarded as the event driven discrete dynamic system. This paper focuses on the division of the state space in hybrid system, a hybrid automata control structure applied to VSVP wind power generation system is set up. As estimation with certain information foundation is a useful way to overcome large inertia delay of the wind power generator, estimation control of chain system theory[3-6,8] is used to realize the system's control algorithm, which is the innovation from other control. Section 1 presents the analysis and model of the control structure. Section 2 realizes estimation control algorithm. Simulation results are given in section 3 to verify the proposed control strategy. Section 4 is conclusion.

1 Analysis and Model of VSVP Wind Power Generation System

The structure of the VSVP wind power generation is very complex, through mechanism analysis, the model of the control structure is set up.

1.1 Structure of VSVP Wind Power Generation System

VSVP wind power generation system consists of three main parts: generator, transmission and wind rotor.

The discussed generator in this paper is three-phase wound rotor induction generator. According to reference [9], without thinking the change of wind direction, the electromagnetic anti-torque is given in the d-q reference frame rotating at synchronous speed as follows:

$$T_e = n_p \frac{L_m}{L_r} I_{sq} \varphi_r \tag{1}$$

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Where n_p is the number of poles, L_r is the inductor of the rotor, L_m is the mutual inducor between rotor and stator, φ_r is the total rotor flux vector, and I_{sq} is the q-axis current component.

Ignoring the stator copper loss, generator's output power(P_g) is equal to electromagnetic power(P_e).

$$P_g=P_e=T_e\omega_r \tag{2}$$

Without thinking of transmission damping of the wind rotor and the generator, the rotor rotation equation can be deduced as follows:

$$\omega_r(T_r,T_e)=\frac{1}{J_r}\int(T_r-nT_e)\mathrm{d}t \tag{3}$$

In the above equation, J_r is the rotational inertia, n is the gear transmission ratio, and T_r is the output torque.

From equations(1)-(3), we know that the electromagnetic anti-torque of the generator can be controlled by the q-axis current component, so that the rotor speed can be regulated.

According to empirical formula[10], the mechanical power of the wind turbine extracted from the wind is:

$$P_r=\frac{1}{2}\rho\pi C_p(\lambda,\beta)v^3 \tag{4}$$

Where v is wind speed; C_p is the power coefficient of the wind turbine, which is a function of the tip speed ratio λ and the blade pitch angle β. An empirical formula[11] is introduced to describe C_p as shown in equation(5).

$$C_p=(0.44-0.0167\beta)\sin\frac{\pi(\lambda-3)}{15-0.3\beta}-0.00184(\lambda-3)\beta \tag{5}$$

λ is defined as:

$$\lambda=\frac{\omega_r R}{v} \tag{6}$$

β can be reduced as a first-order inertia link[12]:

$$\beta(s)=\frac{\beta_r}{T_\beta s/K_\beta+1} \tag{7}$$

Where β_r is inferred to as input pitch angle, T_β is inferred to as time constant, K_β is scale factor.

From the above analysis, the structure diagram of VSVP wind power generation system can be obtained as shown in fig.1.

In fig.1, U is the control signal of pitch change and I_{sq} is the control signal of speed change. We can see that the processes of pitch change and speed change are intercoupling, so the traditional control structure is difficult to achieve the desired control effect.

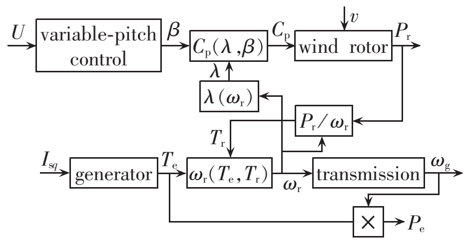

Fig.1 Structure of VSVP wind power generation system

1.2 Model of Hybrid Automata

The basic control strategy can be determined by the performance evaluation of the VSVP wind power generation control system as follows: when below the rated wind speed, in order to obtain maximum wind energy, the wind turbine adjusts the rotor speed to maintain optimum tip speed ratio; when above the rated wind speed, it changes the blade pitch angle and limits collection of the wind energy to keep a rated output power[13].

