Simulation and control of DFIGs connected to the grid

Jian Dou1,*, Shuang Qie1, Xingqi Liu1 and Yi Ren1

1 China Electric Power Research Institute, Beijing, 239000, China.

*Corresponding author’s e-mail: doujian@epri.sgcc.com.cn
*Corresponding author’s ORCID: https://orcid.org/0000-0003-1345-2295

Abstract. Due to the development of renewable energy generations, the reasonable grid-connected control strategy for wind turbines is of great significant. Doubly-fed Induction Generator (DFIG) is one of the variable speed constant frequency (VSCF) motors, which is regarded as the object in this paper. To decouple the control of active and reactive power, the strategies for both grid-side and rotor-side converter are designed. The simulation model of DFIG is built with MATLAB/Simulink software, and the grid-connection simulation experiment is carried out.

1. Introduction
Wind turbine is an important form of renewable energy generations, which captures wind energy from the air and converts it into electric energy [1]. VSCF wind power generation with power electronic equipment has been widely studied and developed. DFIG is one of the mainstream types of VSCF turbines [2-5]. It is similar to the winding Induction motor in structure, which has two sets of windings for stator and rotor [6-8]. It’s called a doubly-fed wind turbine, therefore it can feed to the power grid simultaneously through two channels of generator stator and converter.

As shown in the figure above, the stator of DFIG is directly connected to grid, while the rotor side is connected to grid through two back to back converters to provide excitation, which are called the rotor-side converter (RSC) and grid-side converter (GSC). Among them, the RSC is used to provide excitation for rotor circuit, and adjust active power output from wind turbine stator. The GSC does help to keep DC voltage stability [9].

The control strategy of DFIG is designed. The simulation model of DFIG is built with MATLAB/Simulink software [10], and the grid-connection simulation experiment is carried out.

2. Wind turbines mathematical model
The mathematical model of DFIG is divided into two parts, one is mathematical model of transmission system, the other is mathematical model of DFIG.

The turbine blades can convert wind energy captured from the air into mechanical energy, which is transmitted to DFIG through transmission system to realize the conversion of electric energy. Based on the knowledge of aerodynamics, the relationship between the mechanical input torque T_w and the wind speed V_w is as follows:

\[ T_w = \frac{\rho \pi R_w^2 V_w^2 C_p}{2 \lambda} \]  \hspace{1cm} (1)

\[ \lambda = \frac{W_w R_w}{V_w} \]  \hspace{1cm} (2)
where $\rho$ is air density, $R_w$ is blade radius of the wind turbine, $V_w$ is wind speed, $\lambda$ is tip velocity; $C_p$ is wind energy utilization coefficient, which is related to pitch angle and blade tip speed. The output power is equal to the product of input torque and angular velocity of blades.

$$R_w = T_w W_w = \frac{\rho \pi R_w^2 V_w^3 C_p}{2} \left( \frac{R_w}{\lambda} \right)^3$$  \hspace{1cm} (3)

According to the above formula, when the pitch angle remains constant, in order to maximize the output power, it is needed to adjust tip speed to the optimal tip speed. $W_w$ will change with the wind speed $V_w$.

The stator windings of DFIG all adopt the motor convention, that is, the current inflow is positive. In order to simplify mathematical model, the three-phase static ABC coordinate system can be transformed into two-phase rotating DQ coordinate system through coordinate transformation. Under the synchronous rotating DQ coordinate axis, the voltage equations of the stator windings are:

$$u_{rd} = R_{r rd} i_{rd} + p\psi_{rd} -(\omega_s - \omega_r)\psi_{rq}$$ \hspace{1cm} (4)
$$u_{rq} = R_{r rq} i_{rq} + p\psi_{rq} + (\omega_s - \omega_r)\psi_{rd}$$
$$u_{sd} = R_{s sd} i_{sd} + p\psi_{sd} - \omega_s \psi_{sq}$$
$$u_{sq} = R_{s sq} i_{sq} + \omega_r \psi_{ds}$$  \hspace{1cm} (5)

In the formula, subscript $s$ represents the quantity at stator side, $r$ represents the quantity at rotor side, $p$ represents the differential symbol, $\omega_s$ is synchronous speed, and $\omega_r$ is rotor speed.

