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# Studies on a Wind Turbine Generator System using a Shaft Generator System

**Fujio Tatsuta*, Toshiyuki Tsuji**, Nobuharu Emi** and Shoji Nishikata****

**Abstract** - In this paper a new dc-link type wind turbine generator system using a shaft generator system, which is widely used for power sources in a ship, is proposed. The basic configuration of the proposed wind turbine generating system is first explained. And the equations expressing the system are derived. Then the steady-state characteristics of the generating system are discussed. We use an experimental system that can simulate the characteristics of a wind turbine in this study, because it is hard to operate an actual wind turbine in a laboratory. In addition, the transient responses of this system are investigated when the velocity of the wind is changed. It is shown that experimental results were very close to the simulated ones, supporting the usefulness of the theory.

**Keyword:** low distortion, shaft generator, synchronous compensator, thyristor inverter, wind turbine generator

## 1. Introduction

Recently, environmental pollution and depletion of resources by heavy consumption of the fossil fuel have become serious problems. The utilization of natural energy such as wind power is one of the effective answers to these problems.

In general, the wind turbine generator system is operated with the utility power system because the change in output power depends on widely unexpected fluc-tuations in wind. There are two types of interconnecting method for the power systems including wind power generator system. One is ac-link type in which the output power in the generator is directly connected with utility power system. The other is dc-link type in which the power produced by the wind turbine generator is converted once into dc power with the converter, and then it is converted again to ac power with constant frequency and voltage through the inverter. Although the ac-link type has been put into practice because of its simplicity, the dc-link type has been increasingly used because the wind turbine speed may be controlled arbitrary without depending on the frequency of the electric power utility [1].

In this paper a new dc-link type wind turbine generator system using a shaft generator system is proposed. The shaft generator system usually supplies electrical power required in a ship by using a part of the power produced by the main engine. This type of power generating system is widely used for power sources in large ships since it can reduce fuel and operation costs. The system consists of a shaft generator driven by the main engine, a thyristor rectifier, a current-source thyristor inverter, an ac reactor, and a synchronous compensator to provide reactive power for loads and for commutation of inverter thyristors. Since the speed of the main engine can vary over a wide range when the ship makes a voyage, the output voltage and frequency of the shaft generator can also be changed. Hence, ac power produced by the shaft generator is converted once into dc power with the thyristor rectifier, and then the dc power is converted again into ac power with constant voltage and frequency with the inverter. This system can be applied to obtain the power with constant frequency and constant voltage from the wind turbine generator whose speed is changed irregularly with fluctuations in natural wind.

The basic configuration of the proposed wind turbine

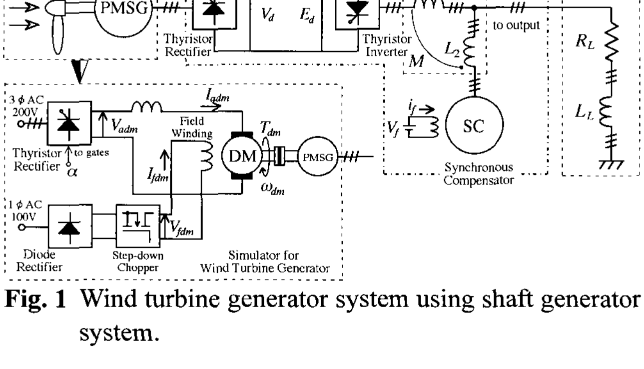

**Fig. 1** Wind turbine generator system using shaft generator system.

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generating system is first explained. And the equations expressing the system are derived. Then the characteristics of the generating system are discussed. We use an experimental system which can simulate the characteristics of a wind turbine in this study, because it is hard to operate an actual wind turbine in a laboratory. In addition, the transient responses of this system are investigated when the velocity of the wind is changed. It is shown that experimental results were very close to the simulated ones, supporting the usefulness of the theory.

## 2. Experimental System

### 2.1 Wind turbine generator system with shaft generator system

The power conversion system used in the proposed wind turbine generating system is widely used for power sources in large ships since it has many advantages, such as high reliability and low distortion of the output waveform [2].

The shaft generator system generates the electric power from the shaft generator in the propeller shaft connected with the screw propeller and the main engine of the ship. The output voltage and frequency of the shaft generator may be changed because of the change in the speed of the main engine. Hence, the power produced by the shaft generator is converted into ac power with constant voltage and frequency by controlling the inverter to feed the loads in the ship.

