Modeling of a Variable Speed Wind Turbine in Dynamic Analysis

Seul-Ki Kim*, Eung-Sang Kim* and Jin-Hong Jeon**

Abstract - This paper describes the dynamic performance of a variable speed wind turbine system responding to a wide variety of wind variations. Modeling of the wind generation using power electronics interface is proposed for dynamic simulation analysis. Component models and equations are addressed and their incorporations into a transient analysis program, PSCAD/EMTDC are provided. A wind model of four components is described, which enables observing dynamic behaviors of the wind turbine resulting from wind variations. Controllable power inverter strategies are intended for capturing the maximum power under variable speed operation and maintaining reactive power generation at a pre-determined level for constant power factor control or voltage regulation control. The components and control schemes are modeled by user-defined functions. Simulation case studies provide variable speed wind generator dynamic performance for changes in wind speed

Keywords: controllable power inverter, dynamic performance, variable speed wind turbine, wind model

1. Introduction

Variable speed operation yields 20 to 30 percent more energy than fixed speed operation, providing benefits in reducing power fluctuations and improving var supply. Falling prices of power electronics have made variable speed technology more economical [1]. Such a generation cannot be easily connected to electric power networks without performance and impact analysis. Furthermore, reliable tools for assessing the dynamics of the new generation need be developed and provided.

The purpose of this work is to provide the capability of analyzing the dynamic performance of a variable speed wind energy conversion system using a power system transient program. The modeled system consists of fixed-pitch type wind blades, a direct-drive without a gear-box, a high pole permanent magnet synchronous generator [2], and rectifier and voltage source inverter system. Models of the components and their control schemes are proposed for dynamic simulation and implemented as user defined components into a PC version of the transient analysis program PSCAC/EMTDC [3]. Implementing the proposed model into the program is partly supported by the pre-developed models of the program. The study results demonstrate the modeling work provided by a simulation tool for evaluating the transient impacts of variable speed wind turbines integrated into power systems.

2. A Variable Speed Wind Turbine Model

The variable speed wind turbine model consists of the following subsystems.

- Wind model
- Wind blade dynamics
- Shaft dynamics
- Synchronous generator model
- Power electronics control

The entire schematic diagram is shown in Fig. 1. Each component model as well as the entire system control will be addressed in the following sections.

For modeling the shaft and synchronous generator, models provided by the EMTDC program are used, and models of the wind speed, wind turbine, power electronics block and control block are built into the program by coding in FORTRAN and constructing control block circuits.

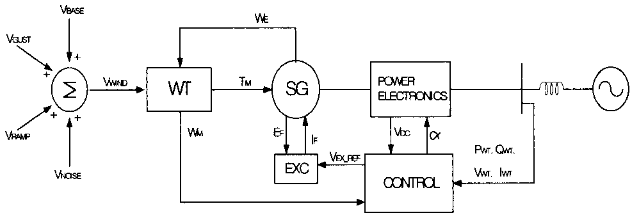

Fig. 1 Modeled VSWT

2.1 Wind Model

Wind is intermittent and ever changing. Such characteristic as an energy resource is unique to the wind

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turbine-generator system and is not required for other generator systems. The wind model selected for this study is a four-component model [4], and can be presented by (1).

$$V_{WIND} = V_{BASE} + V_{GUST} + V_{RAMP} + V_{NOISE} \qquad (1)$$

Where, V_{BASE} = base wind speed [m/s]
V_{GUST} = gust wind component [m/s]
V_{RAMP} = ramp wind component [m/s]
V_{NOISE} = noise wind component [m/s]

The base component is a constant speed, which is assumed in this study to be ever present in case the wind turbine is required to be in service, and is described by (2).

$$V_{BASE} = K \text{ [m/s]} \qquad (2)$$

The wind gust component is usually expressed as a sine or cosine wave function [5]. In this simulation, a combination of an arbitrary number of different cosine functions is used for wind gust as may be given in (3).

