Electrical Engineering in Japan, Vol. 177, No. 2, 2011
Translated from Denki Gakkai Ronbunshi, Vol. 128-B, No. 7, July 2008, pp. 937–944

Power Smoothing and MPPT for Grid-Connected Wind Power Generation with Doubly Fed Induction Generator

TAKAAKI KAI,[1] YUJI TANAKA,[2] HIROTOSHI KANEDA,[2] DAICHI KOBAYASHI,[1] and AKIO TANAKA[1]
[1]Oyama National College of Technology, Japan
[2]Meidensha Corporation, Japan

SUMMARY

Recently, doubly fed induction generators (DFIG) and synchronous generators have been applied mostly to wind power generation, and variable speed control and power factor control have been implemented for high efficiency of wind energy capture and for high quality of power system voltage. In variable speed control, the wind speed or generator speed is used for maximum power point tracking. However, the properties of wind generation power fluctuations due to wind speed variation have not yet been investigated for those forms of control.

The authors discuss power smoothing by these forms of control for DFIG interconnected to a 6.6-kV distribution line. The performance is verified by means of the power PSCAD/EMTDC system simulation software for actual wind speed data and is investigated by using an approximate equation for wind generation power fluctuations as a result of wind speed variation. © 2011 Wiley Periodicals, Inc. Electr Eng Jpn, 177(2): 10–18, 2011; Published online in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/eej.20958

Key words: wind power generation; DFIG; power smoothing; MPPT.

1. Introduction

The introduction of wind power generation is increasing rapidly worldwide due to energy problems and global warming.

The rated power of wind power generation is becoming steadily larger, and recently the megawatt class has predominated. Offshore wind power generation with a rated power of 5 MW has been developed in Germany. In recent wind power generation, variable speed control has been adopted in order to capture wind energy with high efficiency; power factor control is performed to maintain the voltage quality of the grid interconnecting with this power generation. Synchronous generators and doubly fed induction generators (DFIG) are used for wind power generation. The converter and inverter used are equipped for variable speed control and power factor control [1].

Wind energy is proportional to the cube of wind speed, and the acquisition efficiency of wind power energy depends on the power coefficient, which depends on the tip speed ratio, that is, the ratio of the tip speed to the wind velocity.

The power coefficient reaches a maximum at the optimal tip speed ratio. Therefore, maximum power point tracking (MPPT) is done by control that attempts to maintain the optimal tip speed ratio in wind power generation with variable speed control. In addition, the reactive power is maintained at a constant power factor.

MPPT is performed by using wind speed measurement in DFIG [2, 3] and squirrel cage induction generators of the DC linked type. A torque control scheme has been proposed to reduce power fluctuation due to wind speed variation in the latter. However, this scheme has the disadvantage of reducing the acquisition efficiency of wind energy. MPPT of DFIG is performed by obtaining the reference value of the stator active power from a lookup table. The relation between the generator speed and the maximum output is shown in the table, and the measured generator speed is input to the table. MPPT of DFIG is performed by using the measured generator speed; the transfer function of power fluctuation due to wind speed variation is examined in Ref. 4. Active power control of DFIG is investigated on the basis of a lookup table in Refs. 5 and 6. However, the table characteristics are not described. Usually, MPPT of DFIG is done by obtaining the reference value of the active power from the lookup table.

The generator speed is input to the table, in which the relation between the generator speed and the maximum output is shown. In Ref. 3, the optimal generator speed calculated from the measured wind speed is input to the maximum output curve, and the reference value is obtained from the output of the curve, namely, the wind speed control method.

On the other hand, in Ref. 4, the measured wind speed is input directly to the maximum output curve, and the reference value is obtained from the output of the curve, namely, by the generator speed control method. When the power fluctuation of wind power generation due to wind speed variation is large, it could cause deterioration of power quality with regard to the voltage and frequency. In a power system with a large wind power generation capacity, power fluctuation should be mitigated by providing a power storage system such as a battery system. In this case, wind power generation with high-performance power fluctuation smoothing has the advantage that the required battery system capacity is small.

However, the performance of power fluctuation smoothing in wind speed control and generation speed control has not yet been described.

The authors examined the performance of power fluctuation smoothing of wind speed control and generation speed control for DFIG by a new vector control method [7, 8]. These investigations, conducted with the simulation software PSCAD/EMTDC, were performed by using the transfer function of the power fluctuation derived in this paper. It was confirmed that the power fluctuation of the wind speed control is considerably larger than that of the generator speed control. The reason is that the wind speed control cannot achieve the mitigation effect of power fluctuations by the inertia of the wind turbine.

2. Maximum Power Point Tracking

2.1 Wind turbine

Because the wind energy is proportional to the cube of the wind speed, the wind power energy P_T captured by the wind turbine is expressed as follows:

$$P_T = \frac{1}{2} C_P A \rho V_W^3 \quad [\mathrm{W}] \tag{1}$$

where C_P is the power coefficient, A $(= \pi R^2)$ is the area of the blade (m^2), R is the radius of the blade (m), ρ is the air density 1.225 (kg/m^3), and V_W is the wind speed (m/s).

