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Research on the Composite Control Strategy of the Doubly Fed Induction Generator Grid Side Converter

Xinyu Liu, Ke Bai and Guoquan Wang

School of electric power North China University of Water Resource and Electric power, Zhengzhou, 450011, China
lxy22101@163.com

Abstract

Aiming at the existing problems of the DFIG grid side converter, this paper studies its control technology and proposes a composite control strategy which includes a terminal sliding mode variable structure control of the current inner-loop and a PI controller of the voltage outer-loop in grid side converter. The simulation results show that the control strategy proposed in this paper can achieve better control of the inverter output voltage and input current. What's more important, this method can not only reduce the adverse effects on the grid side converter due to parameter variations and other factors, but also increases the robustness of the system. It has important actual significance and practical application value.

***Keywords**: DFIG; Grid side Converter; Sliding Mode Variable Structure; Complex control*

1. Introduction

The task of the grid side converter of the doubly fed induction generator mainly includes two aspects: Firstly it can maintain a constant DC bus voltage through the feedback control by the acquisition of dc link voltage. Secondly, it can achieve the unit power factor input of the grid side through the input current feedback of the grid side converter. According to the requirements of the control task on grid side converter, domestic and foreign scholars have done a lot of research work on its control method and have made some progress, but these results shows its validity in a way, it is difficult to ensure its generality. Literature [1] adopts a control method of the stator flux-oriented vector and uses the double closed loop PI regulator to control the grid side converter. Literature [2-3] proposes a control strategy of the grid side PWM converter based on grid voltage orientation and applies it on the doubly-fed generator connected to the grid. It realizes the same function of the stator flux-oriented vector control and overcomes the instability of the vector control method of the stator flux-oriented when the motor parameters change. Aiming at the shortcoming of the stator flux -oriented vector control and grid voltage oriented-vector control, Literature [4-5] proposes a direct power control of the grid side converter. This control strategy detects the grid voltage and current and calculates the instantaneous active and reactive power. Through comparing the given active and reactive power, this method gives the control signals of the switch tube according to the switch table where the grid voltage vectors locate. The unit power factor operation of the converter is realized by directly controlling the active and reactive power of the system.

Based on the control methods which have been put forward by the domestic and overseas scholars, This paper proposes a complex control strategy of the terminal sliding mode variable structure control of the current inner loop and the PI control of the voltage outer loop and realizes the effective control of grid connected of DFIG.

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2. Analysis of the Grid-Side Converter Mathematical Model of the DFIG

The main circuit of the grid side converter is shown in Figure 1. u_{ga} 、 u_{gb} 、 u_{gc} are the phase voltage of the three-phase power grid respectively; i_{ga}、 i_{gb}、 i_{gc} are the three-phase input current respectively; v_{ga}、 v_{gb}、 v_{gc} are three three-phase voltage of the converter AC side respectively; u_{dc} is the converter DC side voltage; C is the DC bus capacitor; i_{load} is the DC load current. L_{ga}、 L_{gb}、 L_{gc} are the inductance of per phase line reactor respectively; R_{ga}、 R_{gb}、 R_{gc} are phase circuit resistance respectively. The load of grid side converter is the rotor side converter which is connected with the rotor winding.