$$V_{GUST} = \begin{cases} 0, & t < T_{IG} \ or \ t > T_{2G} \\ \sum_{i}^{N} \frac{K_{MAXG,i}}{2} \cos\{\frac{2\pi}{T_i}(t - T_{shf,i})\}, & T_{IG} \le t \le T_{2G} \end{cases} \qquad (3)$$

where N = arbitrary number of total gust types
i = number of i th gust
$K_{MAXG,i}$ = i th gust peak [m/s]
Ti = i th gust period [s]
$T_{shf,i}$ = time shift of i th gust [s]
T_{1G} = gust start time [s]
T_{2G} = gust end time [s], where $T_{2G} > T_{1G}$.

The ramp wind component is described by (4).

$$V_{RAMP} = \begin{cases} 0, & t < T_{IR} \ or \ t > T_{2R} \\ \pm K_{MAXR}[1 - \frac{(t - T_{2R})}{(T_{1R} - T_{2R})}], & T_{IR} \le t \le T_{2R} \end{cases} \qquad (4)$$

where, K_{MAXR} = ramp maximum [m/s]
T_{1R} = ramp start time [s]
T_{2R} = ramp end time [s] and where $T_{2R} > T_{1R}$.

The noise component of wind speed is defined in this study by a triangle wave function, the frequency and magnitude of which are adjustable. Since there is a triangle wave generator available in the commercial version, it is used as a noise generator.

Based on the equations related to the four components, a wind speed model is constructed by integrating the functions provided in the program. To approximate the wind speed shape a real-life pattern is possible by combining the four components described above and manipulating their parameters, even though it may take some degree of trial and error.

2.2 Wind Blade Dynamics

The wind blade dynamics are described by the following relationships.

$$\lambda = \frac{\omega_M R}{V_{WIND}} \qquad (5)$$

$$\begin{aligned} P_M &= \frac{1}{2}\rho\pi R^2 C_P V_{WIND}^{\ 3} \\ &= \frac{1}{2}\rho\pi R^5 C_P \frac{\omega_M^{\ 3}}{\lambda^3} \end{aligned} \qquad (6)$$

$$T_M = \frac{P_M}{\omega_M} \qquad (7)$$

where λ = tip speed ratio
ω_M = blade angular speed [mechanical rad/s]
R = blade radius [m]
V_{WIND} = wind speed [m/s]
P_M = mechanical power from wind blades [kW]
ρ = air density [kg/m^3]
C_P = power coefficient
T_M = mechanical torque from wind blades [N·m]

The mechanical torque obtained from (7) enters into the synchronous generator from the input torque and drives the generator. C_P may be expressed as a function of the tip speed ratio (TSR) λ given by (2) [6].

$$C_P = (0.44 - 0.0167\beta)\sin\frac{\pi(\lambda - 2)}{15 - 0.3\beta} - 0.00184(\lambda - 2)\beta \qquad (8)$$

where β is the blade pitch angle. For a fixed pitch type the value of β is set to a constant value. Fig. 2 displays a typical power curve used in this study.

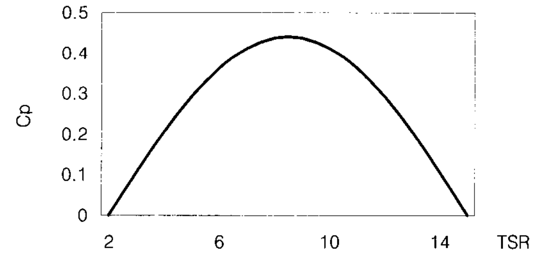


Fig. 2 C_P - λ curve

2.3 Shaft Dynamics

Since the shaft of the studied wind energy system is a direct drive type, and the wind blade and the generator are rotating at the same mechanical speed via the same shaft, shaft dynamics can be characterized by a swing equation on a rotating single mass. The equation that describes the motion of the single direct drive shaft is given by (9).

