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THE HYBRID COORDINATE CUTTING-IN CONTROL TECHNOLOGY OF THE DOUBLY-FED VARIABLE SPEEDAND PITCH WIND-POWER GENERATOR

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ABSTRACT

In view of the cutting-in problems of the doubly-fed wind power generator, this paper deals with it's control strategies in detail and proposes a coordinate cutting-in control method based on the hybrid system theory, and establishes the hierarchical control model of the doubly-fed wind power generator around the cutting-in. On the basis of the model, the model information and structure information of the system are decentralized. On the one hand, the control algorithm is designed for the continuous variable of the system with the d-axis current and q-axis current as its controlled outputs according to the estimated mechanisms and control strategies. On the other hand, the hybrid automaton is used for the state transition of the system discrete variable. Simulation results show that compared with the traditional control methods this new control method can make the d-axis current and the q-axis current of DIFG to the reference values in finite time and achieve the effective control of the rotor current. What's more important this method can not only improve the no off-grid ability during the grid-voltage fluctuation, but also prevent the rotor and rotor-side converter over current effectively. It has important actual significance and practical application value.

Keywords: *Doubly-fed; Hybrid system; Hybrid automata; Estimate control; PI control*

1. INTRODUCTION

At present, the cutting-in technology of DFIG mainly includes the cutting-in control and the generating operation control after cutting-in. The main control algorithms include PI control, robust control, the synovial variable structure control, immunity control, predictive control, fuzzy control and other control methods. All of these methods show an aspect of their advantages in cutting-in of VSCF generator, but each has its limitations. Literature [1-2] proposed a Piecewise hierarchical control strategy, but they both don't regard the wind turbine as a whole hybrid system from systematic consideration. Literature [3-5] put forward one kind of the grid-connection control method with PI (proportional integral) controller, and realized the decoupling control of active and reactive power. However, due to nonlinear and uncertainty of the variable speed constant frequency wind turbine itself which make the control parameters of the PI regulator changed with the motor parameters change, the real-time and anti-disturbance performance of the system is poor. Literature [6] introduced the sliding mode variable structure control into the doubly-fed generator cutting-in control technology which improved the dynamic response speed of cutting-in, and the system has strong robustness to the internal parameters perturbation and external disturbance. However, this control method is still not free from the shackles of the PI control thoughts, its performance to a certain extent depends on the controller parameters. Literature [7] proposes a control strategy of the self-immunity grid connection according to the cutting-in characteristics of the DFIG. This control strategy can realize cutting-in control without precise motor parameters and can be achieved grid connection, and has good robustness to the parameter perturbation and internal and external perturbations. However, this method is highly theoretical and too dependent on designer experience. It did not show too many advantages than the traditional method in the application. Literature [8-9] adopts the precise mathematical model of the doubly fed induction generator to realize dynamic control and effectively reduced the over current of the rotor and the rotor side converter devices caused by the grid voltage fluctuation during the electricity generation operation after the cutting-in, furthermore it also improved the DFIG low voltage ride through capability. But the essence of this method is also PI control and the controller parameter is still the

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decisive factor to the performance of grid - connected. Literature [10] researches the complementary independent hybrid power generation system of the wind power and solar energy. Literature [11] Studies the hybrid wind power generation system which has accumulator. But the hybrid system theory which applied to the cutting-in control of the variable speed variable pitch turbine research has not yet been mentioned.

Through the combination of the hybrid system control and structure decentralized control, this paper presents a kind of hybrid control mode decentralized control strategy of doubly-fed wind power system and the model both ensure the generator rotor d-axis current and q-axis current fast convergence and better tracking accuracy. It improves the off-grid ability of the DFIG during the grid voltage fluctuations and opens up a new way for the DFIG cutting-in control.

2. THE HYBRID MODEL OF THE DFIG WIND POWER SYSTEM

According to the cutting-in control performance index of the doubly-fed wind power generation system[12-16], the basic control strategy is determined as follows: the no-load cutting-in control strategy of the double fed wind generator is implemented before cutting-in. When the generator stator voltage is equal to the voltage of the grid and the generator speed is around the synchronous speed, the cutting-in operation is executed. After the implementation of the cutting-in, the maximum wind energy tracking control strategy is carried out. The hybrid control structure[17] of the DFIG wind power system is shown in Figure 1.