The flux equation is:

$$\psi_{rd} = L_s i_{rd} + L_m i_{rd}$$
$$\psi_{rq} = L_r i_{rq} + L_m i_{rq}$$
$$\psi_{sd} = L_s i_{sd} + L_m i_{rd}$$
$$\psi_{sq} = L_r i_{sq} + L_m i_{rq}$$  \hspace{1cm} (6)

In the formula, $L_s$ represents the equivalent self-inductance of the stator winding under synchronous rotating DQ axis, $L_r$ represents the equivalent self-inductance of the rotor-side winding under the synchronous rotating DQ axis, and $L_m$ represents the equivalent mutual inductance between coaxial windings of the synchronous rotating DQ axis.

The relationship between voltage and current can be obtained according to voltage and flux equation. Therefore, electromagnetic torque equation is:

$$T_{em} = \frac{3}{2} p L_m (i_{sq} i_{rd} - i_{sd} i_{rq})$$  \hspace{1cm} (7)

where $p$ represents the polar logarithm of the DFIG.

The rotor motion equation is:

$$\frac{J}{p} \frac{\dot{\theta}}{} = T_w - T_{em}$$  \hspace{1cm} (8)

where $T_w$ is input torque, and $T_{em}$ is electromagnetic torque.

The stator side power equation is:

$$P_s = \frac{3}{2} (u_{sd} i_{sd} + u_{sq} i_{sq})$$
$$Q_s = \frac{3}{2} (u_{sq} i_{sd} - u_{sd} i_{sq})$$
$$P_r = \frac{3}{2} (u_{rd} i_{rd} + u_{rq} i_{rq})$$
$$Q_r = \frac{3}{2} (u_{rq} i_{rd} - u_{rd} i_{rq})$$  \hspace{1cm} (9)
3. **PWM converter control strategy**

The converter channel consists of two back-to-back converters. Among that, one is the GSC to stabilize voltage, and the other is the RSC that provides excitation current to rotor circuit and regulates active power output. The control strategy adopts double closed-loop structure, which is including both outer loop voltage control and inner loop current control. The outer loop control is used to stabilize voltage and to set the value of the current signal related to the active power. The inner loop current control does help to achieve the current output tracking set value.

3.1. **Vector control strategy for GSC**

Specifically, the vector control strategy of GSC is according to grid voltage orientation technology. Because the rotor power is equal to power exchanged between GSC and power grid. Therefore, the rotor power equations are written as:

\[
\begin{align*}
P_r &= \frac{3}{2} (u_{gd} i_{id} + u_{gq} i_{iq}) \\
Q_r &= \frac{3}{2} (u_{gd} i_{id} - u_{gq} i_{iq})
\end{align*}
\]

where \(u_{gd}\) is the D-axis component of grid voltage under synchronous rotating DQ coordinate axis, \(u_{gq}\) is the Q-axis component, \(i_{id}\) is D-axis current component of GSC, and \(i_{iq}\) is Q-axis current component.

After grid voltage orientation \(u_{gd} = u_g\) and \(u_{gq} = 0\), the power equation of the rotor can be rewritten as:

\[
\begin{align*}
P_r &= \frac{3}{2} u_{gd} i_{id} \\
Q_r &= -\frac{3}{2} u_{gd} i_{iq}
\end{align*}
\]  

The grid voltage orientation technology decouples rotor active and reactive power, so that active power is only related to D-axis current, and the reactive power is only related to Q-axis current.

