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Power Control of a Doubly Fed Induction Machine for Wind Energy Generation without Rotational Transducers

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풍력발전을 위한 회전변류기가 없는 이중여자 유도기의 전력제어

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ABSTRACT

This paper describes variable speed drive and power control of a doubly fed induction machine(DFIM) for wind energy generation without rotational transducers. A stator flux orientation scheme and rotor speed estimator are employed to achieve decouple control of active and reactive power. To verify the theoretical analysis, a 5-hp DFIM prototype system and PWM power converter are built. Results of computer simulation are presented to support the discussion.

Key Words : Power control, Stator flux orientation, Rotor speed estimator

I. Introduction

The capability of capaturing wind energy is essential to variable speed wind power generating system. In recent years, doubly fed induction machine(DFIM) with field orientation control(FOC) is very attractive to the variable speed wind power generating system because it is effectively possible to improve the capturing wind energy capability[1)-3)]. The fundamental feature of a variable speed wind power generating system is that the power processed by the power converter is a fraction of the total system power and the output power must be always maintained at a constant frequency. Using only a small power converter, it is possible to achieve active and reactive power control within a certain speed range(from cut-in to cut-out speed).

If rotor speed is over synchronous speed, the output power is recovered to power source from power converter connected in rotor field and if not, slip power flow will be reversed. So real generating power is the total of stator and rotor output power. To achieve the slip power control, a rotor angle and synchronously rotating angle are necessary for a variable speed wind power generating system. So we have to find the two kinds of angle. Due to connect the stator of a DFIM to the power grid, stator flux

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always keeps constant[5]. It is easy to find the synchronously rotating angle by stator flux estimation and the rotor angle if uses a rotor position sensor. But it is not easy to construct the rotor position sensor to large generator shaft with mechanical gear system. This is a big disadvantage. To overcome the former disadvantages, the proposed scheme dose not have rotor position sensor. For finding the rotor position information, stator flux and speed estimator are applied to the system[4)-5)].

With the result of this system, it is possible to provide a convenient regulation of active and reactive power flow between the power grid and the variable speed generator[1)-3)]. In this paper, the concept and implementation of FOC of a DFIM for a variable speed drive and wind power generating system without position sensor are proposed. Independent control of active and reactive power and variable speed drive are presented. To verify the proposed method, a 5-hp DFIM prototype system and PWM power converter are built. Results of computer simulation are presented.

II. Variable Wind Power Generating System

The efficiency of wind power generating system will be decreased if use the fixed turbine speed system under the variable wind speed region. Because it can not capature the maximum power from wind energy as shown in Fig.1. As illustrated in Fig. 1, the output of electrical power is related to the cube of the wind speed[6)].

$$P_w = \frac{1}{2} \cdot \rho \cdot C_p \cdot A \cdot V^3 \cdot \eta \qquad (1)$$

where ρ : specific mass of air [kg/m^3]

A : blade area [m^2]

V : wind speed [m/sec]

C_p : coefficient of output power

η : system efficiency

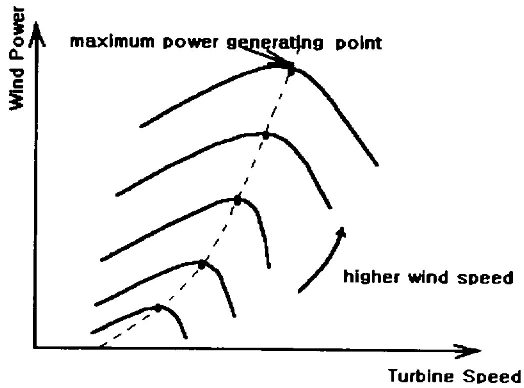

Fig. 1 Wind turbine power characteristics

C_p depends on the particulars of blade design. So the efficiency of this system is depend on how to capature the wind energy in variable wind speed region. In oredr to capature the maximum power energy, we have to control the system with maximum power tracking point in accordance to variable wind speed as illustrated in Fig.1. Doubly fed induction machine and doubly excited reluctance machine are possible to apply to this system. But only prototype of a doubly excited reluctance machine is developed so it is impossible to apply to industrial field. On the other hand, doubly fed induction machine has many kinds of large ratings. So this machine has a big advantage in variable wind speed generating system. The configuation of a variable wind speed generating system with a doubly fed induction machine system is shown in Fig. 2. The major component of the system is a wound rotor induction machine which needs to be excited at both the stator and rotor terminals. It is common practice that the stator winding is connected to the power grid directly, while the rotor winding is connected to the power supply through a variable frequency power converter under variable wind speed.

