Grid Power Quality with Variable Speed Wind Turbines

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***Abstract*—Grid connection of renewable energy sources is essential if they are to be effectively exploited, but grid connection brings problems of voltage fluctuation and harmonic distortion. In the paper, appropriate modeling and simulation techniques are discussed for studying the voltage fluctuation and harmonic distortion in a network to which variable speed wind turbines are connected. Case studies on a distribution network show that the voltage fluctuation and harmonic problems can be minimized with the proposed power electronics interface and control system while the wind energy conversion system captures the maximum power from the wind as wind speed varies. The studies have also demonstrated the ability of the advanced converter to assist the system voltage regulation.**

***Index Terms*—Harmonic minimization, maximum power capture, reactive power control, voltage regulation, wind power.**

I. Introduction

RENEWABLE sources often produce power and voltage varying with natural conditions (wind speed, sun light etc.,) and grid connection of these sources is essential if they are ever to realize their potential to significantly alleviate the present day problems of atmospheric pollution and global warming. However, electric utility grid systems cannot readily accept connection of new generation plant without strict conditions placed on voltage regulation due to real power fluctuation and reactive power generation or absorption, and on voltage waveform distortion resulting from harmonic currents injected by nonlinear elements of the plant.

The paper describes a wind farm comprising a number of turbines housing direct-drive, variable-speed permanent-magnet generators of a novel type proposed in [1] and whose variable-speed capability is achieved through the use of an advanced power electronic converter as described in [2]. The modeling of the wind power converter with the network is addressed using case studies of voltage fluctuation and harmonics propagation. The studies have demonstrated that the impacts on voltage fluctuation and harmonic distortion can be minimized and furthermore, the network voltage control could also be improved by the advanced power electronic converters proposed.

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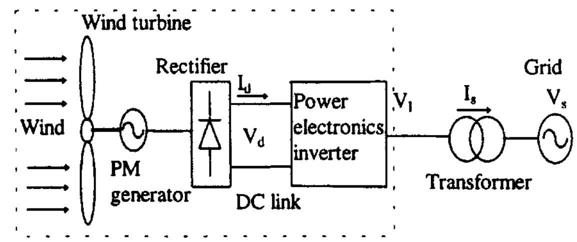


Fig. 1. Schematic wind energy conversion system.

II. Wind Power Converter Modeling

The wind power conversion system studied has the configuration shown in Fig. 1. The system consists of a wind turbine, a high pole number modular PM generator [1], a modular rectifier system [3] and a controllable power electronics inverter [2], [4]. The modeling and simulation of these elements are discussed below.

A. Wind Modeling

Wind is an intermittent and variable source of energy. Wind speed varies with many factors and is random in magnitude and direction. For this study, the wind is simulated with four components, namely, base component, ramp component, gust component and noisy component [5] as:

$$V_{wind} = V_{base} + V_{ramp} + V_{gust} + V_{noise} \quad \text{(m/s)}. \tag{1}$$

B. Wind Turbine Characteristics

The power in the wind is proportional to the cube of the wind speed. However, only part of the wind power is extractable. Although a complete aerodynamic model of the wind turbine could simulate the interaction between the wind and the turbine blades in detail, the simple expression of (2), which is quite often used to describe the mechanical power transmitted to the hub shaft, is sufficient for this study.

$$P_{turbine} = 0.5\, C_p \rho A\, V_{wind}^3 \quad \text{(W)}. \tag{2}$$

Where ρ (kg/m^3) is the air density and A (m^2) is the area swept out by the turbine blades. C_p, a dimensionless power coefficient, depends on the type and operating condition of the wind turbine. For a fixed-pitch turbine, C_p may be expressed as a function of λ [6], the ratio of blade tip speed to wind speed ($\lambda = R\omega/V_{wind}$), with R being the radius (m) of the wind

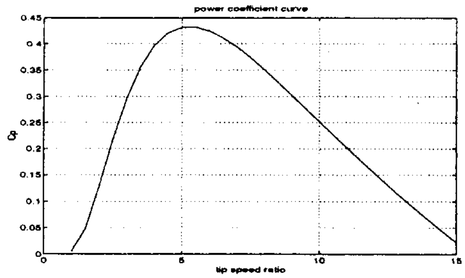


Fig. 2. C_p–λ curve.