This system can be readily applied to the wind turbine generator system to obtain the power with constant frequency and constant voltage, as the speed of the wind turbine is changed desultorily.

Fig. 1 shows the configuration of the wind turbine generator system proposed in this paper [3,4]. As in the figure, the system consists of a wind turbine, a permanent magnet synchronous generator, a thyristor rectifier, a thyristor inverter, and a synchronous compensator.

The permanent magnet synchronous generator is driven by the wind turbine. However, the output voltage and frequency of the generator are changed due to unexpected fluctuation of the wind. So, the generated ac power is converted once into dc power with the thyristor rectifier, and then the dc power is converted again into ac power with constant frequency and constant voltage with the inverter, which is supplied to the loads. The synchronous compensator provides reactive power for commutation of inverter thyristors and for loads. In the ordinary type of shaft generator system there is a large amount of harmonic components in the output voltage waveform because of the existence of the subtransient inductance of the synchronous compensator. In the proposed system, however, the adoption of ac duplex reactor as shown in Fig. 1 can eliminate the distortion in the output voltage almost completely [2].

### 2.2 Wind turbine simulator using a direct current motor

Usually, the output of the wind turbine depends on the wind velocity which changes with respect to time. Hence it is hard to carry out the experiments for any desirable condition with an actual wind turbine in a laboratory. For this reason we provide a wind turbine simulator with a dc motor which can simulate any characteristics of the actual wind turbine exactly, and this simulator is used to discuss the performance characteristics of the power conversion system shown in Fig. 1 [5].

In general, the output power of the wind turbine $P_{turbine}$ is given by:

$$P_{turbine} = \frac{1}{2} C_P \rho A_{wind} V_{wind}^3 \tag{1}$$

where $C_P$ is power coefficient, $A_{wind}$ is the swept area of the wind turbine, and $V_{wind}$ is wind velocity.

When the angular speed of the turbine is $\omega_{turbine}$, torque gained from the wind turbine $T_{turbine}$ is obtained by:

$$T_{turbine} = \frac{P_{turbine}}{\omega_{turbine}} \tag{2}$$

On the other hand, torque produced by the dc motor $T_{dm}$ becomes:

$$T_{dm} = pM \cdot I_{adm} I_{fdm} \tag{3}$$

where $pM$ is dc motor constant, $I_{fdm}$ is field current, and $I_{adm}$ is armature current.

When equation (2) and (3) are supposed to be equal, the output torque of the dc motor is identical to that of the wind turbine. Then we obtain the armature current of the dc motor $I_{adm}$ as:

$$I_{adm} = \frac{T_{turbine}}{pM \cdot I_{fdm}} \tag{4}$$

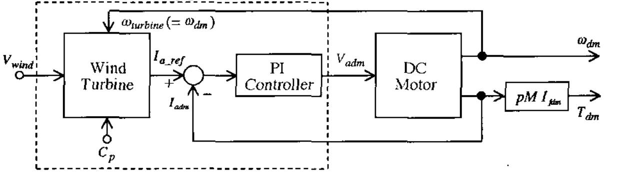


Fig. 2 Simulator for wind turbine.