The power coefficient C_P of the wind turbine depends on the tip speed ratio λ and the blade pitch angle β, and is expressed as follows [2]:

$$C_P = 0.5\left(\frac{RC_f}{\lambda} - 0.022\beta - 2\right)e^{-0.255(RC_f/\lambda)} \tag{2}$$

The coefficient C_f is a constant (0.675) based on the designed value of the blade. The tip speed ratio λ is expressed as in Eq. (3), where ω_{mb} is the angular speed of the blade. Figure 1 shows the relation between the tip speed ratio λ and the power coefficient C_P with the pitch angle β as a parameter. The optimal tip speed ratio λ_{opt} is calculated by setting the derivative of Eq. (2) with respect to the tip speed ratio λ to zero. The optimal power coefficient C_{Popt} is obtained by substituting λ_{opt} into Eq. (2). C_{Popt} and λ_{opt} are expressed by Eqs. (4) and (5):

$$\lambda = \frac{R\omega_{mb}}{V_W} \tag{3}$$

$$C_{Popt} = 1.961e^{-(1.51+0.00561\beta)} \tag{4}$$

$$\lambda_{opt} = \frac{RC_f}{5.9216 + 0.022\beta} \tag{5}$$

The pitch angle β of the blade is constantly controlled from the cut-in wind speed to the ratings wind speed. When the pitch angle β is 5° and the radius R is 35 m, C_{Popt} and λ_{opt} become 0.421 and 3.917, respectively, by substituting these values into Eqs. (4) and (5). When the rated wind power output is 1500 kW, the rated wind speed is about 11.5 m/s according to Eq. (1). There is a gear between the wind turbine and the generator. The optimal angular speed of the generator ω_{mopt} is obtained from Eqs. (3) and (5) as follows:

$$\omega_{mopt} = \frac{GC_f}{5.9216 + 0.022\beta} V_W \tag{6}$$

where G is the gear ratio.

The wind turbine output P_T is obtained by substituting Eqs. (2) and (3) into Eq. (1):

$$P_T = 0.25A\rho\left(GC_f\frac{V_W}{\omega_m} - 0.022\beta - 2\right)e^{-0.255GC_f(V_W/\omega_m)}V_W^3 \tag{7}$$

where the angular speed of the generator ω_m is the product of G and ω_{mb}.

The relation between the optimal output P_{Topt} and the optimal tip speed ratio λ_{opt} is obtained by substituting Eqs.

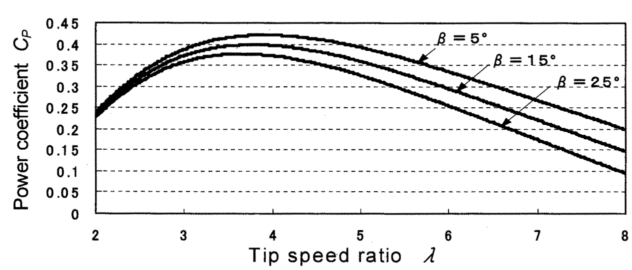


Fig. 1. Tip speed ratio λ versus power coefficient C_p.

(4) and (6) into Eq. (1). Thus, P_{Topt} is proportional to the cube of the generator speed:

$$P_{Topt} = 0.9805A\rho e^{-(1.51+0.00561\beta)} \times \left(\frac{5.9216 + 0.022\beta}{GC_f}\right)^3 \omega_{mopt}^3 \quad (8)$$

The relation (7) between the wind turbine output P_T and the generator angular speed ω_m with the wind speed V_W as a parameter is shown in Fig. 2 for $C_f = 0.675$, $R = 35$ m, $\beta = 5°$, and $G = 110$. The relation (8) between the optimal output P_{Topt} and the optimal generator angular speed ω_{mopt} is also shown in the figure.

2.2 MPPT scheme

The kinetic equation of wind power generation is

$$I\omega_m \frac{d\omega_m}{dt} = P_T - P_E \quad (9)$$

where I is the inertia of wind power generation (kg-m^2), P_T is the mechanical input to the generator (W), and P_E is the electrical output of the generator (W).

The mechanical input to the generator is equal to wind turbine output P_T. When losses are neglected, the electrical output of the generator P_E is equal to the output of wind power generation P_G. The active power of the rotor is almost equal to the product of the slip and the active power of the stator in DFIG. MPPT of wind power generation is performed by using this relation. Measurement of the wind speed or the generator speed is used for this control. When $\omega_m > \omega_{mopt}$, ω_m tends to ω_{mopt} due to the deceleration force because $P_T < P_E$; ω_m tends to ω_{mopt} due to an acceleration force under the opposite condition. The generator speed ω_m is steady at the intersection of the P_{Topt} curve and the P_T curve as shown in Fig. 2, resulting in the optimal generator speed ω_{mopt}.