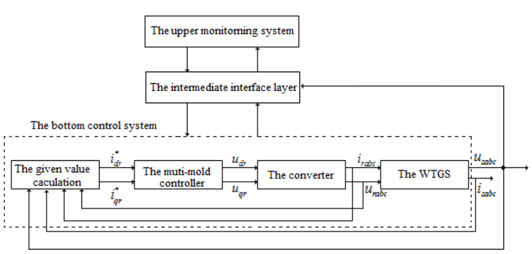

Fig.1 The Hybrid Control Structure Of The DFIG Wind Power System

As is shown in Figure 1, the control structure is composed of the upper monitoring system, the intermediate interface layer and the bottom control system. The functions of each layer are described as follows:

1）The upper monitoring system

The upper monitoring system is a discrete event dynamic system (DEDS) which can be described by the automata form, it is used to monitor the generator stator voltage and grid voltage and transfer the no-load cutting-in state of the DFIG unit to the power operation state through the intermediate interface. The extended automata model of the upper monitoring system can be described by a quintuple[18]:

$$H = \left(D, C, Init, f_1(s_i), f_2(\delta_i)\right) \quad (1)$$

Where D is a discrete state space finite set, C is a continuous state space finite set, $Init$ is the initial value and initial state space collection, $f_1(s_i \mid s_i \in C)$ is the continuous state evolving rule corresponding to the discrete event of the system, $f_2(\delta_i \mid \delta_i \in D)$ is a discrete event change enable set.

According to the grid-connection requirements, there are two main continuous state space in the system: The no-load operation state before the grid-connection and the generator operation state after the grid-connection. As the stator terminal voltage is affected by the grid voltage, the cutting-in system switches back and forth in the two continuous state space. The hybrid automata model of the upper monitoring system is shown in Figure 2.

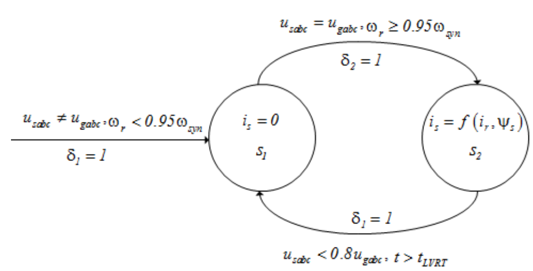

Fig.2 The Hybrid Automata Model Of The Upper Monitoring System

The wind power cutting-in automata model can be specified as follows:

(1)The discrete state space finite set $D = \{u_{sabc}, u_{gabc}, t_{LVRT}, \omega_r, \delta_1, \delta_2\}$,where u_{sabc} is the three-phase stator terminal voltage, u_{gabc} is the three-phase grid voltage, ω_r is the generator rotor speed, $\delta_i \in D$ is the discrete event variable of system.

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(2)The continuous state space finite set $C=\{s_1, s_2\}$, where s_1 is the no-load operation state, s_2 is the generator operation state.

(3)The initial value and initial state space collection $Init=\{u_{sabc0}=0, \omega_{r0}=0, t_{LVRT}\equiv 0.635, \delta_1=1, \delta_2=0\}$, the initial state space is s_1 .

(4) The continuous state evolution corresponding to the discrete event of the system $f_1(s_i)=\{f_1(s_1), f_2(s_2)\}$ $i=1,2.$, where $f_1(s_1)$ is the no-load operation continuous state evolving rule, $f_2(s_2)$ is the generator operation continuous state evolving rule.

(5)The discrete event change enable set $f_2(\delta_i)=\{f_2(\delta_1), f_2(\delta_2)\}$ $i=1,2.$, where $f_2(\delta_1)$ stands for switching to the state s_1 , $f_2(\delta_2)$ stands for switching to the state s_2 .