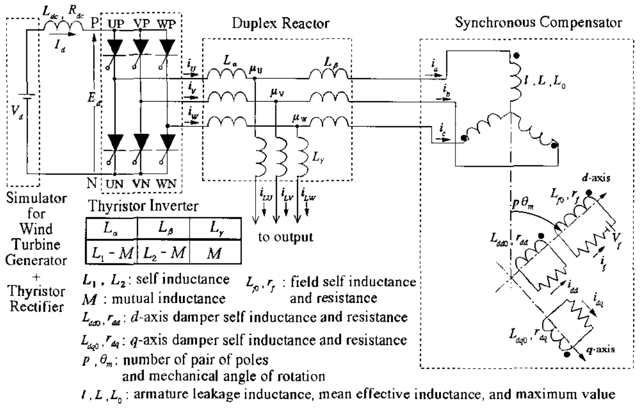


**Fig. 3** Equivalent circuit for shaft generator system.

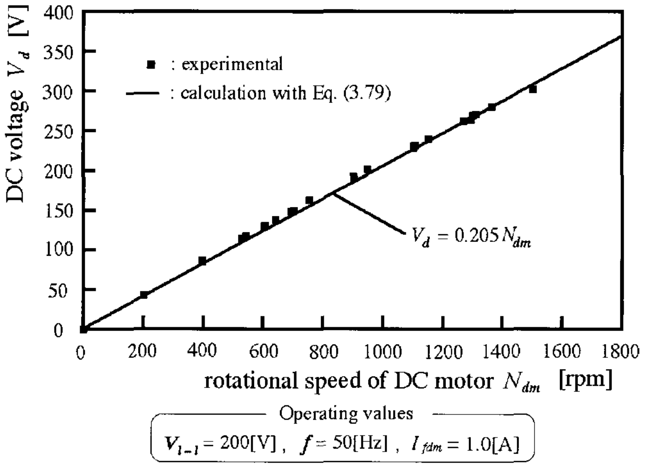


**Fig. 4** $N_{dm}$-$V_d$ characteristic of experimental system.

Therefore, as in Fig. 2, we equate the rotational angular speed of the dc motor $\omega_{dm}$ to $\omega_{turbine}$, and the armature current of the dc motor is controlled so that it becomes to the reference current $I_{a\_ref}$, which is given by (4), with the PI controller. Consequently, we can simulate the wind turbine by controlling the dc motor.

## 3. Analytical Results

### 3.1 Steady-state equations

In order to discuss the steady-state characteristics of this system and clarify its operating range, a set of steady-state equations is derived here.

Fig. 3 shows the equivalent circuit of the shaft generator system [6]. In this figure, the dc input voltage $V_d$ represents the output voltage of the rectifier whose input is the output voltage of the permanent magnet generator as in Fig. 1. It should be noted that $V_d$ is almost proportional to the wind velocity. We derive the steady-state equations of this system based on the equivalent circuit of Fig. 3. The derived equations are given in Table 1 [2].

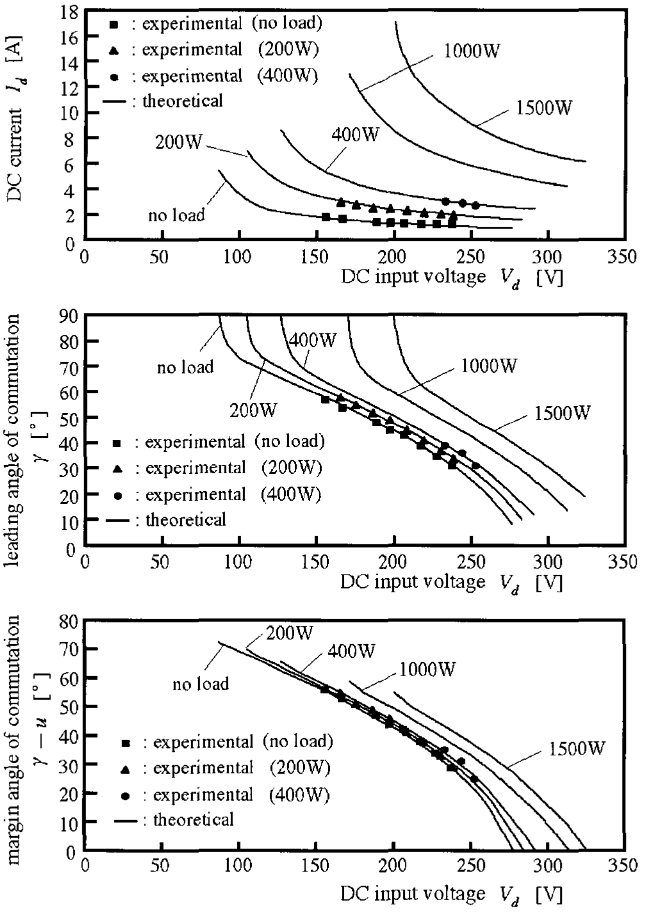


**Fig. 5** Steady-state characteristics.

### 3.2 Steady-state characteristics

Tables 2 and 3 show the ratings and the parameters of the experimental system, respectively. Fig. 4 shows the relationship between the dc voltage rectified from the output of the permanent magnet synchronous generator $V_d$ and the rotational speed of the dc motor $N_{dm}$. The plotted points show the experimental values with the tested system, and the solid line is an approximation curve. From this figure, it is shown that $V_d$ is almost directly proportional to $N_{dm}$, and this relation is given by:

$$V_d = 0.205 N_{dm} \qquad (36)$$

Fig. 5 shows the steady-state characteristics of the tested system when the system output is kept constant at $V_{l\text{-}l}$ = 200 V, and $f$ = 50 Hz. In these figures, the theoretical values and the experiment results of dc side current $I_d$, leading angle of commutation of the inverter $\gamma$, and margin angle of commutation $\gamma$-$u$ are given for various values of $V_d$ , which is proportional to $N_{dm}$. It is shown that the theoretical and experimental values are very close, supporting the validity of the theory.

