On Closed-loop Decoupling Control Strategy for Grid-connected Double-fed Generator

CHE Yanbo[1] WANG Yu[2] WANG Chengshan[3]

Abstract - This paper first introduces the basic theory of double-fed wind power generation system, and builds the mathematical model in two-phase rotary coordinate system. In order to deal with the strong coupling problems, the vector control technology is introduced, and the idea of double-fed generator stator-flux-oriented vector control strategy is presented. Based on the two-phase simplify mathematical model and stator-flux-oriented vector control strategy, no-load grid-connected control strategy and power control strategy after grid-connected for double-fed generator are introduced: they both use dual-channel closed-loop decoupling control frame, both consider rotor current's mt component as the inner-loop. By passing key control variables, the flexible connectivity between generator and grid can be carried out and the soft switch of the control strategy also can be achieved during grid-connected. In MATLAB/SIMULINK, the simulation model is set up, and the results show that the control strategy is correct and effective.

Keywords - Closed-loop decoupling control, double-fed inductor generator, grid-connected, maximum power point tracking, output power control, rotor current.

I. INTRODUCTION

At present, the double-fed wind-power generation system has been increasingly widely used, its motor is double-fed inductor generator(DFIG).It has some advantages, including that it allows the prime mover operates in a wider speed range, which can simplify the adjustment device and reduce the mechanical stress during changing motor speed. Moreover, DFIG system's frequency converter occupies only part of the rated capacity, which reduces the frequency conversion device's size and cost [1].

DFIG wind power generation system has become a new focus in the renewable energy power generation field, and its control strategy is the key problem, including the control strategy before and after grid-connected. Most researchers have researched the two control methods independently. This article will summarize the previous researchers' experience, study the decoupling closed-loop control structure, and achieve the soft switch of the two control strategy**.**

II. THE BASIC THEORY FOR DFIG

A. The Basic Structure for DFIG

DFIG's structure is similar to the wound induction motor. Its stator and rotor are both installed with three-phase symmetric winding. Its stator winding is connected to the power grid through a transformer, and it is excited by symmetric three-phase power with fixed frequency [2]. Its rotor winding is excited by symmetric three-phase power with variable frequency. The frequency can be regulated by back-to-back PWM converter, including rotor side converter and grid side converter. They are both controlled by DSP controller. The basic structure for DFIG system is showed in Fig. 1.

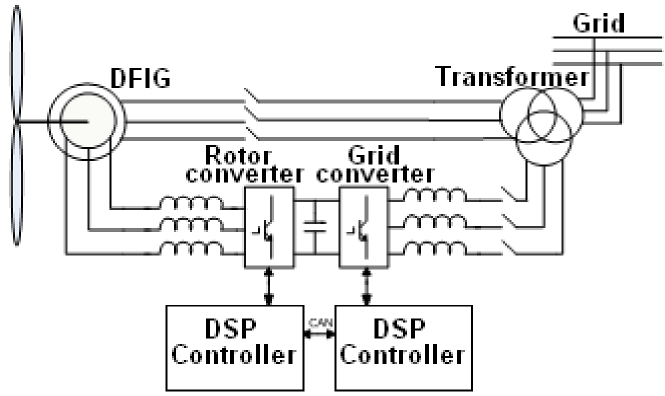

Fig. 1: DFIG system structure

B. The Mathematical Model

The mathematical model for DFIG with synchronous rotary coordinate system is converted from the three-phase model through coordinate transformation [3]. Assume that the voltage and current of the stator side is directed by generator; Voltage and current of the rotor side is directed by motor. Based on the aforementioned assumptions we get the DFIG mathematical model in synchronous rotation coordinates as (1) - (6).