2）The middle interface layer

The middle interface layer plays a key role in the hybrid cutting-in control of the DFIG wind power system, it mainly completes the mutual transformation of the discrete variables and the continuous variables. The mapping relationship which transfers the continuous state set C to discrete event set D can be expressed as:

$$\delta_i=\begin{cases}\delta_1=1 & \begin{matrix}(u_{sabc}\neq u_{gabc})\cap(\omega_r<90\%\omega_{syn})\\(u_{sabc}<0.8u_{gabc})\cap(t>t_{LVRT})\end{matrix}\\ \delta_2=1 & u_{sabc}=u_{gabc}\end{cases} \qquad (2)$$

Where u_{gabc} is the three-phase grid voltage, ω_{syn} is synchronous speed. The mapping function (2) corresponds to the discrete event generator which transfers the continuous states into the discrete events. The continuous system state space can be mapped to different events through this mapping relationship.

Similarly, the mapping relationship which transfers the discrete state set C to continuous event set D can be expressed as:

$$s_i=\begin{cases}s_1=1, & \delta_1=1\\ s_2=1, & \delta_2=1\end{cases} \qquad (3)$$

The mapping function (3) corresponds to the event generator which transfers the discrete events into the continuous states. The different discrete events can be mapped to the continuous state space through this mapping relationship so that the upper monitoring system is able to control the dynamic behavior of the continuous process.

3）The bottom control system

(1) The given values

The given values of the bottom control system are the rotor currents i_{dr}^* and i_{qr}^* which can be adjusted according to the operational status of the wind power system.

The output expression for a given value can be expressed as:

$$i_{dr}^*(i_{qr}^*)=\begin{cases}i_{drn}^*(i_{qrn}^*) & \delta_1=1\\ i_{drl}^*(i_{qrl}^*) & \delta_2=1\end{cases} \qquad (4)$$

Where $i_{drn}^*(i_{qrn}^*)$ is the given value of the rotor d(q) axis current in the no load operating condition, $i_{drl}^*(i_{qrl}^*)$ is the given value of the rotor d(q) axis current in the generating condition.

When the cutting-in system of the wind power generator is in the state $\delta_1=1$, the given value is the rotor d(q) axis current $i_{drn}^*(i_{qrn}^*)$, the system is in the no load operating condition. Similarly, When the cutting-in system of the wind power generator is in the state $\delta_2=1$, the given value is the rotor d(q) axis current $i_{drl}^*(i_{qrl}^*)$, the system is in the generating condition.

（2）The controller

The controller can divide the control process into a plurality of stages according to the decision results of the upper control system, and each stage adopts different control rules so as to meet multiple state control requirements. The controller's structure is shown as Fig.3:

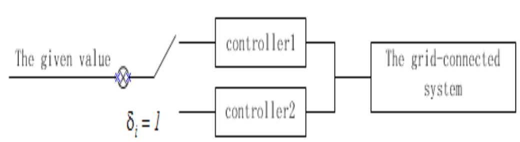

Fig.3 The Controller's Structure Of The Bottom Control System

3. THE RELATIONAL STRUCTURE MODEL OF THE BOTTOM CONTROLLER

The no-load relational-structure diagram of the bottom controller of doubly-fed wind power

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generation system is shown in Figure 4 which consists of two unit model, two causal chains and two linkages.

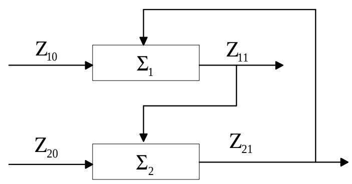

Fig.4 The No-Load Relational-Structure Diagram Of The Bottom Controller

Where Z_{10} is the current control signal of the rotor d-axis $u_{dr}(k)$, Z_{11} is the rotor d-axis current $i_{dr}(k)$. Z_{20} is the current control signal of the rotor q-axis $u_{qr}(k)$, Z_{21} : the rotor q-axis current $i_{qr}(k)$.

According to literature [19], we can get the no load relational-structure model of the bottom controller in the form：

$$\begin{cases} Z_{11}(t+1)=aZ_{11}(t)+bZ_{21}(t-d_{21}^{11})+cZ_{10}(t-d_{10}^{11}) \\ Z_{21}(t+1)=aZ_{21}(t)+bZ_{11}(t-d_{11}^{21})+cZ_{20}(t-d_{20}^{21}) \end{cases} \quad (5)$$

Where d_{ij-1}^{ij} is the lag number of steps of the Z_{ij-1} relative to Z_{ij}.