$$J_M \frac{d\omega_M}{dt} = T_M - T_E - D\omega_M \tag{9}$$

where J_M = a single rotating inertia [kg·m^2]
T_E = electric torque produced by generator [N·m]
D = damping [J·s/rad]

2.4 Synchronous Machine Model

The nonlinear differential equations of synchronous generators can be obtained from Park equations and with this model both sub-transient and transient behavior can be examined. It is considered that the synchronous generator is equipped with an exciter identical to the IEEE type 1 model [7]. The exciter plays the role of meeting the dc link voltage requirement of (10) for the three-phase voltage source inverter, which is used in this study and will be addressed in later sections.

$$V_{DC} \geq \frac{2\sqrt{2} \cdot V_{AC\_RMS}}{D_{MAX}} \tag{10}$$

where V_{DC} = dc link voltage of power electronics
V_{AC_RMS} = rms value of the ac line-to-ground voltage of the inverter
D_{MAX} = maximum duty cycle

PM generators have a large number of poles and rated electrical speed ω_E of the wind turbine generator is determined by (11). This datum should be entered as one of input data into the synchronous model.

$$\omega_E = \frac{P}{2} \cdot \omega_M \tag{11}$$

where P = number of poles in the generator.

2.5 Power Electronics Control

Several types of power electronics interface have been investigated. A six-diode rectifier and voltage sourced inverter system is modeled for ac-dc-ac conversion. The six diodes rectifier converts ac power generated by the wind generator into dc power in an uncontrollable way and so control must be implemented by the power electronics inverter. Current-controlled VSIs can generate an ac current that follows a desired reference waveform so that it can transfer the captured actual power along with the controllable reactive power [8]. A widely used method for current control of voltage source inverters is DQ control, which is adapted for this modeling study. Variables in the three-phase reference frame may be transformed into those in the d-q reference frame rotating at synchronous speed by the rotational d-q transformation matrix T(θ) in (12).

$$\mathrm{T}(\theta) = \frac{2}{3}\begin{bmatrix} 1/2 & 1/2 & 1/2 \\ \cos\theta & \cos(\theta - \frac{2}{3}\pi) & \cos(\theta + \frac{2}{3}\pi) \\ \sin\theta & \sin(\theta - \frac{2}{3}\pi) & \sin(\theta + \frac{2}{3}\pi) \end{bmatrix} \tag{12}$$

where the transformation matrix is defined in (13) [9].

$$[\upsilon_O \; \upsilon_D \; \upsilon_Q]^T = \mathrm{T}(\theta)[\upsilon_A \; \upsilon_B \; \upsilon_C]^T \tag{13}$$

where υ_O, υ_D, υ_Q = variables on the o-d-q frame
υ_A, υ_B, υ_C = variables on the a-b-c frame
θ = phase angle in radians of υ_A

In the three-phase balanced system, the instantaneous active and reactive power outputs, P and Q, of the wind turbine are described by (14).

$$P = \frac{3}{2}(V_D I_D + V_Q I_Q)\,,\quad Q = \frac{3}{2}(V_Q I_D - V_D I_Q) \tag{14}$$

where V_D = d-axis voltage at the wind turbine
V_Q = q-axis voltage at the wind turbine
I_D = d-axis current at the wind turbine
I_Q = q-axis current at the wind turbine.

Since V_D is identical to the magnitude of the instantaneous voltage at the wind generation system and V_Q is zero, simpler expressions of (15) can be obtained.

$$P = \frac{3}{2}|V_O| I_D\,,\quad Q = -\frac{3}{2}|V_O| I_Q \tag{15}$$

where $|V_O|$ is the instantaneous voltage magnitude of the wind turbine system. Even though the output voltage may change owing to the change of the load and the current output, the voltage remains at a level similar to the voltage of a feeder or a substation at which the wind turbine is connected. As such the voltage variation is very small compared to changes in the magnitude of I_D and I_Q. Accordingly, P and Q are mainly subject to the d-axis current and q-axis current, respectively. Fig. 3 illustrates the real and reactive components of DQ control decouples and enables real power and reactive power to be separately controlled by specifying the respective reference values of P_{REF} and Q_{REF} for both power outputs. It also shows the independent adjustment magnitude of the d-axis current I_D and q-axis current I_Q. The reference values P_{REF} and Q_{REF} of the wind generation are set by the real and reactive power output of the VSI control strategies. Specification of the values will be addressed in the following sections.