Voltage equation:

$$\begin{cases} u_{ms} = -R_s i_{ms} - p\psi_{ms} + \omega_1 \psi_{ts} \\ u_{ts} = -R_s i_{ts} - p\psi_{ts} - \omega_1 \psi_{ms} \end{cases} \quad (1)$$

$$\begin{cases} u_{mr} = R_r i_{mr} + p\psi_{mr} - \omega_2 \psi_{tr} \\ u_{tr} = R_r i_{tr} + p\psi_{tr} + \omega_2 \psi_{mr} \end{cases} \quad (2)$$

Flux equation:

$$\begin{cases} \psi_{ms} = L_s i_{ms} - L_m i_{mr} \\ \psi_{ts} = L_s i_{ts} - L_m i_{tr} \end{cases} \quad (3)$$

$$\begin{cases} \psi_{mr} = -L_m i_{ms} + L_r i_{mr} \\ \psi_{tr} = -L_m i_{ts} + L_r i_{tr} \end{cases} \quad (4)$$

Electromagnetic torque equation:

$$T_e = n_p L_m \left(i_{ts} i_{mr} - i_{ms} i_{tr} \right) \quad (5)$$

Equations of motion:

$$T_m - T_e = J \frac{1}{n_p} \frac{d\omega_r}{dt} \quad (6)$$

Where, u: voltage, i: current, ψ: flux, L: self-inductance, L_m: mutual-inductance between stator and rotor, subscript s and r: stator side and rotor side, subscript m and t: m-axis component and t-axis component in synchronous rotary coordinate system, J: rotational inertia, n_p: pole pairs, T_{em}, T_m: electromagnetic torque, mechanical torque.

The paper first received 31 Dec 2008 and in revised form 22 May 2009.
Digital Ref: Digital Ref: A170701283.

[1 2 3] School of Electrical Engineering & Automation, Tianjin University, Tianjin, China Email: ybche@tju.edu.cn; wangyu.806@163.com; cswang@tju.edu.cn.

C. Decoupling Control

For AC excited double-fed generator system, stator and rotor current are the alternating variables of the power frequency and slip frequency, so the system is a strong coupling multi-variable system. If we simply control the AC current by closed-loop control method without decoupling, the result will not be ideal [4]. In order to achieve the decoupling control for DFIG, referring to the vector control idea, the actual AC variable can be broke into two independent and vertical components, which are controlled by closed-loop respectively. Closed-loop control strategy with decoupling can get better control performance [5].

D. The Stator-flux-oriented Control Strategy

The stator winding is connected directly to the infinite power grid, so the stator voltage's amplitude and frequency can be regarded as constant approximately [6]. If we orient the m-axis by stator flux vector, so do the stator voltage vector and the negative t-axis the stator flux. By stator-flux-oriented method, we can get (7)-(8).

$$\begin{cases}\psi_{ms} = \psi_1 \\ \psi_{ts} = 0\end{cases} \tag{7}$$

$$\begin{cases}u_{ms} = 0 \\ u_{ts} = -u_1\end{cases} \tag{8}$$

We can get (9) by linking (7), (8) into (2).

$$\begin{cases}p\psi_1 = 0 \\ \psi_1 = u_1 / \omega_1\end{cases} \tag{9}$$

From (9), it shows that stator flux is a constant, which is related with voltage and frequency.

III. GRID-CONNECTED CONTROL

A. No-load grid-connected control

Before DFIG system achieves grid-connected operation, stator voltage's amplitude, frequency and phase must be as same as grid side. By controlling the rotor side converter can adjust DFIG rotor excitation current, and control stator voltage indirectly [7]. Assume that there is no-load state before grid connected, that is, $i_{ms}=i_{ts}=0$.Based on $i_{ms}=i_{ts}=0$ and (1)-(4), we can get (10)-(13), which is the no-load mathematical model for DFIG.

$$\begin{cases}\psi_{ms} = -L_m i_{mr} \\ \psi_{ts} = -L_m i_{tr}\end{cases} \tag{10}$$

$$\begin{cases}\psi_{mr} = L_r i_{mr} \\ \psi_{tr} = L_r i_{tr}\end{cases} \tag{11}$$

$$\begin{cases}u_{ms} = -p\psi_{ms} + \omega_1 \psi_{ts} \\ u_{ts} = -p\psi_{ts} - \omega_1 \psi_{ms}\end{cases} \tag{12}$$

$$\begin{cases}u_{mr} = R_r i_{mr} + p\psi_{mr} - \omega_2 \psi_{tr} \\ u_{tr} = R_r i_{tr} + p\psi_{tr} + \omega_2 \psi_{mr}\end{cases} \tag{13}$$