**Table 1** Steady-state equations of wind turbine generator system.

| Items | | Equations | No. |
|---|---|---|---|
| DC circuit | | $V_d = (R_{dc} + 2r_{ac}) I_d + E_d$ | (5) |
| | | $E_d = \frac{3\sqrt{6}}{\pi} V_\mu \frac{\cos(\gamma - u) + \cos\gamma}{2}$ | (6) |
| | | $E_x = \frac{3\sqrt{6}}{2\pi} V_\mu \left\{\cos(\gamma - u) - \cos\gamma\right\}$ | (7) |
| Synchronous Compensator | Armature EMF And current | $V_i = \sqrt{\left\{V_P + I_L (X_\beta + X_\gamma + X_S^{"}) \sin\varphi\right\}^2 + \left\{I_L (X_\beta + X_\gamma + X_S^{"}) \cos\varphi\right\}^2}$ | (8) |
| | | $\varepsilon = \tan^{-1}\left(\frac{I_L (X_\beta + X_\gamma + X_s^{"}) \cos\varphi}{V_P + I_L (X_\beta + X_\gamma + X_s^{"}) \sin\varphi}\right)$ | (9) |
| | | $I_1 = \sqrt{\left(\frac{\sqrt{6} I_d}{\pi}\right)^2 + I_L^2 - 2\frac{\sqrt{6} I_L I_d}{\pi} \cos\left(\gamma + \varphi - \frac{u}{2} + \varepsilon_2\right)}$ | (10) |
| | | $\zeta = \pi - (\varphi + \varepsilon) - \sin^{-1}\left\{\frac{\sqrt{6} I_d}{\pi I_1} \sin\left(\gamma + \varphi - \frac{u}{2} + \varepsilon_2\right)\right\}$ | (11) |
| | Output terminal of compensator | $I_a = \sqrt{\frac{1}{\pi}\left[\left(\frac{2\pi}{3} - \frac{u}{3}\right) I_d^2 + \pi I_L^2 + \frac{2\sqrt{6}}{u} I_d I_L \left\{\sin(\gamma + \varepsilon_2 + \varphi - u) - \sin(\gamma + \varepsilon_2 + \varphi)\right\}\right]}$ | (12) |
| | | $V_{SC} = \sqrt{\left\{V_P + I_L (X_\beta + X_\gamma) \sin\varphi\right\}^2 + \left\{I_L (X_\beta + X_\gamma) \cos\varphi\right\}^2}$ | (13) |
| | | $\varepsilon_1 = \varepsilon_2 - \tan^{-1}\left\{\frac{I_L (X_\beta + X_\gamma) \cos\varphi}{V_P + I_L (X_\beta + X_\gamma) \sin\varphi}\right\}$ | (14) |
| | Damper circuit | $\begin{bmatrix} \psi_{d01} \\ \psi_{q01} \end{bmatrix} = \frac{3}{2}\sqrt{2} I_1 \begin{bmatrix} -L_{add} \sin(-\alpha + \zeta) \\ L_{adq} \cos(-\alpha + \zeta) \end{bmatrix}$ | (15) |
| | Armature reaction angle and field circuit | $V_i = \frac{\sqrt{A^2 + B^2}}{\sqrt{2}}$ | (16) |
| | | $\tan\alpha = \frac{B}{A}$ | (17) |
| | | $\begin{bmatrix} A \\ B \end{bmatrix} = p\omega_m \begin{bmatrix} L_{af} i_f + k_d \psi_{d0} \\ -k_q \psi_{q0} \end{bmatrix} + P \begin{bmatrix} -k_q \psi_{q0} \\ L_{af} i_f + k_d \psi_{d0} \end{bmatrix}$ | (18) |