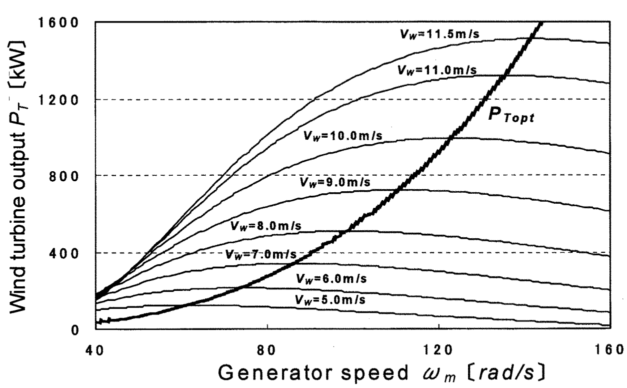


Fig. 2. Wind turbine output P_T versus generator speed ω_m.

2.3 Reference value of active power of stator

(1) Wind speed control

The optimal generator speed ω_{mopt} is obtained by substituting the measured wind speed V_W into Eq. (6). The maximum output P_{Topt} can be calculated from the value of V_W and Eq. (8):

$$P_{Topt} = 0.9805A\rho e^{-(1.51+0.00561\beta)} V_W^3 \quad (10)$$

When losses are neglected, the active power of the rotor P_2 (the output direction is positive) is approximately equal to the product of the slip s and the active power of the stator P_1 (the input direction is positive) as follows:

$$P_2 \fallingdotseq sP_1 \quad (11)$$

The output of wind power generation P_G is

$$P_G \fallingdotseq -(P_1 - P_2) = -(1 - s)P_1 = -\frac{\omega_m}{\omega_{ms}} P_1 \quad (12)$$

where ω_{ms} is the generator angular speed (rad/s).

The output of wind power generation P_G is approximately equal to P_{Topt} in Eq. (10). When Eq. (10) is substituted into Eq. (12), the reference value of the active power of the stator P_1^* can be obtained as follows:

$$P_1^* = -\frac{\omega_{ms}}{\omega_{mopt}} P_{Topt} = -0.9805A\rho e^{-(1.51+0.00561\beta)} \frac{\omega_{ms}}{\omega_{mopt}} V_W^3 \quad (13)$$

where ω_m is approximately equal to ω_{mopt} because of MPPT.

(2) Generator speed control

By setting $\omega_{mopt} = \omega_m$ in Eq. (8), the maximum output P_{Topt} is obtained. The reference value of the active power of the stator P_1^* can be obtained as follows:

$$P_1^* = -0.9805A\rho e^{-(1.51+0.00561\beta)} \times \left(\frac{5.9216 + 0.022\beta}{GC_f}\right)^3 \omega_{ms}\omega_m^2 \quad (14)$$

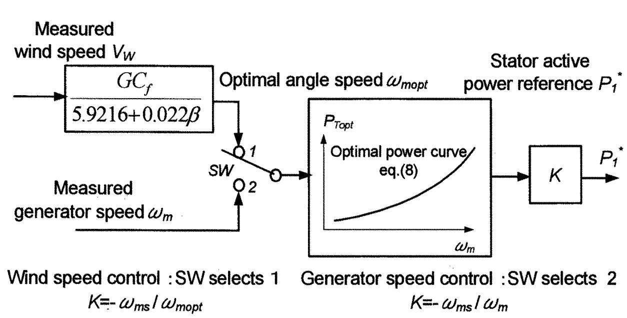


Fig. 3. MPPT by wind speed and by generator speed.

Figure 3 shows a block diagram of the calculation of the reference value P_1^* by generator speed control or wind speed control.

2.4 Transfer function of power fluctuation

(1) Wind speed control

In wind speed control, the output of wind power generation P_G is obtained from Eqs. (12) and (13) as follows by assuming $\omega_m/\omega_{mopt} \sim 1$:

$$P_G = 0.958A\rho e^{-(1.51+0.00561\beta)}V_W^3 \tag{15}$$

The fluctuations ΔP_G due to the small variations of the wind speed ΔV_W are obtained by linear approximation of Eq. (15) at steady state (ω_{mo}, V_{W0}, P_{G0}):

$$\Delta P_G = 3P_{G0}\frac{\Delta V_W}{V_{W0}} \tag{16}$$

The fluctuations are proportional to the variation of the wind speed. Thus, the fluctuations are large.

(2) Generator speed control

In generator speed control, the output of wind power generation P_G in the presence of variations of the generator angular speed $\Delta\omega_m$ is approximately expressed in accordance with Eqs. (12) and (14) as follows:

$$\Delta P_G = 3P_{G0}\frac{\Delta\omega_m}{\omega_{mo}} \tag{17}$$

When Eq. (9) is approximated as linear, we obtain

$$I\omega_{m0}\frac{d\Delta\omega_m}{dt} = \Delta P_T - \Delta P_E \tag{18}$$

Equation (17) is substituted for $\Delta\omega_m$ in Eq. (18). ΔP_T in Eq. (18) is obtained from Eq. (1) by approximating the power coefficient C_P by the optimal C_{Popt}. ΔP_E in Eq. (18) is approximated by ΔP_G. As a result, the transfer function of the output fluctuation ΔP_G as a result of wind speed variation ΔV_W is obtained as follows:

$$\frac{\Delta P_G(s)}{P_{G0}} = \frac{3}{\dfrac{sI\omega_{m0}^2}{3P_{G0}} + 1}\frac{\Delta V_W(s)}{V_{W0}} \tag{19}$$

where $\Delta P_{T0} \sim \Delta P_{G0}$.