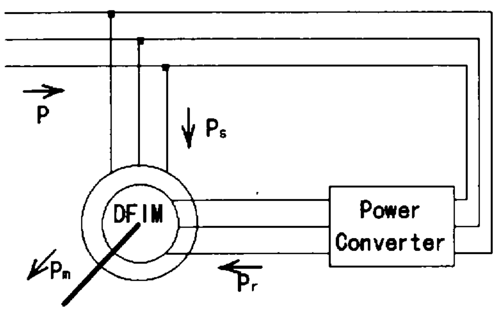

Fig. 2 Power control of slip power

2.1 Field Orientation Control

In variable wind speed generating system, stator voltage and current has constant frequency while the rotor speed is changing by wind speed. And amplitude of stator voltage almost has constant because the stator side is connected to power grid. This means that this machine has constant stator flux. For field orientation control of this machine, the dynamic equations of a DFIM in the arbitary rotating d-q reference frame are as given below:

$$V_{ds}= R_s\, i_{ds}+\frac{d\lambda_{ds}}{dt}- w_e\,\lambda_{qs} \quad (2)$$

$$V_{qs}= R_s\, i_{qs}+\frac{d\lambda_{qs}}{dt}- w_e\,\lambda_{ds} \quad (3)$$

$$V_{dr}= R_r\, i_{dr}+\frac{d\lambda_{dr}}{dt}-(w_e- w_r)\,\lambda_{qr} \quad (4)$$

$$V_{qr}= R_r\, i_{qr}+\frac{d\lambda_{qr}}{dt}+(w_e- w_r)\,\lambda_{dr} \quad (5)$$

$$\lambda_{ds}= L_s\, i_{ds}+ L_m\, i_{dr} \quad (6)$$

$$\lambda_{qs}= L_s\, i_{qs}+ L_m\, i_{qr} \quad (7)$$

$$\lambda_{dr}= L_m\, i_{ds}+ L_r\, i_{dr} \quad (8)$$

$$\lambda_{qr}= L_m\, i_{qs}+ L_r\, i_{qr} \quad (9)$$

$$T_e=\frac{3}{2}\frac{P}{2}\frac{L_m}{L_s}(\lambda_{qs}\, i_{dr}+ \lambda_{ds}\, i_{qr}) \quad (10)$$

The stator flux of q axes in arbitary roating reference frame has almost zero because the stator side is connected in power grid. Therefore Eqns(1), (2), (6), (7) and (10) can be written as given below:

$$V_{ds}= R_s\, i_{ds}+\frac{d\lambda_{ds}}{dt} \quad (11)$$

$$V_{qs}= R_s\, i_{qs}+ w_e\,\lambda_{ds} \quad (12)$$

$$\lambda_{ds}= L_s\, i_{ds}+ L_m\, i_{dr} \quad (13)$$

$$0= L_s\, i_{qs}+ L_m\, i_{qr} \quad (14)$$

$$T_e=-\frac{3}{2}\cdot\frac{P}{2}\cdot\frac{L_m}{L_s}\,\lambda_{ds}\, i_{qr} \quad (15)$$

Recall that the stator sides are always connected to a utility power grid, as shown in Fig. 2. Hence, the level of stator flux remains approximately unchanged, constrained only by the magnitude and frequency of the line voltage of the power system. Therefore as seen from the torque equation, the instantaneous torque control is achieved by controlling the rotor winding quadrature current compnent i_{qr}. From Eqn(15), active power at the stator side can be derived as follow.

$$P_s=-\frac{3}{2}\cdot\frac{P}{2}\, w_e\,\lambda_{ds}\, i_{qr} \quad (16)$$

Reactive power at the stator side terminal can be written as follow.

$$Q_s=\frac{3}{2}\cdot\frac{P}{2}\cdot(v_{qs}\, i_{ds}- v_{ds}\, i_{qs}) \quad (17)$$

Using Eqns(11),(12) and (13), (17) can be written as follows because ω_e and λ_{ds} have almost constant value.

$$Q_s=\frac{3}{2}\cdot\frac{P}{2}\, w_e\,\lambda_{ds}\left(\frac{\lambda_{ds}- L_m\, i_{dr}}{L_s}\right) \quad (18)$$

As a result of Eqns(17) and (18), we know that it is possible to control the active and reactive power at the stator side by controlling i_{qr} and i_{dr}.