| | | $V_f = r_f i_f$ | (19) |
| | Air gap flux | $\psi_g = \sqrt{(L_{af} i_f + k_d \psi_{d0})^2 + (k_q \psi_{q0})^2}$ | (20) |
| Angle of overlap of inverter currents | | $u = \gamma - \cos^{-1}\left\{\frac{2(X_\alpha + X_\beta + X_S^{"}) I_d}{\sqrt{6} V_\mu} + \cos\gamma\right\}$ | (21) |
| Output Load Circuit | | $V_1 = \frac{\sqrt{a_1^2 + b_1^2}}{\sqrt{2}}$ | (22) |
| | | $I_L = \frac{\sqrt{a_1^2 + b_1^2}}{\sqrt{2}\sqrt{R_L^2 + (\omega L_L)^2}}$ | (23) |
| | | $a_1 = \sqrt{2} V_P \cos\left(\gamma + \varepsilon_2 - \frac{\pi}{6}\right) + \frac{\sqrt{6}}{\pi} k_1 V_\mu \left\{-u \cos\left(\gamma - \frac{\pi}{6}\right) + \cos\left(\gamma + \frac{\pi}{6} - u\right) \sin u\right\}$ | (24) |
| | | $b_1 = -\sqrt{2} V_P \cos\left(\gamma + \varepsilon_2 - \frac{\pi}{6}\right) + \frac{\sqrt{6}}{\pi} k_1 V_\mu \left\{u \sin\left(\gamma - \frac{\pi}{6}\right) + \sin\left(\gamma + \frac{\pi}{6} - u\right) \sin u\right\}$ | (25) |
| | | $\eta_1 = \tan^{-1}\left(\frac{b_1}{a_1}\right) + \gamma - \frac{\pi}{6} + \varepsilon_2$ | (26) |
| | | $\varphi_L = \tan^{-1}\left(\frac{\omega L_L}{R_L}\right)$. | (27) |
| | | $\varphi = \varphi_L - \eta_1$ | (28) |
| | | $V_O = \sqrt{V_P^2 + \frac{2}{\pi} k_1^2 V_\mu^2 \left\{u - \sin u \cos(2\gamma - u)\right\} - \frac{2\sqrt{3}}{\pi} k_1 V_P V_\mu \left\{u \cos\varepsilon_2 - \frac{1}{2}\sin(2u - 2\gamma - \varepsilon_2) - \frac{1}{2}\sin(2\gamma + \varepsilon_2)\right\}}$ | (29) |
| | | $k_1 = \frac{\sqrt{3}(X_\beta + X_S^{"})}{2(X_\alpha + X_\beta + X_S^{"})}$ | (30) |
| Imaginary terminal phase voltage | | $V_\mu = \sqrt{(V_P + X_\gamma I_L \sin\varphi)^2 + (X_\gamma I_L \sin\varphi)^2}$ | (31) |
| | | $\varepsilon_2 = \tan^{-1}\left(\frac{X_\gamma I_L \cos\varphi}{V_P + X_\gamma I_L \sin\varphi}\right)$ | (32) |
| Input to inverter, output, and losses | | $P_{in} = E_d I_d$ | (33) |
| | | $P_{out} = 3 V_P I_L \cos\varphi + 3 V_\mu I_L \frac{k_1}{\pi} \times \left\{-\sqrt{3} u \cos(\varepsilon_2 + \varphi) + \frac{\sqrt{3}}{2}\sin(2u - 2\gamma - \varepsilon_2 - \varphi) + \frac{\sqrt{3}}{2}\sin(\gamma + \varepsilon_2 + \varphi)\right\}$ | (34) |
| | | $P_{loss} = 3 r_a I_a^2 + P_m$ | (35) |