In wind speed control, the output fluctuation ΔP_G (s) is the first-order delay for the wind speed variation ΔV_W (s). The time constant T ($= I\omega_{m0}^2/3P_{G0}$) is governed by the inertial constant (I) and the angular speed (ω_{m0}) and the output (P_{G0}) in the steady state. The output fluctuation becomes small because of the effect of inertia.

3. Control Block Diagram of DFIG

The control scheme of DFIG described in Refs. 9 and 10 is applied in this paper.

The control block diagram is shown in Fig. 4. When the transient term and the stator resistance is neglected for the voltage equation in a d/q rotating frame of reference, the stator active power and reactive power are determined by the rotor q-axis current and the rotor d-axis current, respectively. Thus, the reference value of the rotor d-axis current and that of the rotor q-axis current can be obtained from the reference value of the stator reactive power and that of the stator active power, respectively. Because the magnetizing voltages (the rotor voltages) are expressed by the rotor d/q axis currents, the stator voltage and slip, the voltage can be derived from the reference values of the rotor d/q axis currents. PI control is applied for the stator active and reactive power in order to improve control accuracy. It is also applied to the control of the rotor d/q currents. MPPT is performed by obtaining the reference value of the stator active power P_1^* from Fig. 3 as described in the second section. This value is input as P_1^* of Fig. 4, the reference value i_{2q}^* is obtained, and MPPT is performed. Power factor control (P.F.) is performed by obtaining the reference value of the stator reactive power Q_1^* from Eq. (20). This value is input as Q_1^* in Fig. 4, the reference value i_{2d}^* is obtained, and power factor control is performed. Although the model of the wind turbine is not shown in Fig. 4, it is derived from Eqs. (1) and (2). Equation (1) divided by the generator speed ω_m is input as the input torque of the generator. The output voltage of inverter B is fed to the rotor:

$$Q_1^* = \frac{P_G\sqrt{1 - P.F^2}}{P.F} - Q_3 \tag{20}$$

where Q_3 is the reactive power of inverter A.

Inverter A controls the active power supplied to the inverter to keep the voltage of the direct current circuit constant.

4. Simulation Conditions and Results

4.1 Simulation conditions

The simulation software PSCAD/EMTDC (V 4.2) was used for the simulation. It can simulate the DFIG, the inverter circuit, and the wind turbine in detail. The DFIG is interconnected to a distribution line; the power system is shown in Fig. 4. The setting value of the power factor for the DFIG is 0.90. The parameters of the DFIG and the inverter A/B are shown in Tables 1 and 2, respectively.