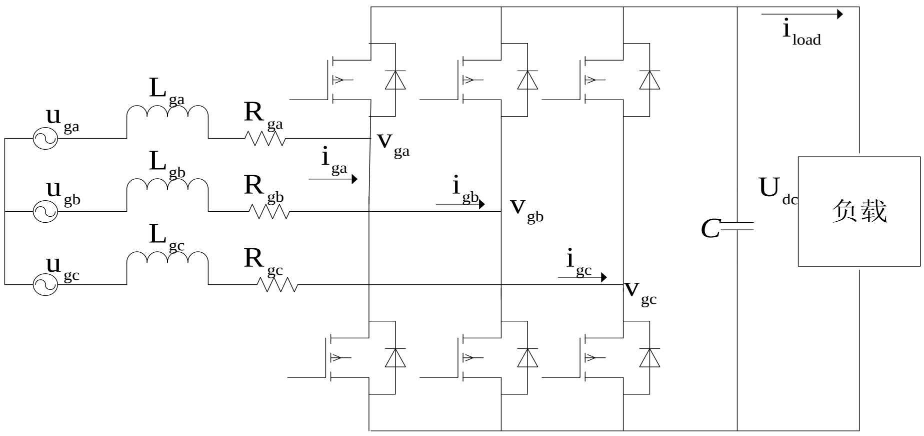

Figure 1. The Main Circuit of the grid Side PWM Converter

In the three-phase synchronous rotating coordinate, the mathematical model of the grid side PWM converter can be described as fellows: [6]

$$\begin{cases} L\dfrac{di_{gd}}{dt} = -Ri_{gd} + \omega L i_{gq} + u_{gd} - v_{gd} \\ L\dfrac{di_{gq}}{dt} = -Ri_{gq} - \omega L i_{gd} + u_{gq} - v_{gq} \\ C\dfrac{du_{dc}}{dt} = (S_d i_{gd} + S_q i_{gq}) - i_{load} \end{cases} \tag{1}$$

Where, u_{gd} 、 u_{gq} is the d, q component of the grid electric potential; v_{gd}、 v_{gq} is the d, q component of the output voltage vector in AC side ; i_{gd} 、 i_{gq} is the d, q component of a three phase input current vector ; S_d 、 S_q is the d, q component of a switching function; ω is the angular velocity of the grid voltage.

When the d-axis of the synchronous rotating coordinate is oriented in the direction of the grid voltage vector, $u_{gd} = u_g$, $u_{gq} = 0$. Then the equation (1) can be simplified as fellows:

$$\begin{cases} L\dfrac{di_{gd}}{dt} = -Ri_{gd} + \omega L i_{gq} + u_g - v_{gd} \\ L\dfrac{di_{gq}}{dt} = -Ri_{gq} - \omega L i_{gd} - v_{gq} \\ C\dfrac{du_{dc}}{dt} = (S_d i_{gd} + S_q i_{gq}) - i_{load} \end{cases} \tag{2}$$

Similarly, the active and reactive power output of the grid side converter can be written as

$$\begin{cases} P_g = -\frac{3}{2} u_g i_{gd} \\ Q_g = \frac{3}{2} u_g i_{gq} \end{cases} \tag{3}$$

It can be seen from equation (3), the current vector i_{gd} and i_{gq} represent active current and reactive current of the grid side converter. Therefore, in the control strategy of the grid side converter, the effective control of the input current i_{gd} 、 i_{gq} plays a vital role in the whole control strategy.

3. The Control Strategy Design of the DFIG Grid-Side Converter

The control of the DFIG grid side converter generally use double closed loop control mode. The inner loop is a power control loop and the outer loop is a DC voltage control loop.

3.1. The Design of the Power Loop Control Strategy

According to equation (2), the structure diagram of the DFIG grid side converter control voltage and the grid side input current as shown in Figure 2.

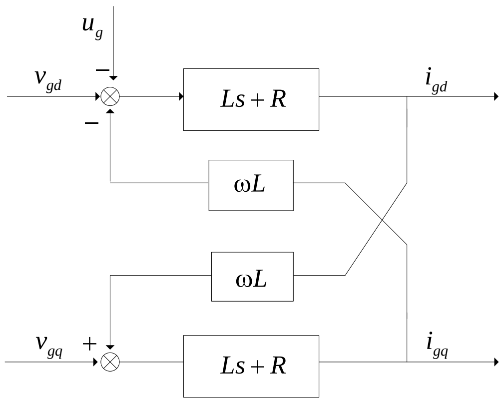

Figure 2. The Relationship between the Control Voltage and the Input Current of the Grid Side Converter