Assuming that power loss of GSC is not taken into account, and the power on both sides of the direct-alternating converter is equal, the relationship between DC bus voltage and D-axis current is established. Thus, the voltage \(u_{dc}\) is controlled by D-axis current \(i_{id}\). Then relationship between current of D axis and converter control voltage can be established to obtain the control voltage. Therefore, the converter control voltage is expressed as:

\[
\begin{align*}
u_{id} &= u_{gd} - (R_g + pL_g) i_{id} + \omega_s L_s i_{iq} \\
u_{iq} &= -(R_g + pL_g) i_{iq} - \omega_s L_s i_{id}
\end{align*}
\]

In the above formula, the control voltage \(u_{id}, u_{iq}\) of the converter and the input current \(i_{id}, i_{iq}\) of the converter are not fully decoupled, so intermediate variables are introduced.

\[
\begin{align*}
u_d &= (R_g + pL_g) i_{id} \\
u_q &= (R_g + pL_g) i_{iq}
\end{align*}
\]

The expression of the converter control voltage can be rewritten as:

\[
\begin{align*}
u_{id} &= u_{gd} - u_d + \omega_s L_s i_{iq} \\
u_{iq} &= -u_q - \omega_s L_s i_{id}
\end{align*}
\]

With the introduction of intermediate variable, the control voltage is fully decoupled step by step. Based on the above discussion, the control strategy for keeping the voltage stability can be realized. In order to ensure that the converter emits as much active power as possible, the GSC is generally set to work near unit power factor.

\[
\begin{align*}
u_{id} &= u_{gd} - u_d + \omega_s L_s i_{iq} \\
u_{iq} &= -u_q - \omega_s L_s i_{id}
\end{align*}
\]
3.2. Virtual synchronous control strategy for RSC

The task of RSC is to control active power, reactive power respectively. The essence of virtual synchronous strategy is to simulate rotor motion equation of synchronous generator and realize synchronous grid-connected operation between DFIG and the power grid.

![Figure 1. Active power control](image1)

The control scheme establishes a connection between active power control of DFIG and excitation voltage phase angle. When the actual reactive power output of stator deviates from reference value, the amplitude of excitation voltage is obtained through the proportional integration link.

![Figure 2. Reactive power control](image2)

The control scheme establishes a connection between reactive power control of DFIG and amplitude of rotor excitation voltage. The active and reactive power output are related to phase angle and amplitude of rotor excitation voltage respectively, so they are able to track reference values of the power demand by controlling excitation voltage.

4. Control Strategy Simulation Based on Simulink

Asynchronous Machine pu Units1 module in Simulink is selected for the DFIG, the pole logarithm is 3 pairs, the output power is 1.5MVA, the bus voltage is 380V, the frequency is 50Hz, resistance of stator winding is 0.023pu, inductance is 0.18pu, the rotor winding is 0.016pu, the inductance is 0.16pu, and the mutual inductance of stator winding is 2.9pu. The following figure shows the overall control framework of DFIGs connected to the grid. Among that, the main part is the strategy for back-to-back converters.

![Figure 3. Overall grid-connection control model of DFIG](image3)
The pulse control signals for the GSC and RSC voltages are the output of control system.

The internal control system mainly includes GSC control and RSC control. The output voltage control signal of two converter control systems is converted to two-phase static coordinate system by coordinate transformation, and PWM wave of the converter control voltage signal is obtained by SVPWM modulation method. The GSC adopts vector control method of grid voltage orientation, and control system is double closed loop control. Before voltage control signal of GSC is modulated by SVPWM, it needs to be transformed from the two-phase synchronous rotating DQ coordinate system to two-phase static αβ coordinate system by 2R/2S coordinate transformation. The coordinate conversion unit of the output voltage control signal of the control unit on the grid side is shown in the figure below:

![Figure 5. 2R/2S coordinate conversion unit for the output control signal of grid-side voltage](image)

The voltage signal output by grid-side control unit is converted to two-phase static coordinate system, and modulated by SVPWM control unit, then the PWM wave of the GSC control voltage is got. The structure diagram of RSC control system is similar to that of the GSC control system, which also includes control unit, coordinate conversion unit, and SVPWM unit. The control unit of RSC adopts virtual synchronous control, which realizes following control of the set values of the output active power and reactive power of DFIG. Before voltage control signal of RSC is modulated by SVPWM control system, it needs coordinate transformation.