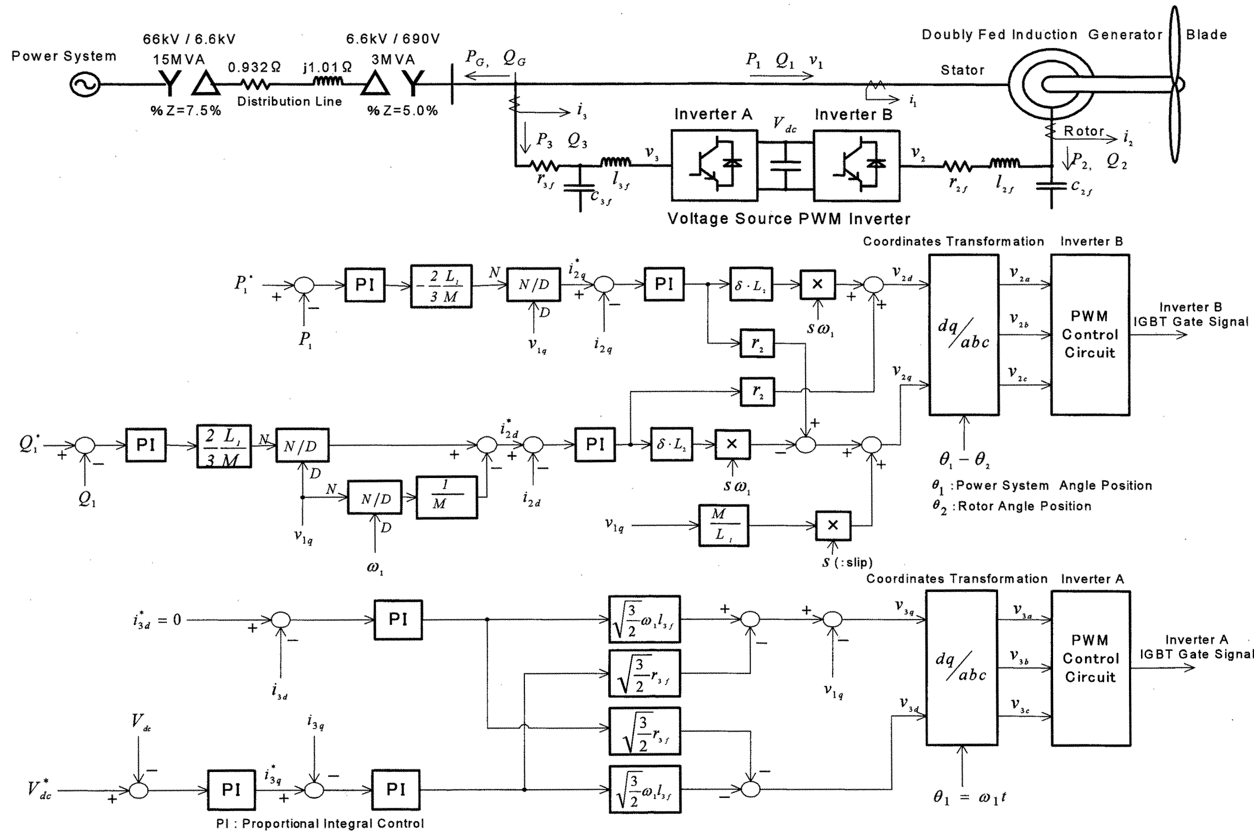


Fig. 4. Control block diagram for DFIG.

4.2 Simulation results

(1) Output fluctuation due to actual wind speed data

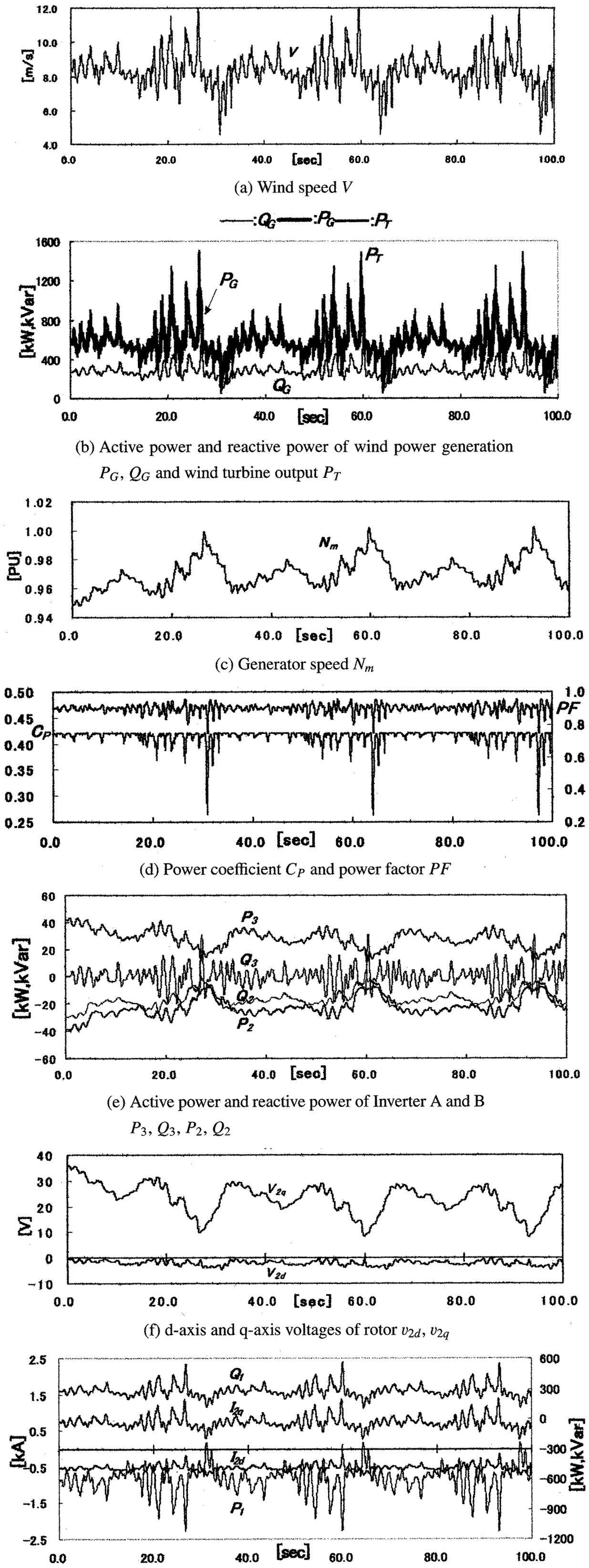
The wind speed data were observed in an actual wind power generation unit with a rated power of 1500 kW. A simulation of wind speed control and generator speed control was carried out using these data, and the power fluctuation smoothing performance was studied. The simulation duration was 100 seconds. The initial value, the maximum value, and the minimum value of the wind speed were 8.4, 11.9, and 4.6 m/s, respectively. The results of the simulation of wind speed control are shown in Fig. 5. The reference value of the stator active power is proportional to the cube of the wind speed as shown in Eq. (13). Thus, the fluctuation of the stator active power caused by the variation of the wind variation is large. The power coefficient C_P is almost

Table 1. Parameters of the DFIG

Rated VA	1750kVA
Rated power	1500kW
Inertia H	3sec
Rated voltage	690V
Rated frequency	50Hz
Pole number	6
Stator resistance r_1	0.024PU
Stator leakage inductance l_1	0.05PU
Rotor resistance r_2	0.015PU
Rotor leakage inductance l_2	0.015PU
Magnetizing inductance M	2.4PU