Through the analysis of Figure 2, when the DFIG grid-side converter is in running state, the output of the system is the input current i_{gd} 、 i_{gq} of converter, and the control input is the output voltage v_{gd} 、 v_{gq} of the converter. Therefore, the system controller can be designed to realize the control of the grid side converter. Therefore, the equation (2) can be written in the form of the following state-space equation

$$\dot{Z} = AZ + BU + F \tag{4}$$

Where F represents the disturbances caused by the grid voltage, $Z = \begin{bmatrix} z_{11} \\ z_{21} \end{bmatrix}$ is a state variable, $U = \begin{bmatrix} z_{10} \\ z_{20} \end{bmatrix}$ is the control input, Z_{11} 、 Z_{21} respectively represent the grid side converter active current and reactive current: i_{gd} 、 i_{gq}. Z_{10} 、 Z_{20} respectively represent the control volume of active current and reactive current: v_{gd} 、 v_{gq}.

$$A=\begin{bmatrix}-R & \omega L\\ -R & -\omega L\end{bmatrix},\quad B=\begin{bmatrix}-1 & 0\\ 0 & -1\end{bmatrix},\quad F=\begin{bmatrix}f\\ 0\end{bmatrix},\quad f=u_s$$

Easy to prove: $rank\begin{bmatrix}B & F\end{bmatrix}=rank\begin{bmatrix}B\end{bmatrix}=2$ (5)

According to equation (5), the sliding mode of the doubly-fed wind power generation system meets the necessary and sufficient condition of imperviousness [7-8]. Therefore, by designing a suitable sliding mode controller, it can make the grid side converter has completely robustness to the disturbance caused by the network voltage and other reasons.

The d-axis error state variable of the system is defined as $e_d=z_{11}^{*}-z_{11}$, According to equation (4), the error state equation of the DFIG grid-side converter d-axis input current can be written as

$$\dot{e}_d=Rz_{11}^{*}-\mathrm{Re}_d+\dot{z}_{11}^{*}+z_{10}-F_d^{'} \tag{6}$$

Where $F_d^{'}=\omega Lz_{21}+u_s$ represents the disturbance caused by the cross-coupling term of the grid voltage and axial currents.

Based on the above, the paper proposes the following integral sliding surface

$$s_d=e_d+\int_0^t(c_{1d}e_d+c_{2d}e_d{}^{p/q})d\tau-e_0 \tag{7}$$

Where, c_{1d} 、 c_{2d} are the coefficient matrix of the mold surface, and c_{1d} 、 c_{2d} are greater than zero, e_0 is the initial value of the tracking error.

When the states of the system reach to the sliding surface, then, $s_d=\dot{s}_d=0$. From the formula (7), we can get

$$\dot{e}_d=-c_{1d}e_d-c_{2d}e_d{}^{p/q} \tag{8}$$

Type (8) shows that, by designing appropriate mold surface coefficient c_1, when the systematic error state is far away from the sliding surface, the first item of type (8) acts to make the system quickly moves to the sliding mode surface again. When the systematic error state is close to the sliding surface, the second item of type (8) acts to ensure the states of the system converge to zero in finite time.

According to the terminal mode surface proposed in this paper, if the generalized disturbance $F_d^{'}$ is bounded and satisfied with type: $\left|F_d^{'}\right|\le k_d$, k_d is a constant which is greater than zero, we can get the following theorem.

Theorem If the double fed wind power grid-connected control system meets $\left|F_d^{'}\right|\le k_d$, and select the terminal mold surface [9] as the formula (7), when switching gain meets $\eta_d>k$, by using the control law of the d-axis input current component of DFIG grid side converter as follows

$$z_{10}=(R-c_{1d})e_d-c_{2d}e_d{}^{p/q}-Rz_{11}{}^{*}-\eta_d\,\mathrm{sgn}(s_d)-z_{11}{}^{*} \tag{9}$$

Where η_d is a constant greater than zero.

It can make the input current error e_d of the DFIG grid side rectifier converge to zero in finite time and the system is robust stable.