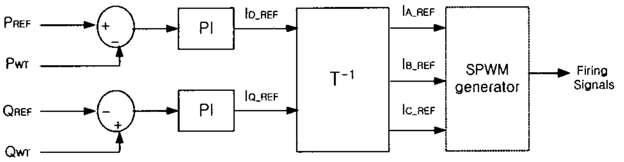


Fig. 3 Decoupled real and reactive power controls

The firing signals are generated by the sine pulse width modulation (SPWM) technique in Fig. 4. The desired current vector I_{ABC_REF} and the actual output current vector I_{ABC_WT} of the wind system are compared and the error signal vector I_{ERR} is compared with a triangle waveform vector to create the switching signals. The inverter is switched at the frequency of the triangle signals.

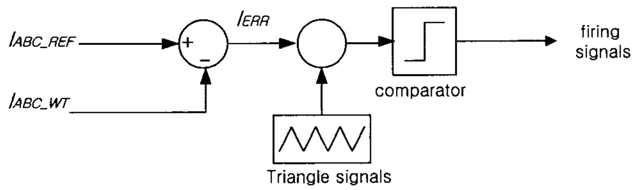


Fig. 4 Sine Pulse Width Modulation (SPWM)

The VSI is a voltage harmonic source in the point view of the ac system and a harmonic filter must be placed appropriately to reduce the voltage harmonics it generates [10]. A L-C harmonic filter consisting of a series interconnection inductor and a parallel capacitor is located at the VSI terminal.

2.5.1 Capturing the maximum power

The power captured by the wind turbine may be described by (6). The power production from the wind turbine can be maximized if the system is operated at maximum C_P. As shown in Fig. 2, the power coefficient varies with TSR. The only operating mode for extracting the maximum energy is, therefore, to vary the turbine speed with varying wind speed such that at all times the TSR is continuously equal to that required for the maximum C_P [1], [11]. The maximum aerodynamic power available P_M^{MAX} is written in (16). To capture the maximum power from the variable speed wind turbine, the reference value of P_{REF} should be set by (17).

$$P_M^{MAX} = \frac{1}{2}\pi\rho R^5 \frac{C_P^{MAX}}{\lambda_{OPT}^3}\omega_M{}^3 \qquad (16)$$

$$\begin{aligned} P_{REF} &= \eta P_M^{MAX} \\ &= K_{WT}\,\omega_M{}^3 \end{aligned} \qquad (17)$$

Where C_P^{MAX} = the maximum power coefficient

λ_{OPT} = value of λ where $C_P^{MAX} = C_P(\lambda_{OPT})$

η = electrical loss in generator and inverter

K_{WT} = wind turbine constant

2.5.2 Regulating reactive power

Various control modes can be used for determining the amount of reactive compensation provided. Possible control modes include power factor, kvar, current and voltage. Constant power factor mode and voltage regulation mode are modeled in this analysis.

In constant power factor control (PFC) mode, the reference value Q_{REF} of the reactive power of the wind turbine may be specified by (18).

$$Q_{REF} = P_{REF} \cdot \frac{\sqrt{1-PF^2}}{PF} \qquad (18)$$

Where PF is the power factor and P_{REF} is the reference value of the real power output of the VSWT.

In voltage regulation (VR) mode, reactive power compensation is controlled in such a manner that the voltage magnitude of the VSWT-connected bus is being kept constant at a specified level. The reference magnitude of the voltage to be regulated must be set as the nominal voltage of the AC grid side where the wind turbine is considered as being interconnected.