The control schematic is shown in fig.2. Where ω_r is the rotor reference rotate speed, and P_{ref} is the generator reference power.

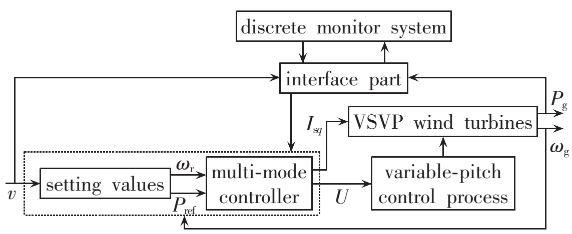

Fig.2 Control of VSVP wind power generation system

The control system consists of discrete monitoring system, interface part, setting values of the control loop and multi-mode controller as shown in fig.2. Discrete monitoring constantly adjusts the setting values of the control loop along with the wind speed change. Using control signals, multi-mode controller makes the processes of pitch change and speed change to follow the setting values.

1.2.1 Discrete Monitoring System

With the combination of hybrid automata theory, the equation of mathematical model of the discrete monitoring system is built as follows:

$$H=(Q,L,V_{init},f_1(q),f_2(q)) \tag{8}$$

$$Q=(v,P,\delta_1,\delta_2,\delta_3,\delta_4) \tag{9}$$

$$L=(s_1,s_2,s_3,s_4) \tag{10}$$

$$V_{init}=(v_0,P_0,\delta_1=1,\delta_2=0,\delta_3=0,\delta_4=0) \tag{11}$$

$$f_1(q)=(f_1(s_1),f_1(s_2),f_1(s_3),f_1(s_4)) \tag{12}$$

$$f_2(q)=(f_1(\delta_1),f_2(\delta_2),f_3(\delta_3),f_4(\delta_4)) \tag{13}$$

In the above equations, Q and L are finite set of discrete states and finite set of continuous state respectively, V_{init} is a set of the initial values of variables and initial state space, $f_1(q)$ represents continuous state evolution rule for each discrete state $q \in Q$, $f_2(q)$ specifies an enable set for each state, P is output power of the wind turbine, δ_i represents discrete state variables in different work modes, s_i is referred to state space for different wind speeds, and $i=1,2,3,4$.

1.2.2 Interface Part

Mutual transformation between discrete variables and continuous variables is the main task of the interface part. The mapping between the set of continuous states and the set of discrete events are described as follows:

$$\delta_i=\begin{cases}\delta_1=1 & v<v_{in}\\ \delta_2=1 & v_{in}\leqslant v<v_N, P_{ref}=P_g<P_N\\ \delta_3=1 & v_N\leqslant v<v_{out}, P_{ref}=P_N<P_g\\ \delta_4=1 & v\geqslant v_{out}\end{cases} \quad (14)$$

$$s_i=\begin{cases}s_1=1 & \delta_1=1\\ s_2=1 & \delta_2=1\\ s_3=1 & \delta_3=1\\ s_4=1 & \delta_4=1\end{cases} \quad (15)$$

Where v_{in}, v_N and v_{out} are start wind speed, rated wind speed and cut off wind speed of the wind turbine respectively, P_N is the rated power.

Combining equations (14) and (15), the mutual transformation between discrete events and continuous state space can be achieved. Through these mappings, the dynamic behavior of the controlled process can be controlled by the decisions of the discrete monitoring system.

1.2.3 Setting Values of Control Loop

P_{ref} and ω_r are the setting values of the control loop. Control loop can adjust the values according to the operational status of the wind power generation system.