We can get (14) by linking (7) into (11).

$$\begin{cases}i_{mr} = -\psi_1 / L_m \\ i_{tr} = 0\end{cases} \tag{14}$$

Linking (14) into (13), we can get (15).

$$\begin{cases}u_{mr} = (R_r + L_r p) i_{mr} \\ u_{tr} = \omega_2 L_r i_{mr}\end{cases} \tag{15}$$

Based on no-load mathematical model, a closed-loop decoupling control strategy is presented [8]. Through calculating power grid voltage u_1 and synchronous angular frequency ω_1, we can get flux ψ_1. According to (14), the rotor current m-axis component i_{mr}^* is calculated, the rotor current m-axis component i_{tr}^* should be controlled to be zero. Based on the relationship between rotor voltage and rotor current, which is showed as (15), the rotor current's mt component is selected as inner-loop control variable for PI regulator. The error between i_{mr}^*, i_{tr}^* and i_{mr}, i_{tr} are regulated by PI proportion, the result, which add the compensation voltage are the rotor voltage anticipant value u_{mr}^* and u_{tr}^*. The rotor voltage mt component u_{mr}^* and u_{tr}^* can be changed to the rotor voltage in three-phase coordinate system. The three-phase rotor voltage component can be used to generate the necessary command signals for rotor power's exciting control. According to that, we can get the DFIG no-load grid-connected control model, as in Fig. 2.

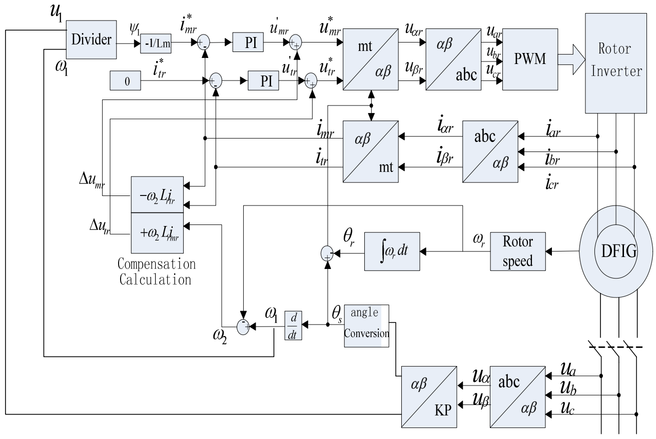

Fig. 2: DFIG no-load grid-connected control model

B. The Output Power Control after Grid-connected

The output power control after grid-connected for DFIG is aim to carry out output active power and reactive power's decoupling control, and achieve Maximum Power Point Tracking (MPPT) technology. The MPPT basic principle is to get the most reasonable rotor speed through controlling the DFIG output active power [9]. So power control is the precondition of MPPT. Linking (7)-(9) to (1)-(4), we can get (16)-(18).

$$\begin{cases}u_{mr} = u'_{mr} + \Delta u_{mr} \\ u_{tr} = u'_{tr} + \Delta u_{tr}\end{cases} \tag{16}$$

$$\begin{cases}u'_{mr} = (R_r + bp) i_{mr} \\ u'_{tr} = (R_r + bp) i_{tr}\end{cases} \tag{17}$$

$$\begin{cases}\Delta u_{mr} = -b\omega_2 i_{tr} \\ \Delta u_{tr} = a\omega_2 \psi_1 + b\omega_2 i_{mr}\end{cases} \tag{18}$$

u_{mr}' and u_{tr}' is the decoupling component for rotor voltage and current, $\triangle u_{mr}$ and $\triangle u_{tr}$ is the compensation for eliminating cross-coupling between the rotor voltage and current. Dividing the rotor voltage into the decoupling component and the compensation can simplify the control process [10].