4. THE PREDICTION AND CONTROL OF THE RELATIONAL-STRUCTURE MODEL

The predictive no-load relational model of the bottom controller is described in the form:

$$\begin{cases} \hat{Z}_{11}(t+D_{11}|t)=a\hat{Z}_{11}(t+D_{11}-1)+b\hat{Z}_{21}(t+D_{11}-d_{21}^{11}-1)+c\hat{Z}_{10}(t) \\ \hat{Z}_{21}(t+D_{21}|t)=a\hat{Z}_{21}(t+D_{21}-1)+b\hat{Z}_{11}(t+D_{21}-d_{11}^{21}-1)+c\hat{Z}_{20}(t) \end{cases} \quad (6)$$

Where $\hat{Z}_{11}(t+D_{11}|t)$ is the estimates of $Z_{11}(t)$, $\hat{Z}_{21}(t+D_{21}|t)$ is the estimates of $Z_{21}(t)$. D_{ij} is the lag number of steps of the Z_{i0} relative to Z_{ij}.

According to the prediction model (6), the future output value and expectation value of the system has the following relationship:

$$\begin{cases} P_1\hat{Z}_{11}(t+D_{11}|t)=H_1Z_{11}^*(t+D_{11}) \\ P_2\hat{Z}_{21}(t+D_{21}|t)=H_2Z_{21}^*(t+D_{21}) \end{cases} \quad (7)$$

where $Z_{11}^*(t+D_{11})$ is the expected value of the rotor d-axis current. $P_1=1-p_1z^{-1}$, $H_1=1-p_1$, $|p_1|<1$. Here z^{-1} is a step delay operator, p_1 is a design parameter. $Z_{11}^*(t+D_{11}|t)$ is the expected value of the rotor d-axis voltage of the no-load cutting-in DFIG. $Z_{21}^*(t+D_{21})$ is the expected value of the doubly-fed machine output rotor q-axis current. $P_2=1-p_2z^{-1}$, $H_2=1-p_2$, $|p_2|<1$. z^{-1} is a step delay operator, p_2 is a design parameter.

From (6) and (7), we can get the no load relational-structure control model in the form:

$$\begin{cases} Z_{10}^*(t)=[p_1\hat{Z}_{11}(t+D_{11}-1|t)+(1-p_1)Z_{11}^*(t+D_{11}) \\ \qquad -a\hat{Z}_{11}(t+D_{11}-1)+b\hat{Z}_{21}(t+D_{11}-d_{21}^{11}-1)]/c \\ Z_{20}^*(t)=[p_2\hat{Z}_{21}(t+D_{21}-1|t)+(1-p_2)Z_{21}^*(t+D_{21}) \\ \qquad -a\hat{Z}_{21}(t+D_{21}-1)+b\hat{Z}_{11}(t+D_{21}-d_{11}^{21}-1)]/c \end{cases} \quad (8)$$

Where a 、b 、c 、a_1 、b_1 、c_1 is the identified parameters, p_1 、 p_2 are the design parameters. Z_{10}^* 、 Z_{20}^* 、 Z_{11}^* 、 Z_{21}^* are the expected values of Z_{10} 、 Z_{20} 、 Z_{11} 、 Z_{21} , $\hat{Z}_{10}$ 、$\hat{Z}_{20}$ 、$\hat{Z}_{11}$ 、$\hat{Z}_{21}$ are the estimated values of Z_{10}、 Z_{20}、 Z_{11}、 Z_{21}.

5. THE SIMULATION AND RESULTS ANALYSIS

In order to verify the rationality of the hybrid control strategy, a practical experimentpointed to the feasibility of the proposed control strategy is made by the MATLAB software platform. The main parameters used in the simulation of 7.5kw doubly-fed motor wind power system experiment

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platform are shown in Table 1. The main simulation curves are shown in Figure 5-8.

Table.1 Simulation Parameters

wind turbine parameters	values	generator/grid parameters	values
impeller diameter（m）	2	number of pole pairs	2
starting wind speed (m/s)	3.5	rated power (KW)	7.5
rated running wind speed (m/s)	10~14	synchronous speed (r/min)	1500
optimal tip speed ratio	7.5	stator/ rotor inductance (mH)	0.470/0.520
drive ratio	1：3	mutual inductance (mH)	0.587
moment of inertia of the wind wheel (Kg/m2)	30205	power line voltage (V)/ frequency (HZ)	380/50

The parameters of (11) and (13) are determined by using the on-line identification method to ensure the real-time adjustment of control parameters.