2.2. Stator Flux and Rotor Speed Estimation

The stator voltage Va,Vb and Vc connected to power grid are converted to stationary domain V_α and V_β. Then, the stator flux $\lambda_{\alpha s}$, $\lambda_{\beta s}$ can be obtained by integrating the phase voltage as given below:

$$\lambda_{\alpha s}=\int(v_{\alpha s}-R_s i_{\alpha s})dt \qquad (19)$$

$$\lambda_{\beta s}=\int(v_{\beta s}-R_s i_{\beta s})dt \qquad (20)$$

where R_s : stator resistance

$i_{\alpha s}$, $i_{\beta s}$: stator current in stationary domain

Stator flux magnitude and synchronous angle (θ_s) can be estimated as given below:

$$|\lambda_s| =\sqrt{\lambda_{\alpha s}^2+\lambda_{\beta s}^2}$$

$$\theta_s=\tan^{-1}\frac{\lambda_{\beta s}}{\lambda_{\alpha s}} \qquad (21)$$

Recall the stator flux and voltage of stator side in synchronous domain. $\lambda_{ds} \doteq$ constant, $\lambda_{qs} \doteq 0$ and $V_{ds} \doteq 0$. Therefore Eqn(5) can be written as:

$$V_{qr}=R_r i_{qr}+(w_e-w_r)\lambda_{dr} \qquad (22)$$

$$sW_e=\frac{V_{qr}-R_r i_{qr}}{\lambda_{dr}} \qquad (23)$$

where $sW_e=w_e-w_r$

ω_e : synchronous angular frequency

ω_r : rotor angular frequency

Eqn(23) represent the slip angular frequency of rotor. In Eqn(23), w_e has almost constant value so estiamated rotor speed can be written as:

$$\omega_r=w_e-sW_e \qquad (24)$$

If use the Eqn(24) for field orientation control of DFIM in variable wind speed generating system, we can control the system without any rotor position sensor like a encoder.

2.3 Implementation

Fig. 3 shows the block diagram of variable speed wind power generating system without rotor position sensor. In this system, the rotor speed is estimated from Eqn(24) and control the rotor current for active and reactive power control in stator side. When starting for generating mode, there will be a large inrush current because system inertia has large value in wind power generating system. This current will affect the characteristics of power grid. As a sloution of this problem, we control the pitch angle and take a maximum energy from wind, when wind velocity is closed to cut in speed. And then we control the inverter system connected in rotor side using soft starting method. We can decrease the inrush current. From this method, if wind velocity is closed to cut-in speed, the DFIM is operated as a motoring mode to the limited speed for generating operation. From wind speed detector, it is possible to estimate the maximum power for reference power command to the rotor current command in inverter system connected in rotor side. In this time, it is possible to control the maximum power point tracking in accordance with wind speed as shown in Fig. 1.

III. Results of Computer Simulation

The principles and control scheme of the position sensorless controlled doubly fed induction machine described in Fig. 3 is implemented by a computer program and then the performance is investigate.

The specifications of the doubly fed induction machine used in the computer simulation are shown in Table 1.

Table 1 Parameters of the model machine

Rated power	5 [HP]	
Rated speed	1720 [rpm]	
Pole No.	4	
	Stator side	Rotor side
Voltage	220 [V]	200 [V]
Current	14.8 [A]	12.0 [A]
R	0.60 [ohm]	0.41 [ohm]
L	43.42 [mH]	43.42 [mH]
Lm	41.51 [mH]	

For the doubly fed induction machine under investigation, the stator is fed from a three phase ac supply at 60 Hz from the power grid. The rotor current is provided by SVPWM power converter. First, in order to evaluate the characteristics of the proposed method, results of speed control are shown in Fig. 4 and Fig. 5. Comparing Fig. 4 and Fig. 5 it is evident that estimated rotor angle is accurately estimated. In Fig. 5 the rotor is accelerated from