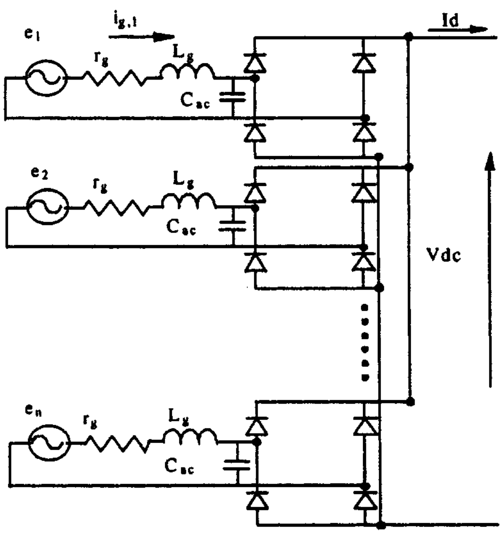


Fig. 3. Modular connection of stator coil and rectifier.

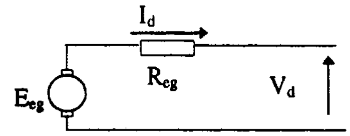


Fig. 4. Circuit model of equivalent DC machine.

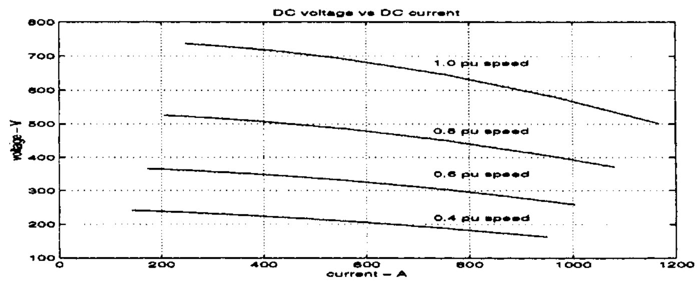


Fig. 5. V_d–I_d characteristics (steady state).

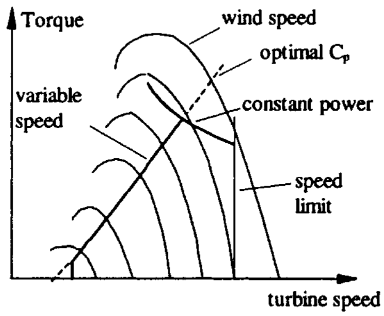


Fig. 6. Variable speed operating curve.

turbine rotor and ω (rad/s) being the angular speed. A typical $C_p - \lambda$ curve is shown in Fig. 2.

C. PM Generator and Rectifier System Modeling

The circuit configuration of n sets of stator and rectifier modules in a modular PM generator system is shown in Fig. 3. The multi-phase rectifier system can be seen as an extension of a three phase parallel bridge rectifier circuit reported in 1970s [7].

A stator coil is represented by an internal resistor (r_g), an inductor (L_g) and an electromotive force (e_j) which is induced by the flux produced by multi-pole set of permanent magnets on the rotor. An ac capacitor is connected in parallel with the ac input terminals of each rectifier module to enhance the power output for matching the wind power characteristic [3].

The above circuit model can be simulated in detail, but a modular PM machine at MW level may have more than a hundred stator modules and associated bridge rectifier units, consequently, the simulation of a circuit model would be very time consuming. A full simulation would only be used when the internal behavior is of interest. With such a large number of phases, the generator-rectifier system produces a smooth dc link voltage and current, therefore, in the steady state, the electrical characteristics as viewed from the dc side may be described by an equivalent DC machine as shown in Fig. 4. The dc system characteristics within the normal operating region are shown in Fig. 5. The dc link voltage V_d and current I_d are related by (3):

$$V_d = E_{eq} - R_{eq} I_d. \tag{3}$$

The parameters (E_{eq}, R_{eq}) of the equivalent DC machine can be expressed as functions of frequency and dc current. These functions can be established by fitting a suitable analytic curve to data obtained by test or numerical simulation [8].