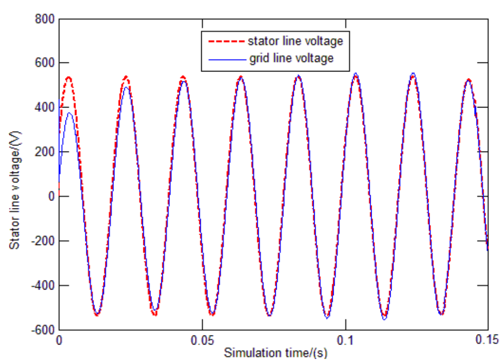

Fig.5 The Stator Voltage Simulation Curve Of The Conventional PI Control

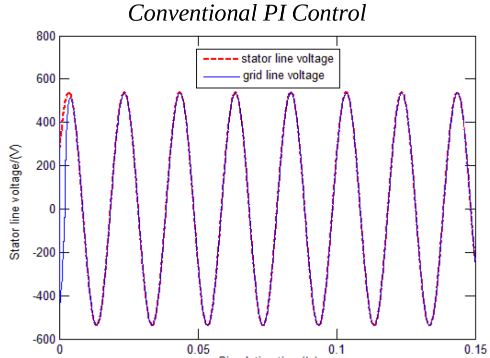

Fig.6 The Stator Voltage Simulation Curve Of The Hybrid System Control

It can be seen from Figure 5 and Figure 6 that the stator voltage of the conventional PI control method meets the requirements of grid voltage accuracy in about seven cycles time. Therefore the stator voltage of the hybrid system method meets the requirements of grid voltage accuracy in only half of the cycle time and has no overshoot.

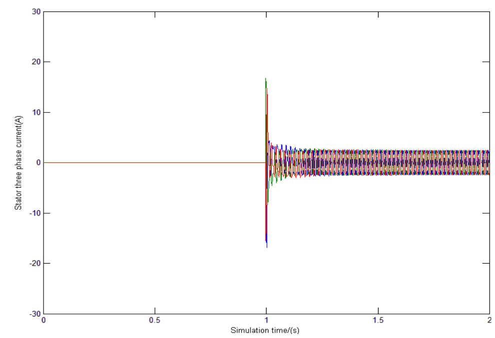

Fig.7 The Stator Three-Phase Cutting-In Current Simulation Curve Of The Conventional PI Controller

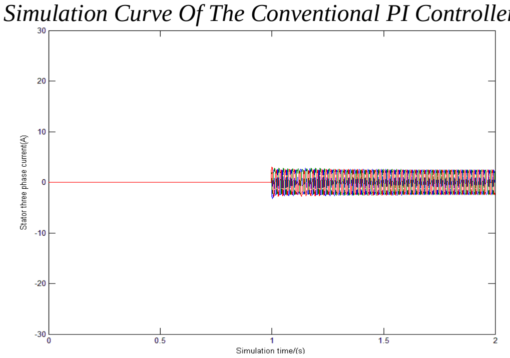

Fig.8 The Stator Three-Phase Cutting-In Current Simulation Curve Of The Hybrid System Control

It can be seen from Figure 7 and Figure 8 that a greater impact current will arise at the moment of the cutting-in of the conventional PI control which will cause the fluctuations in the grid voltage. With the wind turbine capacity increasing, such an impact must be avoided. Therefore the impact current of the hybrid system control is very small and realized the flexible cutting-in of DFIG.

6. CONCLUSION

This paper analyzed the accurate cutting-in model of DFIG by adopting the hybrid system control method. At last, the no-load hybrid control mathematical model and the generator mathematical model have been established respectively by fully considering the coupling relations of each variable in the process of cutting-in. The hybrid control strategy on the one hand improves the quality of the stator output voltage of

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the wind power generation system, on the other hand greatly increases the effective control of the rotor current when the external and power grid voltage fault and realized the ride-through control of the DFIG. Simulation results show that compared with the conventional PI control method, the hybrid control method can make the cutting-in control of the DFIG has better adaptability and stability and thus has great significance to improve the quality of cutting-in of the wind power generation system.

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