Firstly, we prove the robust and stability.

Proof: choose the Lyapunov function $V=\frac{1}{2}s_d^2$, then

$$\dot{V}=s_d\dot{s}_d=s_d(\dot{e}_d+c_{1d}e_d+c_{2d}e_d^{\ p/q})$$

$$=s_d[(c_{1d}-R)e_d+z_{10}+Rz_{11}^*+\dot{z}_{11}^*-F_d^{'}+c_{2d}e^{p/q}]$$

$$=s_d(-\eta_d\operatorname{sgn}(s_d)-F_d^{'})\le-\eta_d|s_d|+|F_d^{'}||s_d|$$

$$=-|s_d|(\eta_d-|F_d^{'}|)\le-|s_d|(\eta_d-k_d)<0$$

Therefore, the control system of the design is stable.

According to equation (7), set $e_{d0}=e(0)$, then $s_d(0)=0$. It indicates that by selecting appropriate initial value of the tracking error, the control system of the DFIG rotor side converter can be in the sliding mode surface at the beginning, which ensures the entire robustness of the control system.

Secondly, we prove the convergence. When $s_d=0$, it can be obtained

$$\dot{e}_d=-c_{1d}e_d-c_{2d}e_d^{\ p/q} \tag{10}$$

From the formula (10) we can get

$$\dot{e}_d\frac{1}{c_{1d}e_d+c_{2d}e_d^{p/q}}=-1 \tag{11}$$

Taking the integral of both sides of (11), the following type can be got

$$\int_{e_d}^{0}\frac{1}{c_{1d}e_d+c_{2d}e_d^{p/q}}de_d=-\int_0^{\Delta t_d}dt \tag{12}$$

Solving the type (10) , the result is as fellows

$$\Delta t_d=\frac{q}{c_{1d}(q-p)}\ln(1+\frac{c_{1d}}{c_{2d}}e_d^{1-\frac{p}{q}}) \tag{13}$$

Type (13) shows that the tracking error of the d-axis excitation current component can be converge to zero in finite time.

Similarly, the control law of the q-axis input current component of DFIG grid side converter is:

$$z_{20}=(R-c_{1q})e_q-c_{2q}e_q^{p/q}-Rz_{21}^*-\eta_q\operatorname{sgn}(s_q)-\dot{z}_{21}^* \tag{14}$$

Where c_{1q}、 c_{2q} are coefficient matrix of the mold surface, and c_{1q}、 c_{2q} are greater than zero, η_q represents a switch gain which is a constant greater than zero.

The convergence time of the q-axis input current component of DFIG grid side converter is as fellows

$$\Delta t_q=\frac{q}{c_{1q}(q-p)}\ln(1+\frac{c_{1q}}{c_{2q}}e_q^{1-\frac{p}{q}}) \tag{15}$$

3.2. The Design of the Voltage Loop Control Strategy

The voltage controller of the DC link can be designed as the following form [10], that is

$$i_c=C\frac{dU_{dc}}{dt}=C\frac{dU_{dc}^*}{dt}+k_{vp}\left(U_{dc}^*-U_{dc}\right)+k_{vi}\int\left(U_{dc}^*-U_{dc}\right)dt$$

Where, U_{dc}^* is the reference value of the DC bus voltage, k_{vp}、 k_{vi} are respectively for the proportional, integral coefficient of the DC voltage controller.

As previously mentioned, the double closed-loop control diagram of the grid side converter voltage and current are shown in Figure3.