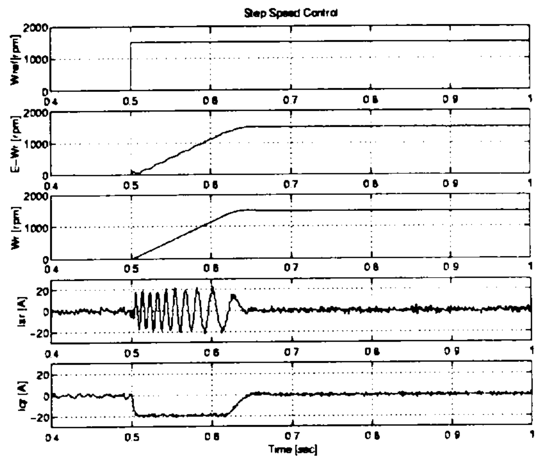

Fig. 4 Simulation results of step speed control

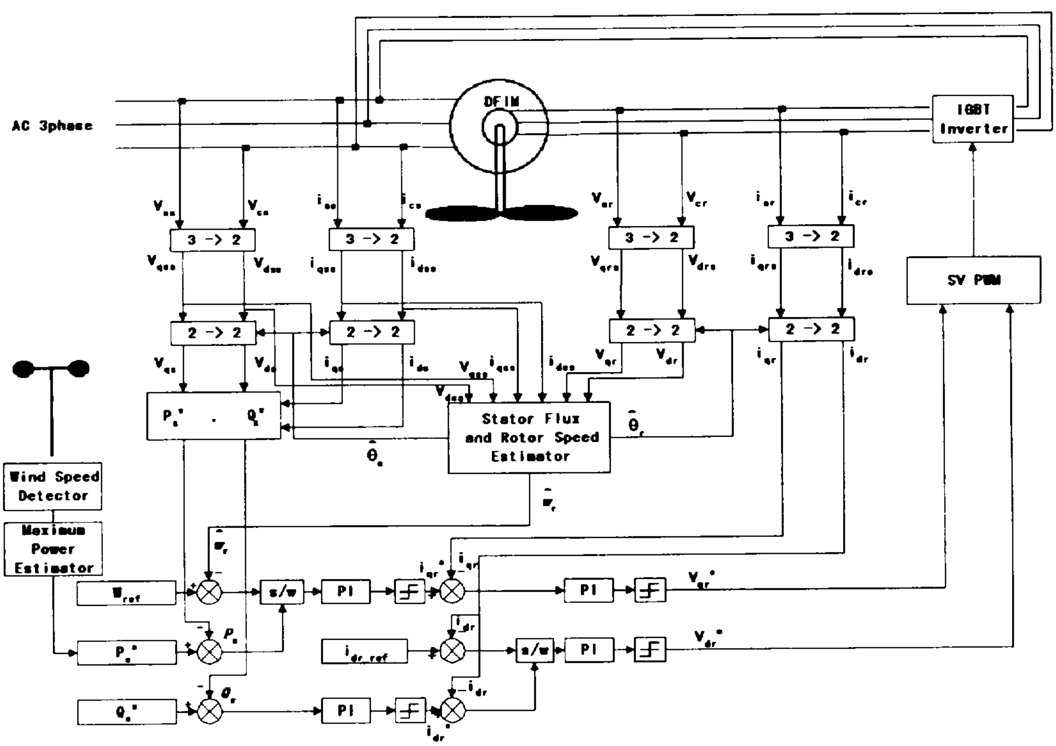

Fig. 3 Block diagram of computer simulation

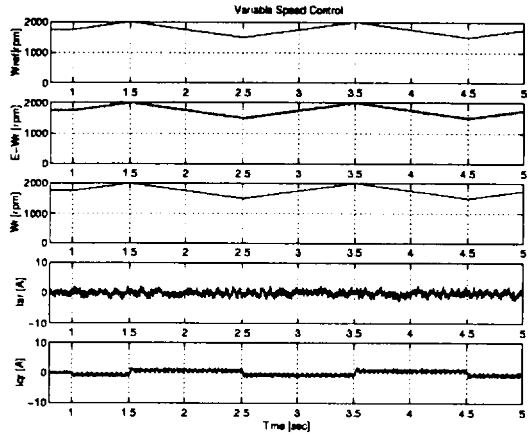

Fig. 5 Simulation results of variable speed control

sub-synchronous speed to super synchronous speed. In these results, the estimated motor speed is very close to the actual one.