**Table 2** Ratings of the experimental system.

(a) DC Motor

| | |
|---|---|
| Output | 2.2[kW] |
| rotational speed | 3000 [rpm] |
| armature voltage | 220 [V] |
| armature current | 10 [A] |
| field voltage | 140 [V] |
| field current | 1.04 [A] |
| Number of poles | 2 |

(b)Permanent Magnet Synchronous Generator

| | |
|---|---|
| Output | 2.0 [kVA] |
| rotational speed | 600 [rpm] |
| armature voltage | 80 [V] |
| armature current | 14 [A] |
| Frequency | 60 [Hz] |
| number of poles | 12 |

(c) Synchronous Compensator

| | |
|---|---|
| Output | 2.77 [kVA] |
| rotational speed | 1500 [rpm] |
| Voltage | 200 [V] |
| Current | 8.0 [A] |
| Number of poles | 4 |

**Table 3** Parameters of the experimental system.

(a) Parameters of DC Motor

| | | | | | |
|---|---|---|---|---|---|
| $R_{adm}$ | 3.103 [Ω] | $R_{fdm}$ | 114.5 [Ω] | $J_{dm}$ | 0.198 [kg-m$^2$] |
| $L_{adm}$ | 300 [mH] | $L_{fdm}$ | 3.7 [H] | | |

(b) Parameters of Shaft Generator System

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $r_{dc}$ | 3.92 [Ω] | $r_f$ | 43.25 [Ω] | $l_f$ | 1.11 [H] | $J$ | 0.31 [kg-m$^2$] |
| $L_{ac}$ | 2.82 [mH] | $L_{dc}$ | 397 [mH] | $L_{ad}$ | 19.7 [mH] | $L_{aq}$ | 9.55 [mH] |
| $L_1$ | 25.38 [mH] | $L_2$ | 11.28 [mH] | $L_s''$ | 5.64 [mH] | $L_{af}$ | 473 [mH] |
| $T_{dd}$ | 10.3 [ms] | $T_{dq}$ | 2.86 [ms] | | | | |

**Table 4** Parameters of wind turbine simulator.

| | |
|---|---|
| Power coefficient | $C_p = 0.35$ |
| Turbine radius | $R_{wind} = 1.62$ [m] |
| Are density | $\rho$=1.255 [kg/m$^3$] |

As to the characteristics of $I_d$, it decreases with an increase in $V_d$, since the output power (therefore, input power) is kept constant for each case.

Also, it is shown that the leading angle $\gamma$ is decreased with $V_d$. This is because $\gamma$ should be decreased to increase $V_d$. 90[°] is minimum value for $\gamma$.

In the characteristics of $\gamma$-$u$, since overlapping angle $u$ increases with an increase in $I_d$, $\gamma$-$u$ shown in the figure is obtained. When $\gamma$-$u$ becomes 0[°], commutation failure occurs and the system will be out of operation.

From these results the operating range of $V_d$ for the experimental system is roughly 80 V to 200 V. Based on the voltage range together with the ratings of the tested dc motor, we have concluded that the parameters of the wind turbine simulator are those given in Table 4.

### 3.3 Transient characteristics

We discuss basic transient performances of the proposed system. Here, transient responses when the wind velocity is changed for the case of open-loop control without any feedback loops are investigated. Fig. 6 shows the block diagram to simulate the open-loop transient responses of the wind turbine system introduced in this paper. This diagram is derived from a set of transient equations for the system of Figs. 2 and 3. As in Fig. 1, an inductive load is considered as a system load, and a position sensor of voltage sensing type is used for stable operation of the inverter [3].