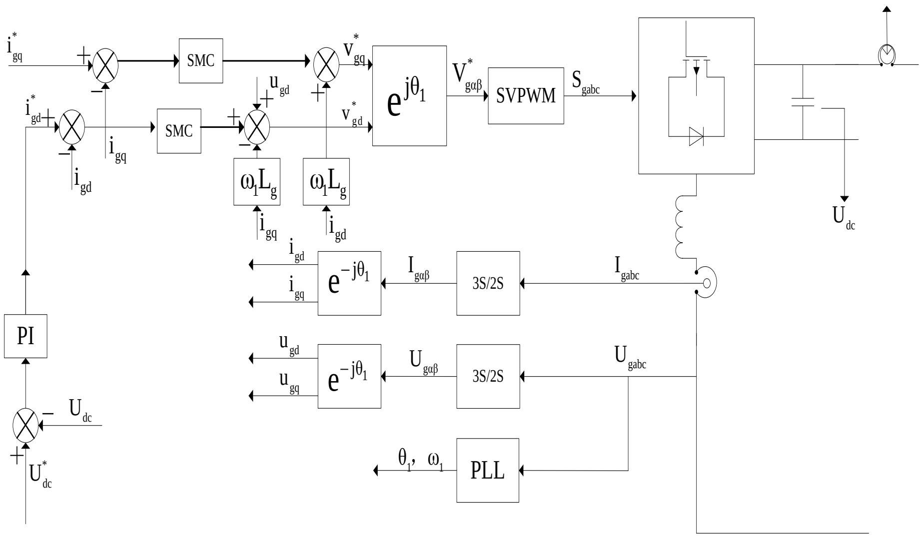

Figure 3. Grid Side Converter Voltage and Current Double Closed-Loop Control Block Diagram

4. The Control Numerical Simulation of the DFIG Grid Side Converter

In order to verify the effectiveness of the control strategy of DFIG grid side converter proposed in this paper, the voltage-current double closed loop simulation model of the DFIG grid side converter by using the simulation software Matlab/Simulink of the Power System toolbox is established shown in Figure 4, the simulation model of the grid side controller is shown in Figure 5.

The parameters used in the simulations are as follows: grid phase voltage 110V, frequency 50Hz, a capacitor C 300 micro method, DC given voltage 500V.