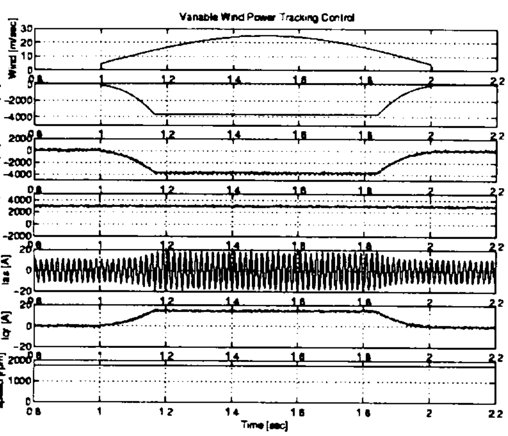

Fig. 6 Simulation results of variable wind speed power control

Fig. 6 shows the results of the active power control from motoring mode to generating mode in accordance with the variable wind speed. In this figure, if wind speed is close to cut in speed(4.5 m/sec), the system is converting to generating system. And the reference of active power is made by maximum power estimator as the cube of wind speed. This implies that the estimated method is also correct in power control mode. Fig. 7 and Fig. 8 show the results of active and reactive power control. At t=1 sec, a step power change is commanded to change the power factor in Fig. 7 and Fig. 8.

We can prove the converting mode from motoring to generating mode as a zoom method at 1 [sec]. These two results are clearly achieved by the position sensorless control method.

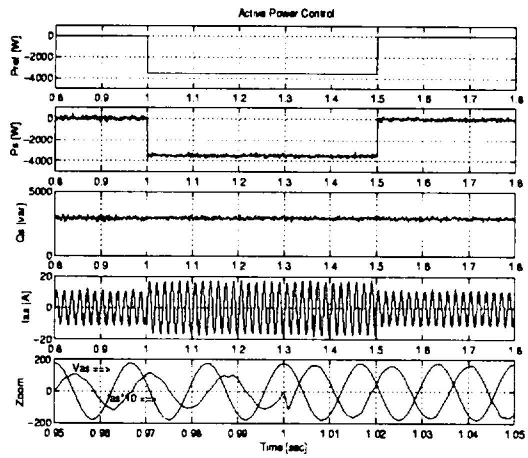

Fig. 7 Simulation results of active power control

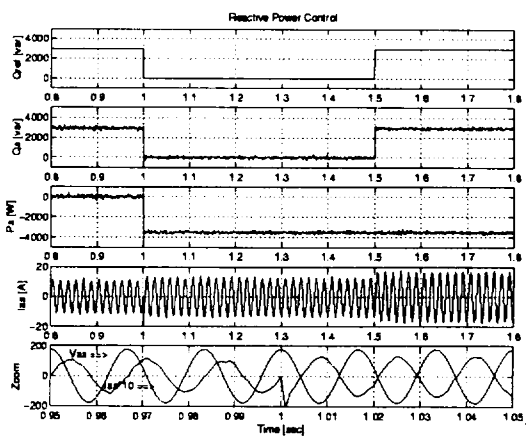

Fig. 8 Simulation results of reactive power control

Ⅵ. Conclusion

A speed drive and variable speed wind power generating system of a doubly fed induction machine without rotor position sensor is proposed in this paper. The stator flux and rotor speed estimator is employed to achieve decoupled control of speed drive and power control through the rotor currents. The results of computer simulation by the estimated speed has desirable performance over speed control and power control.

Ⅶ. 요 약

풍력발전를 위해 회전자 위치검출기가 없는 이중여자 유도기를 이용하여 전력 제어 방법을 나타내었다. 고정자 자속과 회전자 속도 추정기를 이용하여 가변속도 제어 및 유, 무효전력 제어 방법을 제안하였다. 제안된 알고리즘을 컴퓨터를 통해 결과를 나타내었다. 결과를 고찰해 보면 출력 특성이 기준 명령값에 잘 추종하여 제안한 알고리즘의 타당성을 검증하고 있다. 이를 풍력발전 시스템 제어시 유용한 기초 자료로 활용될 것으로 기대된다.

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