The references of power and rotor speed are given as follows:

$$P_{ref}=\begin{cases}0 & \delta_1=1\\ P_{max} & \delta_2=1\\ P_N & \delta_3=1\\ 0 & \delta_4=1\end{cases} \quad (16)$$

$$\omega_r=\begin{cases}\omega_{obj} & \delta_2=1\\ \omega_N & \delta_3=1\\ 0 & \text{otherwise}\end{cases} \quad (17)$$

To ensure the optimum tip speed ratio and maximum wind energy utilization efficiency, the optimal P_{max} is determined by the following equation[14]:

$$P_{max}=K_p(\omega-\omega_{obj})+K_i\int(\omega-\omega_{obj})\mathrm{d}t+K_d\frac{\mathrm{d}(\omega-\omega_{obj})}{\mathrm{d}t} \quad (18)$$

Where K_p, K_i and K_d are proportional coefficient, integral coefficient and differential coefficient respectively. The objective speed of the wind rotor ω_{obj} is:

$$\omega_{obj}=(v\lambda_{opt})/R \quad (19)$$

Where λ_{opt} represents optimum tip speed ratio.

1.2.4 Controller

The blade pitch angle and rotor speed are the actual control objects of VSVP control process. According to the decisions $\delta_i=1$ of the discrete monitoring system, the control process of VSVP power generation system is divided into several stages and different control rules will be taken in different stages so as to meet the requirements of multiple states control.

In this part, the initial values of each state and the state transition conditions are given by equation (8) to equation (19). On the basis of the control objectives of the VSVP wind turbines, the state space of the system is divided into four parts and finally the hybrid automata model is set up as shown in fig.3.

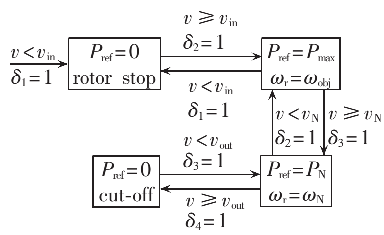

Fig.3 Model of hybrid automata

2 Estimation Control Algorithm

Through the analysis of the previous section, we know that the control of the wind generation system is divided into four parts, and the corresponding control rules can be concluded as follows.

a. If $\delta_1=1$, then the state space will be s_1. From the equations (16) and (19), we have $\omega_r=0$ and $P_{ref}=0$. In this case, both control variables U and I_{sq} are equal to zero.

b. When in the circumstances of $\delta_2=1$, we can see that the VSVP wind generation system is in state space s_2 and the reference values are $\omega_r=\lambda_{opt}v/R$, $P_{ref}=P_{max}$ based on the equations (14) to (19). The output control variable of the pitch change process can be obtained as $U=0$ and fig.4 shows the structure of rotor speed control.

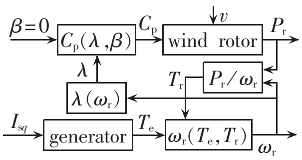

Fig.4 Structure of rotor speed control

The above system's behavior can be described as a difference equation:

$$\omega_r(k+1)=a_1\omega_r(k)+a_0\omega_r(k-1)+b\,I_{sq}(k)+cv(k) \quad (20)$$

Where a_1, a_0, b and c are the parameters to be estimated. Assuming that the system's output value and the desired value have the following relationship[8]:

$$(1-pz^{-1})y(k+1)=(1-p)y^*(k+1) \quad (21)$$

Where p is the design parameter of estimation algorithm.

Combining equations (18), (19) and (21), we can get:

$$(1-pz^{-1})\omega_r(k+1)=(1-p)\omega_r^*(k+1) \quad (22)$$

Where $\omega_r^*(k+1)$ is the desired output rotor speed at the moment of $k+1$.

Then substituting equation (22) to equation (20), we can get the control variable of the rotor speed change process as follows:

$$I_{sq}^*(k)=[(p-a_1)\omega_r(k)+(1-p)\omega_r^*(k+1)-a_0\omega_r(k-1)-cv(k)]/b \quad (23)$$

c. When $\delta_3=1$, the VSVP wind generation system is in state space s_3. By equations (14) and (17), we can get $\omega_r=\omega_N$ and $P_{ref}=P_N$. In order to keep the rotor speed and power of the wind turbine to be a constant value, the control variable of the rotor speed I_{sq} is a constant C, i.e. $I_{sq}=C$. The structure of pitch angle control is shown in fig.5.