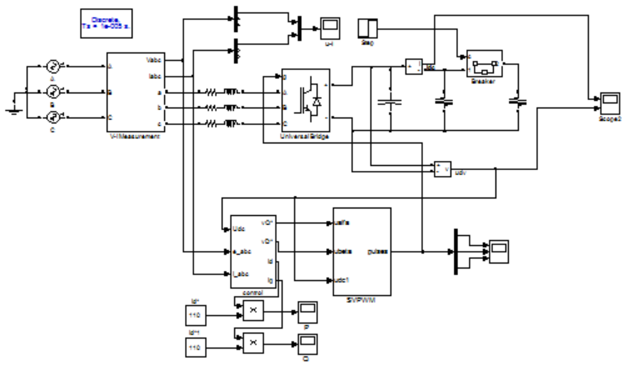

Figure 4. The Simulation Model of the Grid Side Converter

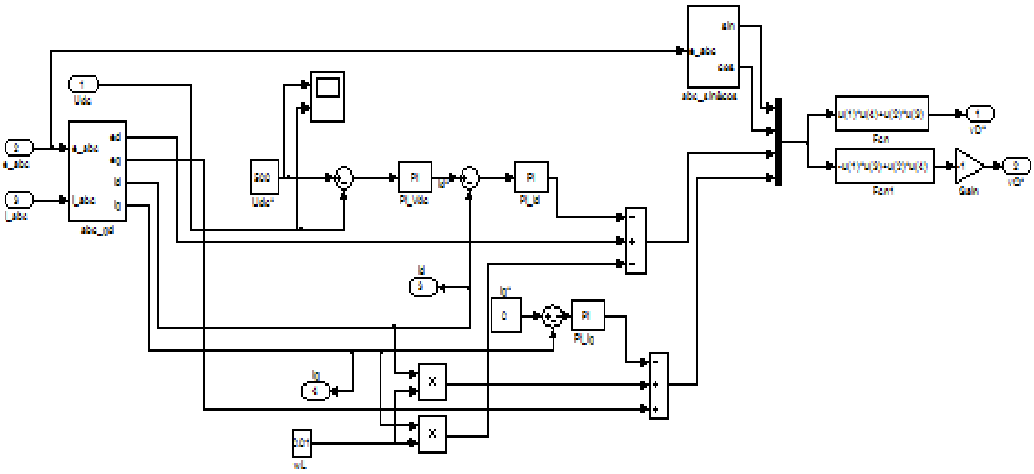

Figure 5. The Simulation Model of the Grid Side Controller

The grid side controller model adopts voltage-current double closed loop structure. The former is used to control the voltage; the latter is used to control the input power factor. The given value of dc bus voltage is 500V, and the sudden load appears in 0.5 seconds, then the simulation results are shown as Figure 6 to Figure 10.

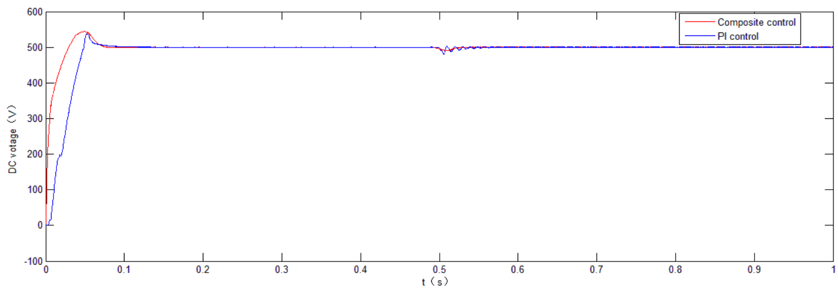

Figure 6. DC Voltage Simulation Diagram

It can be seen from the simulation results of the DC bus voltage in Figure 6, the DC bus voltage achieves stability in 0.08 seconds under two kinds of control methods. At the 0.5 seconds DC voltage occurs fluctuation caused by the change of the load, but the voltage soon returns to the given value. However, when use the composite control strategy of the grid side converter proposed in this paper, the DC bus voltage changes little with load fluctuations. But when the conventional PI control method is used, the DC voltage fluctuations is larger than the voltage fluctuation proposed in this paper when the load changes. Thus, the composite control method of the grid side converter enhances the robustness of the DC bus voltage.

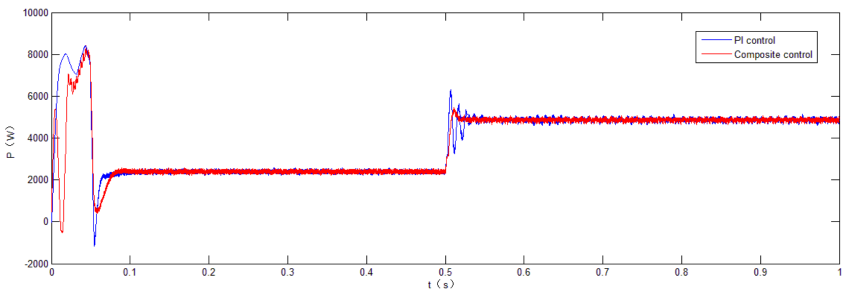

Figure 7. The Input Active Power Simulation Diagram

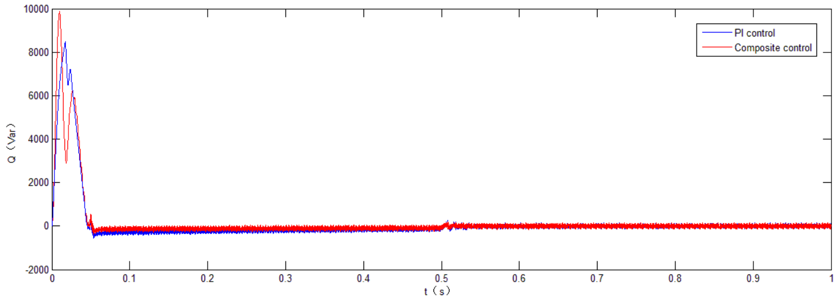

Figure 8. The Input Reactive Power Simulation Diagram

Figure 7 and Figure 8 are the input active power and reactive power simulation diagram of the grid side converter. From the two diagrams, it can be seen that the input active power of the grid side converter is stable in 2500W after 0.08 seconds, and the reactive power is stable in 0W after 0.07 seconds. In 0.5 seconds when the load changes, the input active power rapidly track the change of the load and the active power increases correspondingly and stabilizes in about 5000W, at the same time the reactive power unchanged basically and it was still at 0W. However, when the composite control strategy proposed in this paper is used, the tacking ability of the input active power and reactive power is obviously better than the conventional PI control method.