The reactive capability limits of a VSWT are determined by the MVA rating of the inverter, which may be described by

$$Q_{LIMITS} = \pm\sqrt{S_{INV}^2 - P_{INV}^2} \qquad (19)$$

Where Q_{LIMITS}, P_{INV} and S_{INV} are the reactive power limits, the real power output and MVA rating of the inverter, respectively [12].

3. Case Study

The variable speed wind turbine for the case study is shown in Fig. 5. The proposed model is implemented into the PSCAD/EMTDC software and simulated for analyzing the dynamic performance of the wind turbine with varying wind conditions. Also, both types of reactive compensation, constant power factor control and voltage regulation control, were implemented to compare the impacts on the bus voltage of the wind turbine. In power factor control the set value is unity, and in voltage regulation mode the reference voltage is set for 1.0 pu. The rating capacity is chosen to be 2MVA. The rated speed of the rotor is chosen to be 26.8 rpm. The SPWM switching frequency of the grid interface inverter is 7.2kHz. It is assumed that the system operates in a balanced condition.

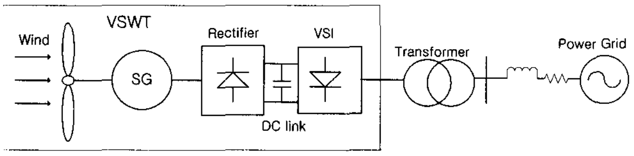


Fig. 5 Simulation system configuration

The wind speed curve used for this study is shown in Fig. 6. The turbine angular speed variations are presented in Fig. 7. Fig. 8 and Fig. 9 illustrate the corresponding tip speed ratio and power coefficient, respectively. When the wind changes, the turbine speed keeps changing, the tip speed ratio goes close to the optimal point of 8.5 and the power coefficient approaches the maximum value of 0.44. Accordingly, it is apparent that the maximum power capture has been well performed. Fig. 10 shows the mechanical torque into and electrical torque from the wind PM generator. The real and reactive power output of the wind turbine in power factor control with varying wind speed is shown in Fig. 11. Inertia smoothing effects are apparent as can be observed in the real power curve. The reactive power output is currently zero for the unit power factor. Fig. 12 demonstrates the voltage fluctuations at the terminal of the wind turbine in the constant power factor. It should be noted that the voltage is varying with power fluctuations and the power variations result from changes in wind speed. Conclusively, wind fluctuation directly causes the voltage changes in case of a variable speed wind turbine operating under a constant power factor, even though the voltage variation width is negligibly small, less than 0.8%, in this case.