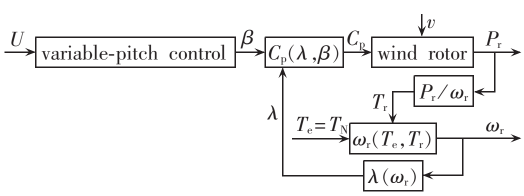

Fig.5 Structure of pitch angle control

In such case, the behavior of the VSVP wind generation system can be described as a second-order difference equation:

$$P_r(k+1)=a_1'P_r(k)+a_0'P_r(k-1)+b'U(k)+c'v(k) \quad (24)$$

Based on equation (19), equation (25) is given as:

$$(1-p'z^{-1})P_r(k+1)=(1-p')P_r^*(k+1) \quad (25)$$

Then substituting equation (25) to equation (24), the control variable of the pitch change process can be deduced as:

$$U^*(k)=[(p'-a_1')P_r(k)+(1-p')P_r^*(k+1)-a_0'y(k-1)-c'v(k)]/b' \quad (26)$$

d. When $\delta_4=1$, the system is in state space s_4. Reference values of the system $\omega_r=0$ and $P_{ref}=0$ can be got from equations (14) and (17). In this condition, both control variables of the pitch change process and the rotor speed change process are equal to zero: $U=0$, $I_{sq}=0$.

3 Simulation Results

In order to verify the reasonability of the modeling and control strategy of the hybrid automata, the space-time wind speed model[15] used in the simulation has four components:

$$v=v_b+v_g+v_r+v_n \quad (27)$$

Where v_b is the basic wind speed, v_g is the gust speed, v_r is the regular wind speed, and v_n is the noise wind speed. Assuming that $v_b=14.5$ m/s, the model of input wind speed is shown in fig.6.

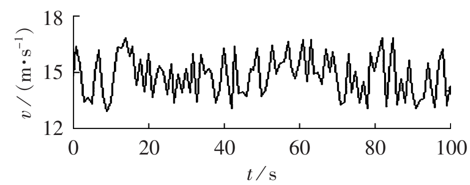

Fig.6 Model of natural wind speed curve

Hybrid automata based 1 300 kW VSVP wind turbine system is simulated in MATLAB/Simulink. The parameters of the system are shown as follows: turbine's blade radius is 31 m, cut-wind speed is 3.5 m/s, rated wind speed is 14.5~20 m/s, optimum tip speed ratio is 7.5, transmission ratio is 1∶80, and inertia is 2 460 106 kg/m^2; generator's pole pair is 8, rated power is 1 300 kW, rotational speed range is 1 600~2 100 r/min, synchronous speed is 1 500 r/min, rotor flux linkage vector is 3.48 Wb, stator inductor is 1.580 mH, rotor inductor is 1.690 mH, inertia is 52 kg/m^2.

The control algorithm relies on accurate system parameters, but in the actual operation, the parameters of the system drift along with the change of the environment as well as the change of the time. In order to realize the real-time control of the system, recursive algorithm of the least square method for online identification is used to determine the real-time value of the system parameters in equations (20)-(24). To verify the validity of the proposed control algorithm, the parameter values[16] are given as follows: a_1=1.501, a_0=1.002, b=−0.46, c=0.409, a_1'=2.403, a_0'=1.801, b'=1.682, c'=0.249, $p=p'$=0.5.

We use a conventional control model for comparison, in this model the variable-speed control and the variable-pitch control is separated. The variable-speed control uses a traditional PI controller, while the variable-pitch control uses a traditional PID controller. The simulation results of the output power of the conventional control model and the proposed control model are shown in fig.7, and the wind power utilization efficiency of the two models are shown in fig.8.