The whole system is a dual-closed-loop structure. The outer ring is for the power control, and the inner ring is for the current control. In power ring, the error between the power command P^*, Q^* and the feedback value P and Q are calculated by power PI regulator, the results are the reactive component i_{mr}^* and the active component i_{tr}^*, which are compared with their feedback value, then the error is calculated by current PI regulator, the output values are the voltage component u_{mr} and u_{tr}, which add $\triangle u_{mr}$ and $\triangle u_{tr}$ are the rotor voltage command u_{mr}^* and u_{tr}^*. According to that, we can get the DFIG power control model after grid-connected, as in Fig. 3.

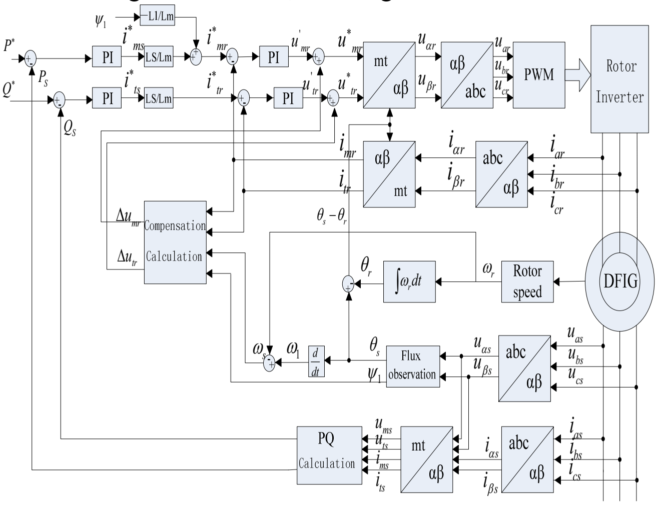

Fig.3: DFIG power control model after grid-connected

C. The Soft Switch before and after Grid-connected

According to compare the control strategy before and after grid-connected, it is known that both control methods adopt the idea of stator-flux-oriented vector control [11], and they both get command signals u_{mr}^* and u_{tr}^* by controlling the rotor current i_{mr} and i_{tr}, u_{mr}^* and u_{tr}^* can be applied to generate SVPWM control variable. So they have same current inner-loop PI regular, both of them apply closed-loop decoupling control structure [12]. Based on that, it proves that the basic control method before and after grid-connected is similar to each other, so the most important problem is the transfer of key variable when grid-connecting.

The rotor current i_{mr} and i_{tr} is the pivotal variable, which are the inner-loop under-control variables. So the value of rotor current i_{mr} and i_{tr} before grid-connected should be passed to the control model when grid-connecting. Besides that, other variables $i_{ms}=i_{ts}=0$, $T_m=T_e=0$ and $P=Q=0$ before grid-connected also need to transfer. When these values have been passed, the no-load grid-connected mode will be disabled, and the output power control model begins to run, the whole model works in order.

IV. Simulation

A. Simulation Model

According to the front analysis, the simulation model is set up in MATLAB/SIMULINK. The simulation parameters are shown in Table I. The whole model is shown as Fig. 4, which includes two models. One is no-load grid-connected model, as in Fig. 5. The other is power control model after grid-connected, as in Fig.6. The simulation time is set to 10s. The state transfer switch is automatic, the switch time is set to 1s. When switch state change, rise signal transfer from 1 to 0, it disables the no-load model, at the same time, it enables power control model. When no-load model ends, it will pass the state value i_{mr} and i_{tr} to next model. The power control model will receive the value, and begin to run.

In order to prove MPPT control, we set reactive command value as 200W, change active power command value by changing the wind speed. The initial wind speed is set to 6m/s, then to 5m/s at 4s, in the end to 7m/s at 7s.