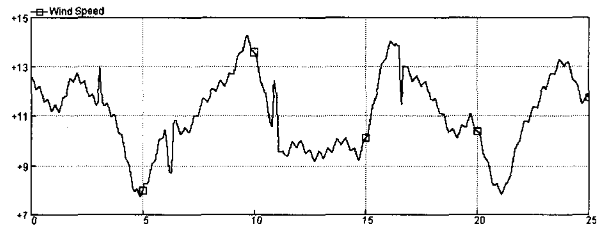


Fig. 6 Wind speed for case study

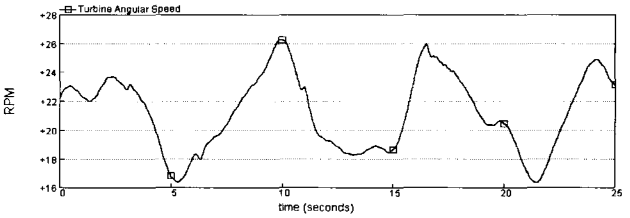


Fig. 7 Mechanical angular speed of wind turbine

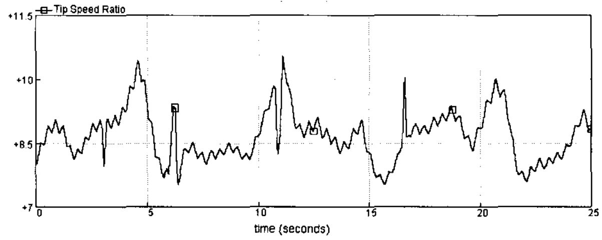


Fig. 8 Tip speed ratio

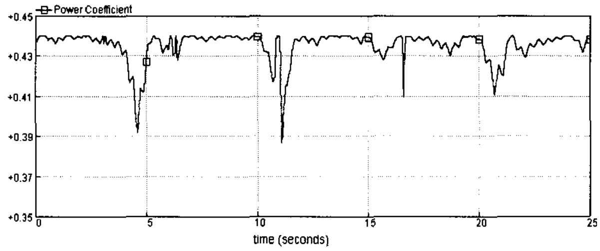


Fig. 9 Power coefficient C_P

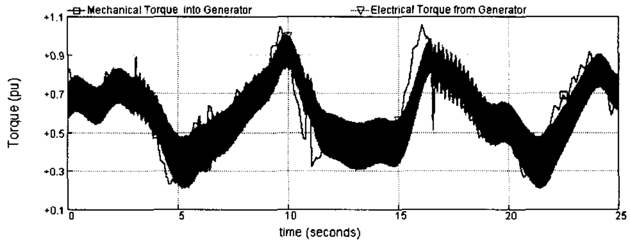


Fig. 10 Mechanical and electrical torque of wind generator

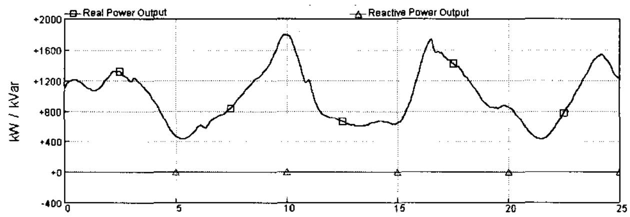


Fig. 11 Real and reactive power of wind turbine in PFC

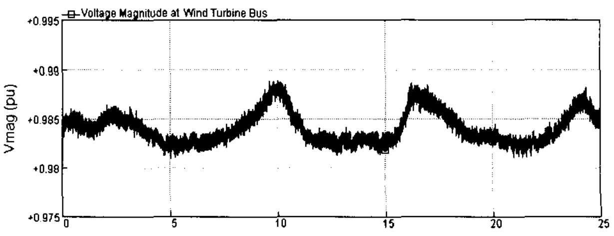


Fig. 12 Terminal bus voltage (rms) in PFC mode

The wind turbine power generation and the corresponding bus voltage are shown in voltage regulation mode in Fig. 13 and Fig. 14, respectively. Since real and reactive power is controlled independently as described earlier, real power generations in PFC and VR mode are identical whereas reactive productions are quite different as presented in Fig. 11 and Fig. 13. In voltage regulation the reactive power is being generated to compensate for the voltage variations that would occur due to wind changes. The bus voltage is being kept constant and uninfluenced by the wind fluctuations.