Table 2. Parameters of inverter

DC circuit rated voltage	1500(V)
DC circuit capacitor	50000(μF)
Snubber circuit	5000(Ω)、0.05(μF)
Carrier frequency	10(k Hz)
Low pass filter of Inverter *A*	L_{3f}=0.0005(H)、 C_{3f}=16(μF) (Δconnection)
Low pass filter of Inverter *B*	L_{2f}=0.0002(H)、 C_{2f}=20(μF) (△connection)



(a) Wind speed V

(b) Active power and reactive power of wind power generation P_G, Q_G and wind turbine output P_T

(c) Generator speed N_m

(d) Power coefficient C_P and power factor PF

(e) Active power and reactive power of Inverter A and B P_3, Q_3, P_2, Q_2

(f) d-axis and q-axis voltages of rotor v_{2d}, v_{2q}

(g) d-axis and q-axis currents of rotor I_{2d}, I_{2q} and active power and reactive power of the stator P_1, Q_1

Fig. 5. Variable speed control by wind speed.

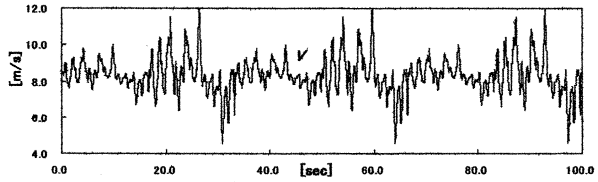
entirely maintained at 0.421 of the optimal value. The value becomes smaller than 0.421 at large values of the wind speed variation, and the minimum value is 0.26. The maximum value of the wind turbine output P_T is 1485 kW, and the minimum value is 59 kW. The fluctuation of the output P_G of the wind power generation is proportional to the wind speed as shown in Eq. (16). The maximum value of the output P_G is 1104 kW and the minimum value is 214 kW. The fluctuation of the output P_G due to the fluctuation of the turbine output P_T is 62%. The setting value of the power factor is 0.90. However, the power factor changes within the range of 0.746 to 0.951 because the fluctuation of the output P_G is large. The stator active power P_1 and the reactive power Q_1 are roughly proportional to i_{2q} and i_{2d}, respectively.

The simulation results for generator speed control are shown in Fig. 6.

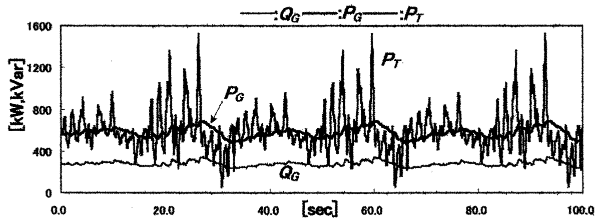
The reference value of the stator active power is proportional to the cube of the generator angular speed, as expressed in Eq. (14). Because the variation of the generator angular speed is smaller than that of the wind speed, the fluctuation of the stator active power is quite small compared with that of the wind speed control. The power coefficient C_P is maintained at 0.421 of the maximum for longer duration than under wind speed control. However, the minimum value is 0.26, as in the case of wind speed control. The maximum value of the wind turbine output P_T is 1524 kW, and the minimum value is 59 kW. The maximum value of the output P_G is 683 kW and the minimum value is 486 kW. The fluctuation of the output P_G due to fluctuations of the turbine output P_T is 13%, which is much smaller than under wind speed control. The reason is that the fluctuation of the output P_G expressed in Eq. (19) is the first-order time lag for the wind speed variation. Because the time constant is governed by the inertia of wind power generation, power smoothing by inertia is achieved in generator speed control. Because the output fluctuation is slight, the power factor is 0.895 to 0.917, and it is maintained close to the setting value of 0.90. MPPT by both wind speed control and generator speed control is effective, as described above. However, under wind speed control, when the output fluctuation becomes large, the power factor control performance decreases slightly. Because the effect of power smoothing is large in generator speed control, the fluctuation of the wind power generation output is only 22% in comparison with that in wind speed control.

(2) Output fluctuation due to stepwise change of wind speed

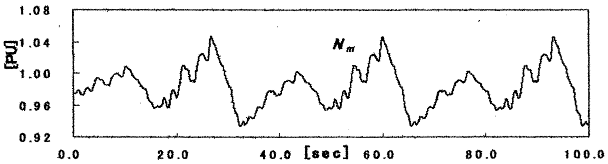
The simulation results for output fluctuation when the wind speed changes stepwise from 8.4 m/s to 10.4 m/s at t = 1.0 s are shown in Fig. 7.