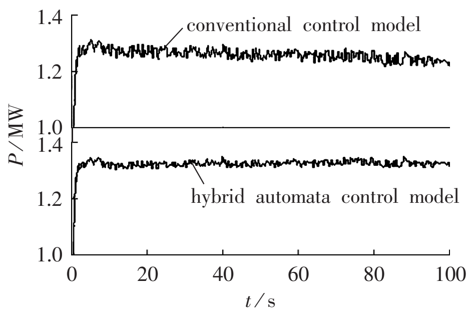

Fig.7 Output power of wind turbine

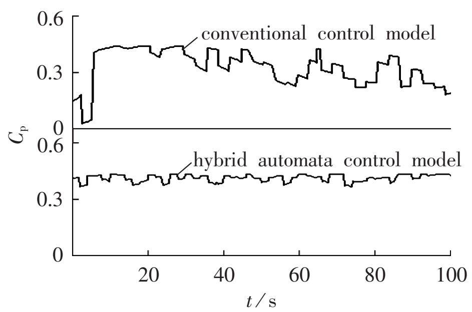

Fig.8 Utilization efficiency of wind power

Based on fig.7, we can conclude that the hybrid automata control strategy with estimation control algorithms can obtain a more stable and smooth output power compared with the conventional control strategy. From fig.8, we can see that the proposed control method has higher wind power utilization efficiency.

The rotor speed curve and the blade pitch angle curve of the hybrid automata based VSVP wind turbines are shown in fig.9 and fig.10.

The speed curve shows that the rotor speed doesn't fluctuate seriously along with the change of the automata state and the wind speed, but always stay in the rated speed range; compared with the traditional control, the blade pitch angle curve shows that the pitch angel can adjust to follow the

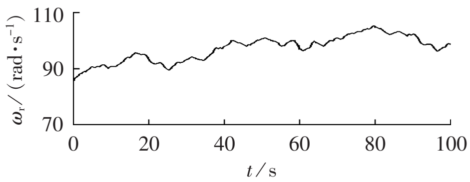

Fig.9 Rotor speed

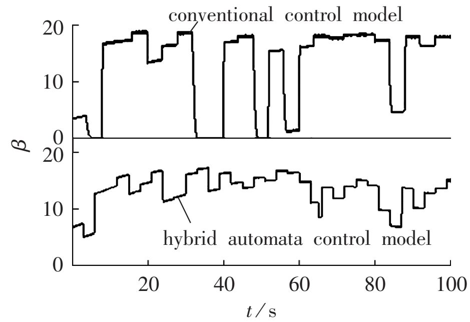

Fig.10 Curves of pitch angle change

wind speed change much faster and has smaller fluctuation, which can reduce the mechanical wear and lengthen using life.

From the above figures, we can conclude that when the wind speed fluctuates around the rated speed, the hybrid automata can regulate the switch between variable-pitch control and variable-speed control to keep the output power of the wind turbine around the rated power. The simulation results show that the proposed control strategy can increase the wind energy utilization efficiency as well as improve the output power quality.

4 Conclusion

This paper focuses on the output power, rotor speed and blade pitch angle of the wind turbine, a hybrid automata based control model of VSVP wind power generation system is set up, and the estimation control algorithm of the controller is given by the full consideration of the coupled relation between variable speed process and variable pitch process. Modeling and simulation of the VSVP wind turbines with 1 300 kW rated power are carried out, the simulation results show that compared with the traditional control method, it has better output power quality and improves the stability and reliability of the wind turbines in bad environment.

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风力发电变速变桨系统的混杂控制

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摘要:针对变速变桨风力发电系统随机扰动大、多工况运行、结构时变的复杂系统控制问题,以风机的输出功率、转速和桨距角为研究对象,提出了一种基于混杂自动机的变速变桨控制模型。充分考虑到系统变速和变桨过程中的耦合关系,将控制过程分成 4 个阶段,结合预估控制给出了各阶段控制器的算法。利用 MATLAB/Simulink 对某额定功率为 1 300 kW 的变速变桨风力机组进行建模和仿真,结果表明与传统控制方法相比,采用该建模和控制方法,既改善了风力机输出电能质量,也提高了变速变桨风力发电系统的风能利用效率。

关键词:风电;混杂自动机;变速变桨控制;预估控制

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