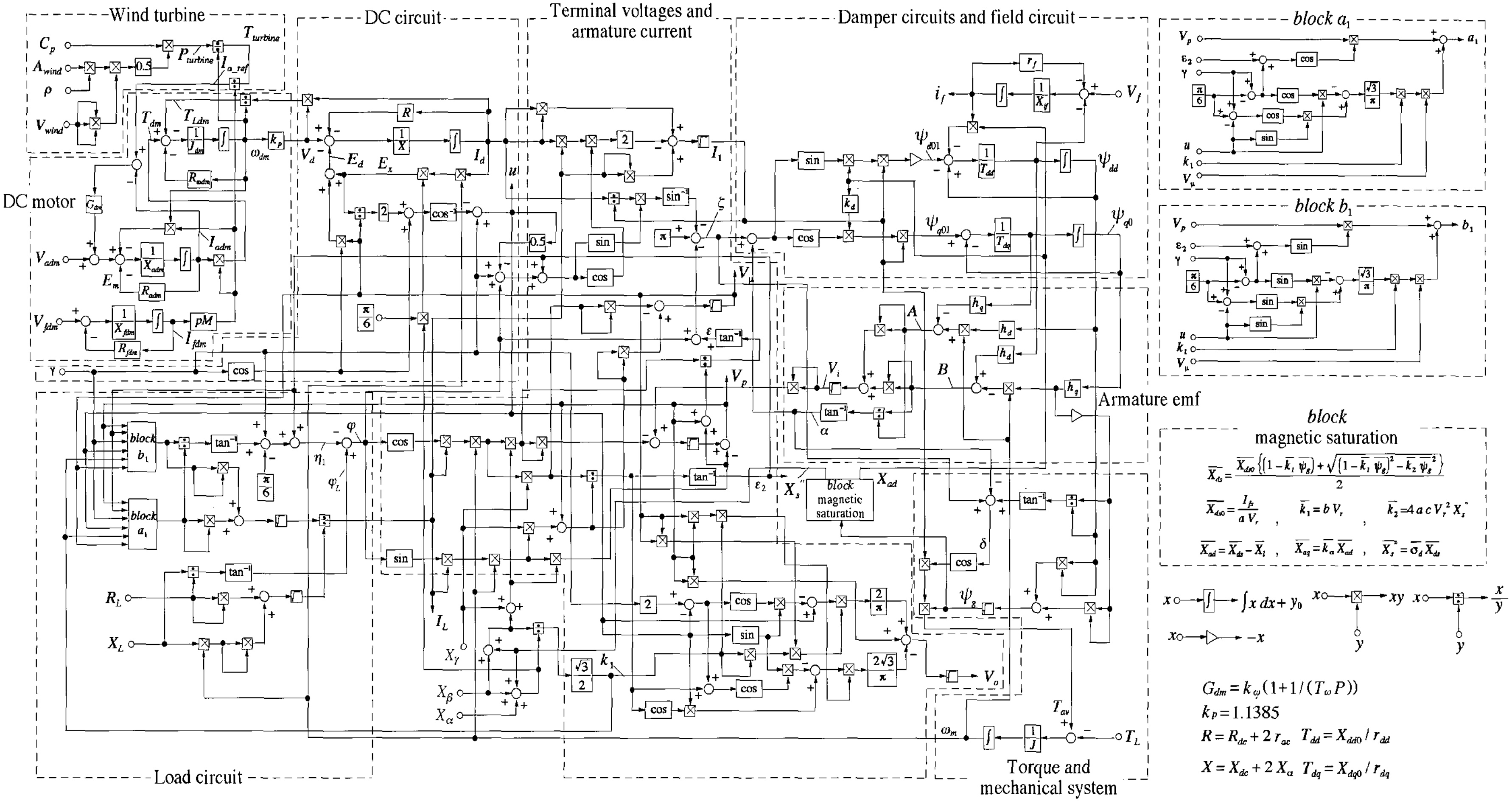
Fig. 7 shows the transient responses of armature current of the dc motor $I_{adm}$, dc motor speed $N_{dm}$, dc side current of the inverter $I_d$, output frequency $f$ and RMS value of the output line-to-line voltage $V_{l\text{-}l}$ when the wind velocity increase from 7.5 [m/s] to 8.0 [m/s] in ramp-form, and Fig. 8 shows those when the wind velocity decrease from 8.0 [m/s] to 7.5 [m/s]. In these responses there are theoretical responses simulated with the block diagram given in Fig. 6 as well as experimental results.

These transient characteristics show the validity of the theory because of a good agreement between the theoretical and experimental values.

## 4. Conclusion

In this paper the steady-state characteristics and the open-loop transient responses of the wind turbine gene-rator system using a shaft generator system have been discussed. The good agreement between the theoretical and the experimental results has shown the validity of the theory.

The transient performances of the closed control system for constant output voltage and frequency should be clarified, and the performance analysis of the proposed system when it is connected with utility power system has to be discussed. These are left for future study.



$V_{wind}$: wind velocity. $A_{wind}$: swept area. $\rho$: air density. $P_{turbine}$: wind turbine power. $C_p$: power coefficient. $T_{turbine}$: wind turbine torque. $J_{dm}$: moment of inertia of DC motor. $T_{dm}$: average torque of DC motor. $T_{Ldm}$: load torque of the DC motor. $pM$: DC machine constant. $I_{a\_ref}$: reference of armature current. $V_{adm}$, $I_{adm}$: armature voltage and current of DC motor. $V_{fdm}$, $I_{fdm}$: field voltage and current of DC motor. $V_d$, $I_d$: DC input voltage and current. $E_d$: average value of inverter DC side voltage. $E_x$: voltage drop due to overlap of armature current. $V_p$: RMS value of output phase voltage when the voltage distortion due to commutation is compensated. $V_o$: RMS value of output phase voltage. $V_i$, $I_1$: RMS value of armature EMF and fundamental component of current. $\psi_{d01}$, $\psi_{q01}$: flux linkages of $d$-axis and $q$-axis damper windings caused by $I_1$. $\psi_{dd}$, $\psi_{q0}$: total flux linkages of $d$-axis and $q$-axis damper windings. $V_f$, $i_f$: field voltage and current of the compensator. $X_{lf}$: field leakage reactance. $T_{av}$: average torque. $T_L$: load torque corresponding to the losses of the compensator. $J$: moment of inertia of compensator. $X_\alpha$, $X_\beta$, $X_\gamma$ : AC reactor reactance. $X_s''$: subtransient reactance. $X_{ad}$, $X_{aq}$: $d$-axis and $q$-axis armature reaction reactance. $X$: DC reactor reactance. $u$: angle of overlap of inverter output current. $\zeta$: leading angle determined by $V_i$ and $I_1$. $\alpha$: armature reaction angle.