![Figure 6. 3S/2S coordinate conversion unit for the output control signal of rotor-side voltage](image)
The voltage signal output by RSC control unit is converted to two-phase static coordinate system, and modulated by SVPWM control unit, then the PWM wave of the GSC control voltage is obtained. The structure of SVPWM control unit is exactly same as the stator side.

5. Results and Analysis
Set the simulation running time to 5s. The per-unit values of three-phase current of stator winding ABC and rotor winding ABC are shown in the below:

![Figure 7. Per-unit value of stator three-phase current](image)

![Figure 8. Per-unit value of rotor three-phase current](image)

Next, the active and reactive power output of DFIG are demonstrated in the figure below:

![Figure 9. Active and reactive power output](image)

![Figure 10. Bus voltage UDC](image)
6. Conclusion
The simulation results demonstrate that power output is stable when doubly-fed wind generator is controlled by grid-connected technology proposed. The active and reactive power outputs of stator side are able to follow set value, indicating the effectiveness and correctness of RSC control strategy proposed. The DC bus voltage U_{DC} between the GSC and RSC is observed, and its waveform remains stable after a period of time, which shows the validity and correctness of GSC control strategy proposed.

Acknowledgments
The authors would like to thank the support of State Grid Science and technology project: Research on Key Technologies of Electricity Information Collection Facing Energy Internet(5600-201955457A-0-00).

References
[1] Wang, T., Ding, L., Yin, S., (2015). A new control strategy of DFIG-based wind farms for power system frequency regulation. In 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Brisbane, pp. 1-5.
[2] Shehata, E. G., (2014) Direct power control of DFIGs connected to harmonically grid voltage conditions. In 7th IET International Conference on Power Electronics, Machines and Drives (PEMD), Manchester, pp. 1-6.
[3] Lianbing L., Peng, Z., Zhiguo, Z., (2013) No-load grid connection strategy research of DFIG based on close loop of voltage. In 2013 25th Chinese Control and Decision Conference (CCDC), Guiyang, pp. 2701-2704.
[4] Camara, M. S., Camara, M. B., Dakyo, B., (2013) Modeling and control of the offshore wind energy system based on 5MW DFIG connected to grid. In 2013 Africon, Pointe aux Piments, Mauritius, pp. 1-5.
[5] Moussaoui, M., Mezouar, A., Boumediene, L., (2015) Analytical study of grid connected DFIG based wind turbine under grid fault conditions. In 2015 7th International Conference on Modelling, Identification and Control (ICMIC), Sousse, pp. 1-6.
[6] Zhang, Y., Raheja, U., (2019) An Optimized Virtual Synchronous Generator Control Strategy for Power Decoupling in Grid Connected Inverters. In 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, pp. 49-54.
[7] Li, M. X., Wang, Y., Xu, N. Y., (2017) A consistent dynamic response control strategy for virtual synchronous generator. In 2017 IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017 - ECCE Asia), Kaohsiung, pp. 1570-1574.
[8] WANG, Y., LUO, L., LI, Y., (2019) Research on Control Strategy of Improved Virtual Synchronous Generator for Improving the Operating Capability of Passive Isolated Islands. In 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), Chengdu, pp. 1485-1490.
[9] Zhang, Y., Zhou, X. (2019) Research on Microgrid Control Strategy Based on Improved Virtual Synchronous Power Generation Technology. In 2019 14th IEEE Conference on Industrial Electronics and Applications (ICIEA), Xian, pp. 708-712.
[10] Su, Z. Y., Wang, P., Song, P. X., (2014) Research on control strategy of DFIG rotor side converter. In 2014 IEEE Transportation Electrification Conference and Expo Asia-Pacific (ITEC Asia-Pacific), Beijing, pp. 1-5.