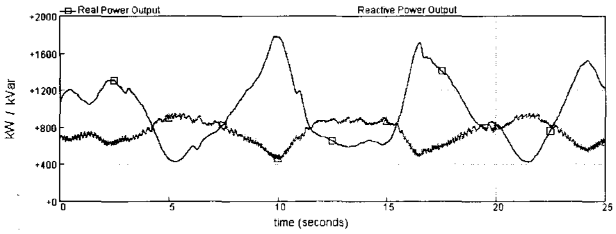


Fig. 13 Real and reactive power of wind turbine in VR

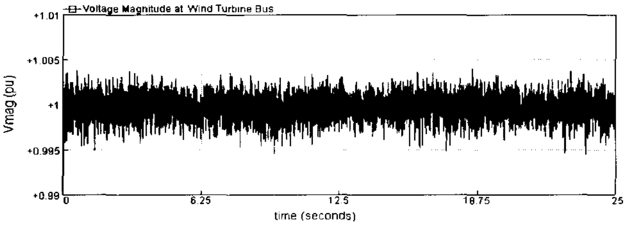
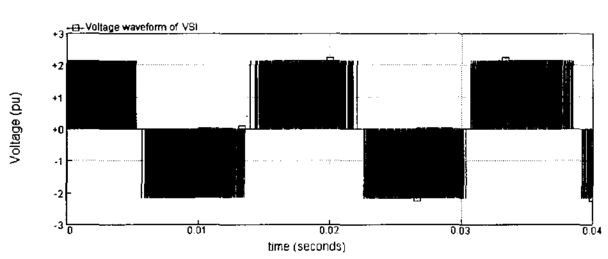
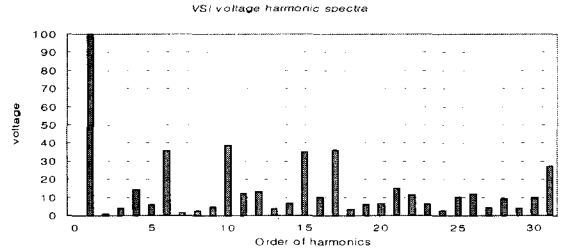


Fig. 14 Terminal bus voltage (rms) in VR mode

The voltage waveform and harmonic spectra at VSI and wind turbine terminal are illustrated in Fig. 15 and Fig. 16. It can be observed that the harmonic distortion can be reduced to a satisfactory level for grid connection through the LC filter.

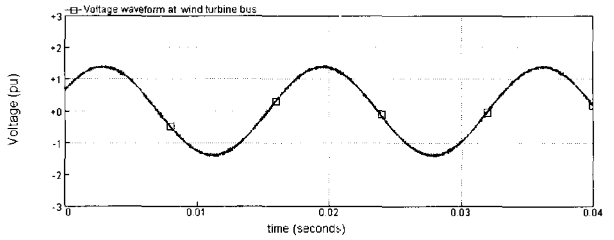


(a) Voltage waveform

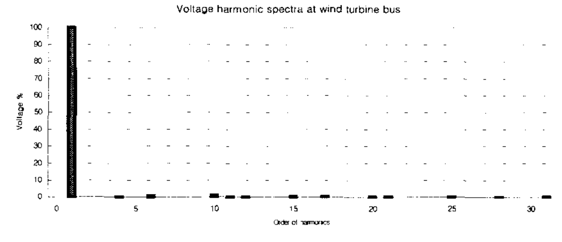


(b) Harmonic spectra

Fig. 15 Voltage at VSI bus



(a) Voltage waveform



(b) Harmonic spectra

Fig. 16 Voltage at wind turbine bus

4. Conclusions

A dynamic model of a variable speed wind generation with power electronic interface was proposed for computer simulation study and implemented into a widely used power system transient analysis program, PSCAD/EMTDC. Component models and controls were built by using user defined functions provided in the software and writing the FORTRAN code. A wind model was integrated into the modeling to see the wind impact. Dynamic responses of the wind turbine to varying wind speeds and under different reactive control schemes were analyzed by simulating the modeled system.

From the viewpoint of electric utilities, grid interface of intermittent generation sources such as wind turbines is a risk that can cause lower power quality in power systems. Impact studies prior to wind turbines being added to real networks are absolutely necessary. Also, users who intend to install wind turbines in networks must ensure their systems meet the requirements for grid connection. Therefore, the work done in this study provides a reliable tool for evaluating the performance of variable speed wind turbines and their impacts on power networks in terms of dynamic behaviors as a preliminary analysis for real applications.

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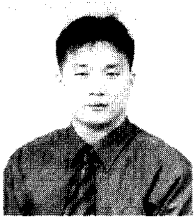

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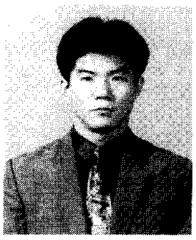

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