**Fig. 6** Block diagram representation of the dynamic model (per-unit representation)

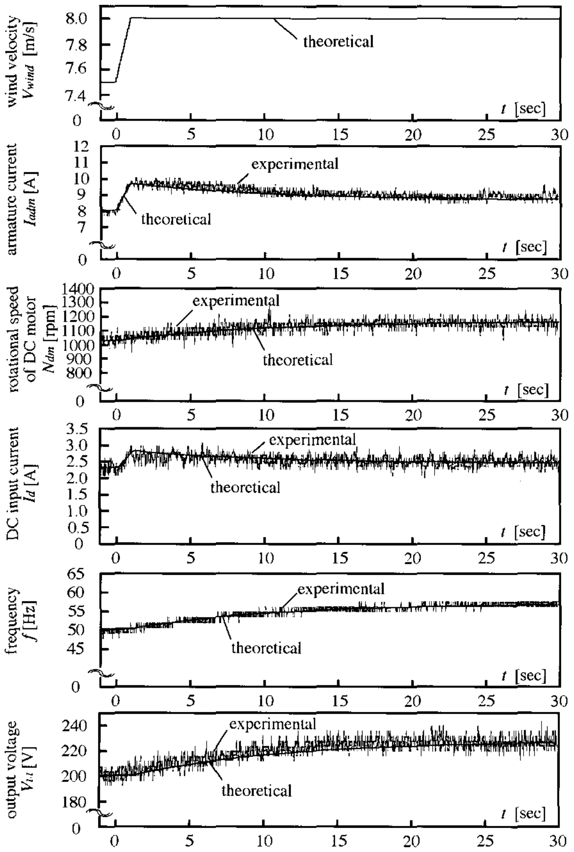


**Fig. 7** Transient responses when $V_{wind}$ was increased.

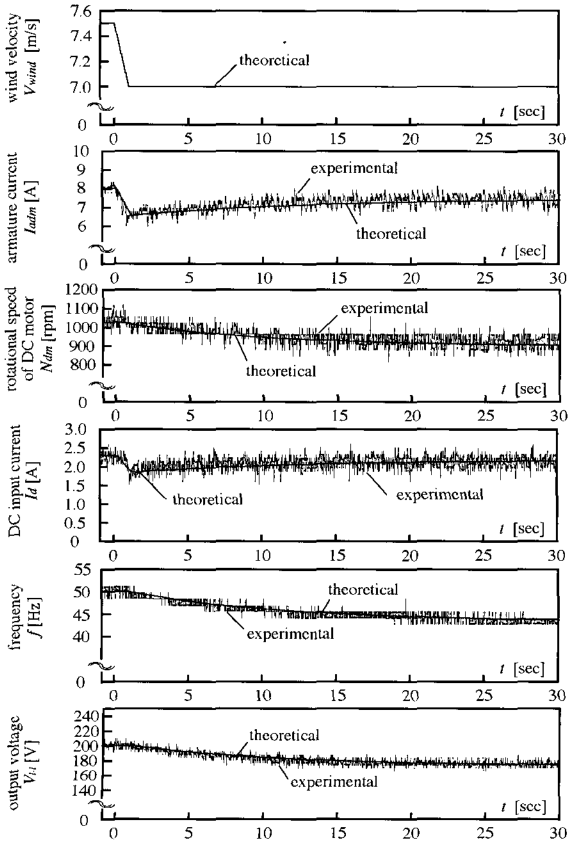


**Fig. 8** Transient responses when $V_{wind}$ was decreased.

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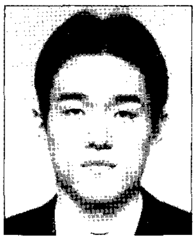

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