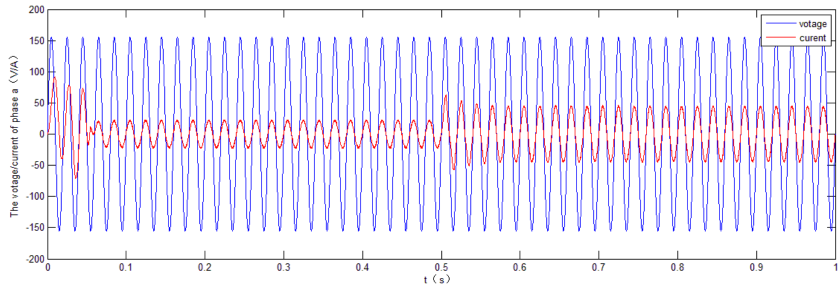

Figure 9. The Grid Side Converter Rectifier Simulation Diagram

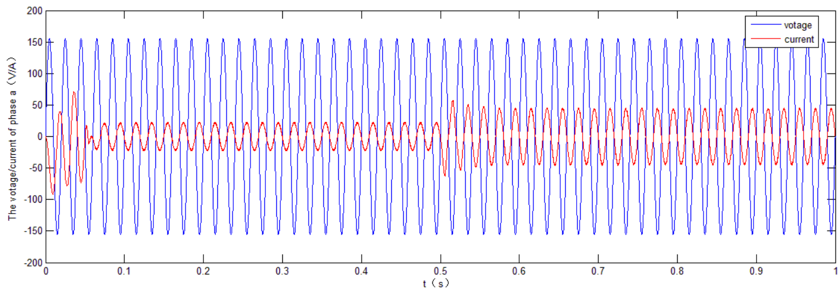

Figure 10. The Grid Side Converter Inverter Simulation Diagram

Figure 9 is the state of the rectification simulation curve of the grid side converter, it can be seen that the grid side voltage and current waveform have the same phase and they are all sine wave. The energy flows into the inverter from the grid, it achieves the design goals of a unity power factor input. Figure 10 is the inverter state simulation curve of the grid side converter, it can be seen that the grid side voltage and the current waveform have a reverse phase and the current waveform is approximate to sine wave. The energy in the converter flows into the power grid, it realizes the two-way flow of the energy.

5. Conclusions

This article mainly takes the grid side converter of the doubly-fed wind power generator as the research object and proposes the composite control strategy of the inner ring terminal sliding mode control of the current and the outer loop PI control of the voltage, which effectively reduces the impact of the load disturbance on the performance of the inverter control and improves the anti-interference performance of the system. The simulation results show that compared with the traditional PI control method, the composite control strategy of the grid side converter can make the wind power grid side converter control more adaptability and stability, and thus to improve the quality of the wind power system.

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Authors

Xin Yu Liu, he was born on January 24, 1976. He is an associate professor and master tutor in North China University of Water Resources and Electric Power. He received his Ph. D degree in 2013 from Zhengzhou University, China. His main research interests include new energy power generation and smart grid.

Ke Bai, he was born on March 21, 1989. He is a master of North China University of Water Resources and Electric Power. His research direction is the control technology of the low voltage ride through under the large-scale wind farms.

Guo Quan Wang, he was born on February 21, 1992. He is a master of North China University of Water Resources and Electric Power. He mainly study on direction is the optimal control of wind energy systems.