TABLE. Simulation parameters

Stator Resistance	1.920Ω
Rotor Resistance	2.575Ω
Stator self-Inductor	0.240 H
Rotor self-Inductor	0.240 H
Mutual-inductance between stator & rotor	0.234 H
Pole pairs	2

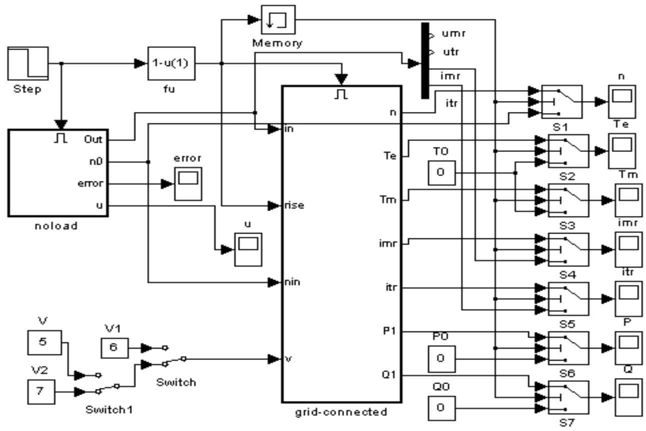

Fig. 4: Whole simulation model

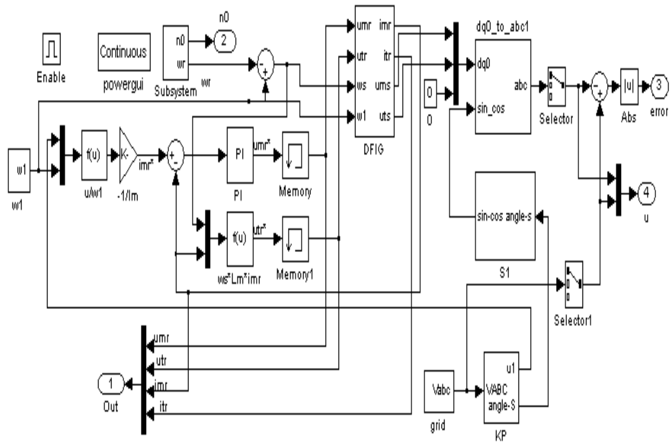

Fig. 5: No-load simulation model

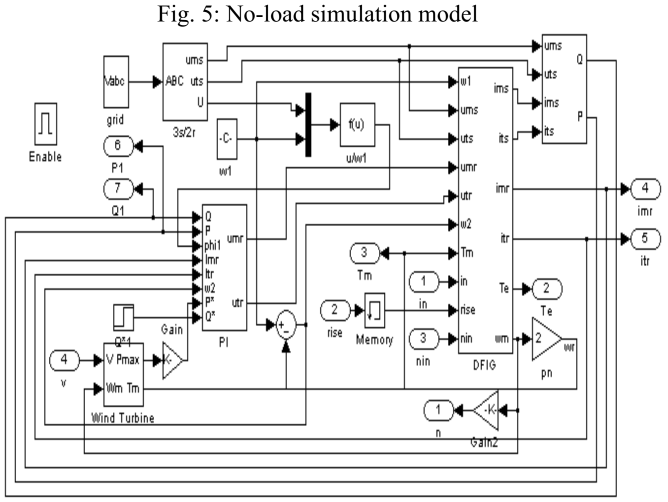

Fig. 6: Power control simulation model

B. Simulation Result

Fig. 7 is the simulation result of stator voltage and grid voltage (a-grid voltage, b- stator voltage), The simulation result shows that stator voltage can follow grid voltage after 0.02s. It proves that the no-load model satisfy the grid-connected condition.

Figs. 8 and Fig. 9 are the simulation results for DFIG active power and reactive power respectively. According to MPPT theory, one wind speed value corresponds to an active power value. Fig. 8 shows that the active power value can follow wind speed's change. Fig. 9 shows that the reactive power remains 200W. Those results prove the model achieve power control well.