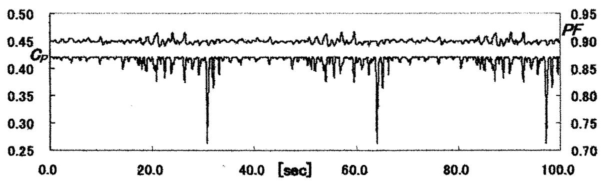
(a) Wind speed V



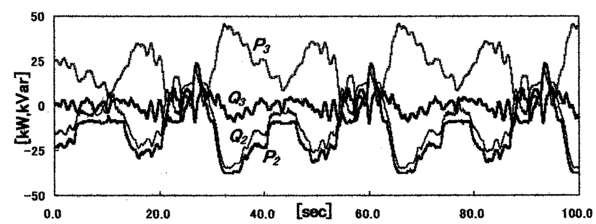
(b) Active power and reactive power of wind power generation P_G, Q_G and wind turbine output P_T



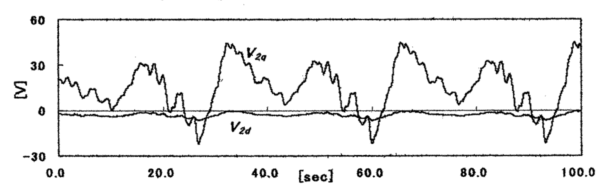
(c) Generator speed N_m



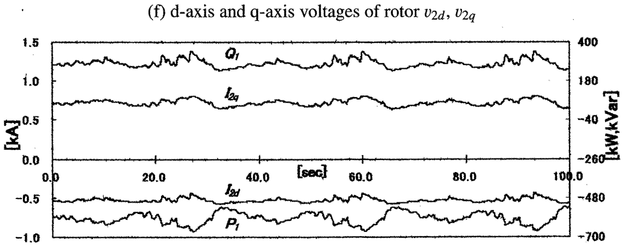
(d) Power coefficient C_P and power factor PF



(e) Active power and reactive power of Inverter A and B P_3, Q_3, P_2, Q_2

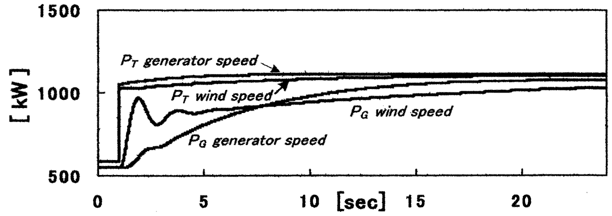


(f) d-axis and q-axis voltages of rotor v_{2d}, v_{2q}

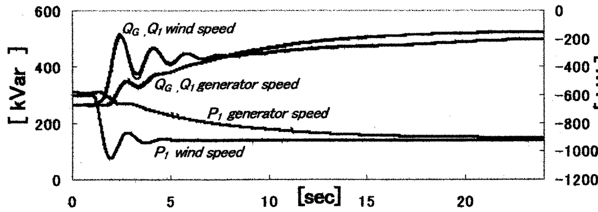


(g) d-axis and q-axis currents of rotor I_{2d}, I_{2q} and active power and reactive power of the stator P_1, Q_1

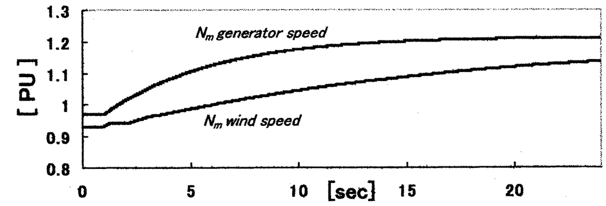
Fig. 6. Variable speed control by generator speed.



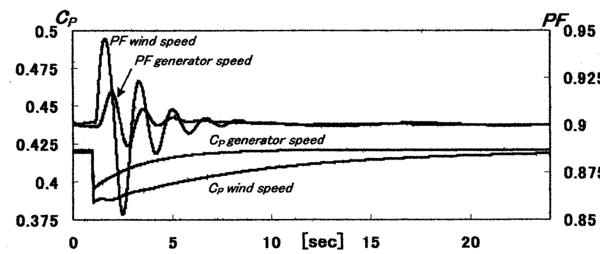
(a) Wind turbine output P_T and active power of wind power generation P_G



(b) Reactive power of wind power generation Q_G and active power and reactive power of the stator P_1, Q_1



(c) Generator speed N_m



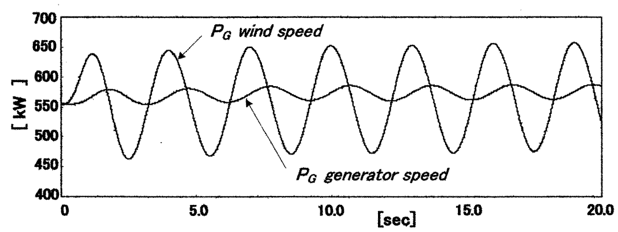
(d) Power coefficient C_P and power factor PF

Fig. 7. Step response to wind speed.

In the figure, "wind speed" denotes wind speed control and "generator speed" denotes generator speed control. In wind speed control, because the reference value of the stator active power is proportional to the wind speed, the reference value varies fast. In generator speed control, because it is proportional to the generator speed, the reference value varies slowly.

ΔP_G reaches a maximum (420 kW) 0.93 seconds after the stepwise change of the wind speed in the simulation results for wind speed control. ΔP_G calculated from Eq. (16) is 395 kW, which agrees approximately with the simulation results. Here P_{G0} = 548 kW and V_{W0} = 8.4 m/s before the stepwise change of the wind speed.