Figs. 10 and Fig. 11 are the simulation results of rotor current i_{mr} 、i_{tr}. The simulation result shows that the rotor current has fulfilled transfer from no-load model to power control model. The rotor current t-axis component i_{tr} and DFIG active power are corresponding to each other, so are the rotor current m-axis component i_{mr} and DFIG reactive power. It proves the decoupling closed-loop control strategy is effective.

Figs. 12 and Fig. 13 are the simulation results of DFIG electromagnetic torque and mechanical torque respectively. Fig. 14 is the simulation result of rotor speed. Figs. 12-14 also can prove the validity of MPPT control. All of them can follow wind speed's change.

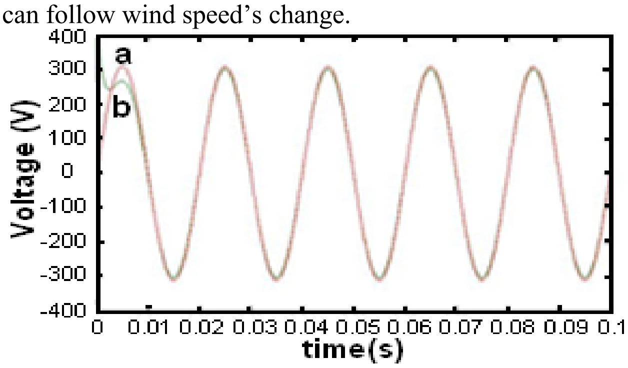

Fig. 7: Stator voltage and grid voltage simulation result

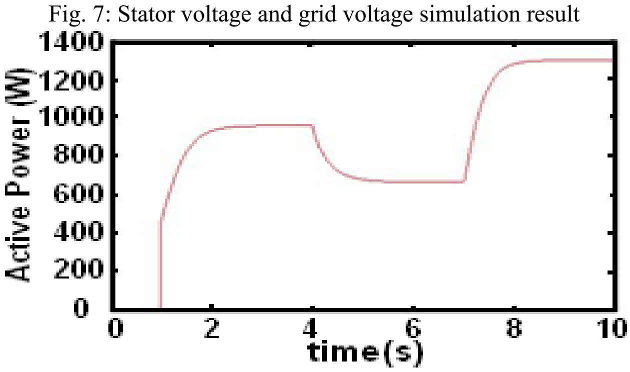

Fig. 8: DFIG active power simulation result

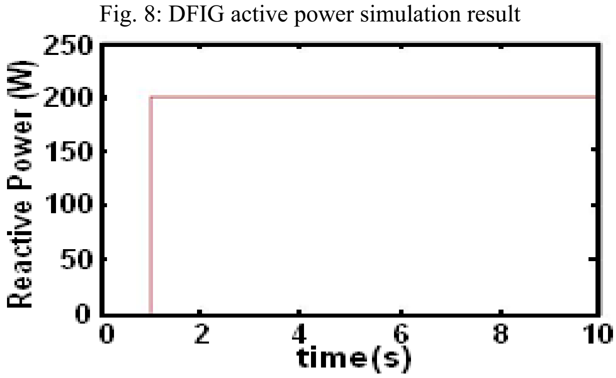

Fig. 9: DFIG reactive power simulation result

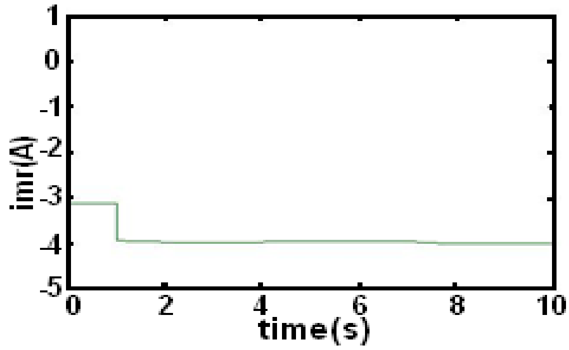

Fig. 10: Rotor current m-axis component i_{mr} simulation result

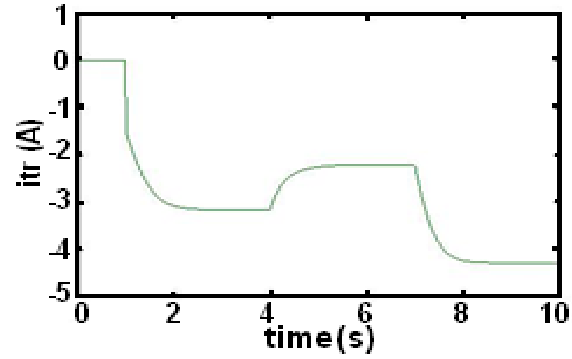

Fig. 11: Rotor current t-axis component i_{tr} simulation result

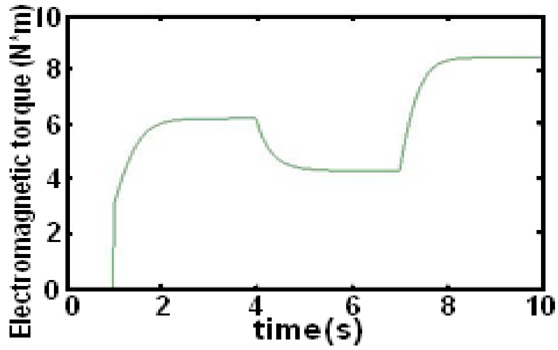

Fig. 12: DFIG electromagnetic torque simulation result

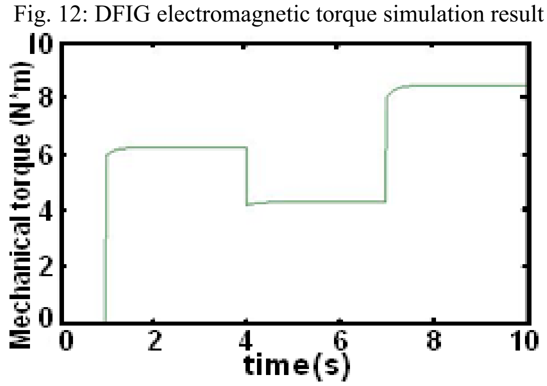

Fig. 13: Mechanical torque simulation result

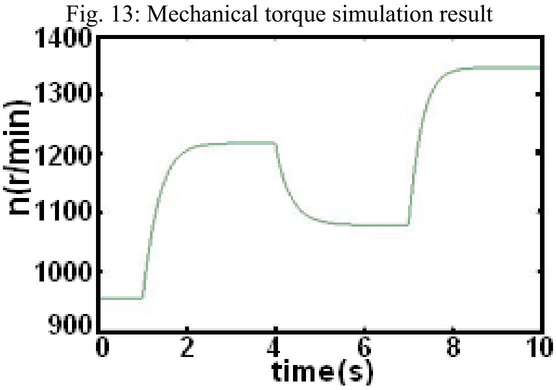

Fig. 14: Rotor speed simulation result

V. CONCLUSION

The simulation results show that the closed-loop decoupling control strategy on wind power generation is effective. Before grid-connected, no-load control model can satisfy grid-connected condition by controlling rotor current i_{mr} and i_{tr}. The stator voltage's amplitude and frequency are as same as grid. When grid-connected operation happens, model can achieve the transfer for rotor current decoupling component i_{mr} and i_{tr}, and realize the soft switch between two control models. The out power control model after grid-connected can achieve active and reactive power respectively decoupling control and MPPT control also by regulating rotor current i_{mr} and i_{tr}. They both adopt closed-loop decoupling control strategy, the simulation results prove the strategy is correct and it can be applied for double-fed wind power system.

ACKNOWLEDGMENT

This work is supported by Youth Foundation Project of National Natural Science Foundation Committee "Distributed Generation System Simulation and Optimization Control" (NO.50625722); National Basic Research Program of China (973 Program) "Distributed Generation Supply System Pertinent Foundational Research" (NO.2009CB219700), and National Natural Science Foundation Key Project "Key Technique Research of Distributed Generation Micro-Grid System Control and Protection" (NO. 50837001).

REFERENCES

[1] T. Ackermann, L. Soder "An overview of wind energy status 2002", Renewable and Sustainable Energy Reviews, Vol. 6, No. 1-2, 2002, pp. 67-127.

[2] S. Muller, M. Deicke, R.W. De Doncker "Doubly Fed Induction Generator Systems for Wind Turbines", IEEE Industry Applications Magazine, Vol. 8, No. 3, May/June 2002, pp. 26-33.

[3] R. Pena, J. C. Clare and G. M. Asher "Doubly fed induction generator using back-to-back PWM converters and its application to variable speed wind-energy generation", IEE Proc.-Electr. Power Appl., Vol. 143, No 3, May 1996, pp. 231-241.

[4] A. Petersson, "Analysis, Modeling and Control of Doubly-Fed InductionGenerators for Wind Turbines", Chalmers Univ. Goteborg, Sweden, 2005.

[5] J. G. Slootweg, S. W. H. de Haan, H. Polinder and W. L. King "General model for representing variable speed wind turbines in power system dynamics simulations", IEEE Trans. On Power Systems, Vol. 18, No. 1, February 2003, pp. 144-151.

[6] D. I. Kim, I. J. Ha and M. S. Ko. "Contrl of induction motor via feedback linearization with input-output decoupling", Int. J. Contr. Vol. 51, No. 4, Mar 1990, pp. 863-883.

[7] Y. Lei, A. mullane, G. Lightbody and R. Yacamini, "Modeling of the Wind Turbine with a Doubly Fed Induction Generator for Grid Integration Studies", IEEE Transactions on Energy Conversion. Vol. 21, No. 1, 2006, pp. 257-264.

[8] Hui Li and Zhe Chen "A new current control strategy of maximizing the generated power from a doubly fed induction generator system", 12th International Power Electronics and Motion Control Conference, 2006, pp. 1557 – 1562.

[9] F. Mei and B. C. Pal, "Modeling and small-signal analysis of a grid connected doubly-fed induction generator", Proceedings of IEEE PES General Meeting 2005, San Francisco, USA, Vol. 3, 2005, pp. 2101-2108.

[10] M. Yamamoto and O. Motoyoshi "Active and reactive power control for doubly-fed wound rotor induction generator", IEEE Trans. on Power Electronics, Vol.6, No. 4, Aug. 1991. pp. 624-629.

[11] Y. Tang and L. Xu "A flexible active and reactive power control strategy for a variable speed constant frequency generating systmmm", IEEE Transactions on Power Electronics, Vol. 10, No. 4, 1995, pp. 472 -478.

[12] Nitin N. Joshi and N. Mohan "New scheme to connect DFIG to power grid", The 32nd Annual Conference of the IEEE Industrial Electronics Society, 2006, pp. 4225-4230.

BIOGRAPHIES

Che Yanbo received his B.E degree from Zhejiang University in 1993, and obtained his M.E and PhD degrees both from Tianjin University in 1996 and 2002 respectively. The major fields of study were Industrial Automation and Power System respectively.
He joined in the School of Electrical Engineering & Automation, Tianjin University since 1996 and was appointed as Lecturer, Associate Professor in 1998 and 2003 respectively. Now he is the tutor of graduate students majoring in Power Electronics and Drives.
In recent years his research interests focus on the field of renewable energy, especially on the inverter technology for the micro-grid operation. He has taken charge of many projects in the field of electrical engineering and control, so far he has published over 50 papers.

Wang Yu was born on June 28th, 1984. He was form ShenYang, Liaoning Province, P.R. China. He obtained both his B.E. and M.E. degrees from School of Electrical Engineering and Automation, Tianjin University in 2007 and 2009 respectively. His research interests are all aspects of Power Electronics and Electric Drive, particularly in Doubled-fed inductor generation control.