ΔP_G responds as a first-order time lag for stepwise change of the wind speed in the simulation results for



Active power of wind power generation P_G

Fig. 8. Frequency response to wind speed variation.

generator speed control. The time constant is 5.8 s. The time constant calculated from Eq. (19) is 4.7 s. Although the difference between the calculated value and the simulation result is about 1.0 s, the time constant can be roughly estimated from Eq. (19). Here $P_{G0} = 553$ kW and $\omega_{m0} = 97.8$ rad/s before the stepwise change of the wind speed.

(3) Output fluctuation due to sine wave variation of wind speed

The simulation results for P_G when a sinusoidal wind speed variation is superimposed on a constant wind speed of 8.4 m/s at $t = 1.0$ s are shown in Fig. 8. The amplitude and the period of the wave are 0.5 m/s and 3 s ($f = 0.333$ Hz), respectively.

The simulation result ΔP_G for wind speed control varies sinusoidally. The period is the same as that of the wind speed variation, and the amplitude is 89 kW (0-P). The steady-state value of ΔP_G calculated from Eq. (16) is 99 kW (0-P), and is close to the simulation result. The simulation result ΔP_G for generator speed control varies sinusoidally. The period is the same as that of the wind speed variation. Because the effect of power smoothing is large in generator speed control, the amplitude is 11 kW (0-P). The steady-state value of ΔP_G calculated from Eq. (19) is 9 kW (0-P), and is close to the simulation result.

5. Conclusions

MPPT of wind power generation for a doubly fed induction generator was performed on the basis of the measured wind speed or the measured generator speed. The former is wind speed control, and the latter is generator speed control. The power smoothing performance of these types of control was examined.

The simulation was carried out by using the simulation software PSCAD/EMTDC based on the measured wind speed data. MPPT was excellent under both types of control. Because power smoothing by inertia can be achieved in generator speed control, the output fluctuation of the power generation is small. However, this kind of smoothing is not available in wind speed control, and thus the output fluctuation is larger than that of generator speed control. The transfer function of the output fluctuation for wind speed variation was also derived.

Although the power factor can be largely maintained at the setting value in generator speed control, the control performance decreases slightly due to power fluctuation in wind speed control.

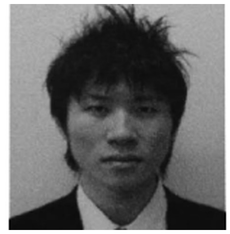
Generator speed control has the advantage that the voltage deviation and the frequency deviation of the power system become small. It is necessary to smooth power fluctuations due to wind speed variation in order to maintain the power quality in the power system with a high ratio of wind power generation capacity to total generation capacity. Thus, a power storage system such as a battery system must be installed in new wind power generation facilities. When the battery system is included in a wind power generation facility in which MPPT is controlled by generator speed control, the amount of system charging and discharging becomes small, and thus the inverter loss of the system is reduced and the lifetime is increased.

REFERENCES

1. Muller S, Deicke M, De Doncker RW. Doubly fed induction generator systems for wind turbines. IEEE Industry Applications Magazine, May/June 2002.
2. Lei Y, Mullane A, Lightbody G, Yacamini R. Modeling of a wind turbine with doubly fed induction generation for grid integration studies. IEEE Trans Energy Conversion 2006;21(1).
3. Takahashi R, Tamura J, Futami M, Kimura M, Ide K. A new control method for wind energy conversion system using a doubly fed synchronous generator. IEEJ Trans PE 2006;126:225–235. (in Japanese)
4. Luo C, Banakar H, Shen B, Ooi BT. Strategies to smooth wind turbine fluctuations of wind generator. IEEE Trans Energy Conversion 2007;22(2).
5. Tapia A, Tapia G, Ostolaza JX, Saenz JR. Modeling and control of a wind turbine driven doubly fed induction generator. IEEE Trans Energy Conversion 2003;18(2).
6. Sun T, Chen Z, Blaabjerg F. Flicker study on variable speed wind turbines with doubly fed induction generators. IEEE Trans Energy Conversion 2005;20(4).
7. Kai T, Tanaka Y, Kaneda H, Kobayashi D, Tanaka A. A vector control for grid-connected wind power generation with doubly fed induction generator. IEEJ Trans PE 2008;128:41–47. (in Japanese)
8. Kai T, Tanaka Y, Kaneda H, Kobayashi D, Tanaka A. A vector control method for grid-connected wind power generation with doubly fed induction generator. ICEE ’2007 Hong Kong ICEE-36.

AUTHORS (from left to right)




Takaaki Kai (senior member) obtained his master’s and doctoral degrees from Tokyo Institute of Technology in 1978 and 1991. He is now a professor at Oyama National College of Technology. He is a senior member of IEEE.

Yuji Tanaka (member) graduated from Gunma University in 2004 and joined Meidensha Corporation.

Hirotoshi Kaneda (member) received a bachelor’s degree from Waseda University in 1994 and joined Meidensha Corporation.

Daichi Kobayashi (student member) received a bachelor’s degree from Oyama National College of Technology in 2009 and joined Honda Corporation.

Akio Tanaka (member) received a master’s degree from Nagaoka University of Technology in 1992. He is now an assistant professor at Oyama National College of Technology.