D. Modeling of Machine Motion

As shown in Fig. 1, the wind turbine is directly connected to the generator rotor without a gearbox. The rotational system may therefore be modeled by a single equation of motion:

$$J_{WG} \frac{d\omega_r}{dt} = \frac{1}{\omega_r}(P_W - P_G) - D_{WG} \tag{4}$$

where

ω_r	rotor speed (rad/s)
J_{WG}	mechanical system inertia (kg m^2)
D_{WG}	friction coefficient (N m/rad)
P_W	wind turbine input aerodynamic power (W)
P_G	generator output power plus electrical loss (W) may be approximated as $P_G = V_d \cdot I_d + R_c \cdot I_d^2$
R_c	the combined coil resistance (Ω).

E. Variable Speed Operation

A typical variable speed operating curve is shown in Fig. 6. Above rated wind speed, power output remains at the rated value. As the wind speed reaches cut-off speed, the rotor speed is decreased to induce stall. Below the rated wind speed, the wind turbine follows the optimal tip speed ratio to extract maximum power from the wind. One set of optimal operating

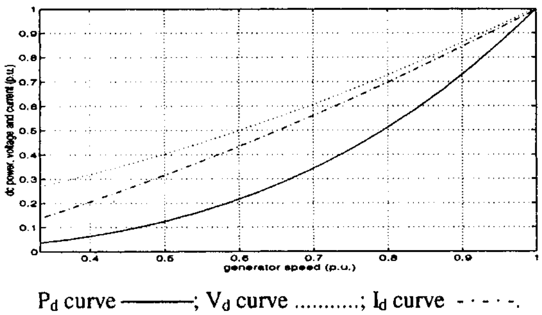


Fig. 7. Generator-rectifier optimal power transfer characteristics.

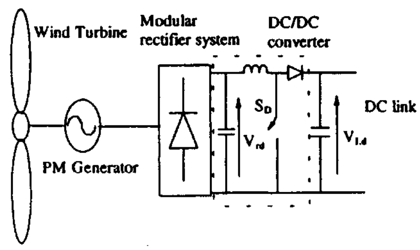


Fig. 8. Modular PM generator-rectifier unit.

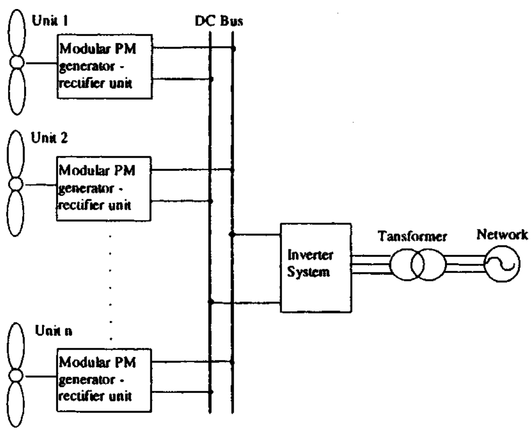


Fig. 9. Schematic wind farm and grid connection.

curves for the modular generator and rectifier (dc terminal) is shown in Fig. 7.

F. Controllable Power Electronics

Below rated wind speed, the control objective is to track wind speed, to capture and transfer the maximum power to the grid. The generator and rectifier system is uncontrolled and so control has to be implemented by the power electronics converters. Several types of power electronics interface have been investigated [2], [4]. One of the options, using a DC/DC converter is shown in Fig. 8.

In a wind farm, there may be dozens of turbines of the type as shown in Fig. 8. These units may be connected in parallel at the dc side to supply power to a common dc bus and current controlled voltage source inverters can then be used to convert the dc power into ac for connection to the grid. Such an arrangements is shown in Fig. 9.

DC/DC Converter Control: DC/DC converters regulate the dc voltages of generator-rectifier units by varying the switching ratio, so that the optimum dc voltage profile, as shown in Fig. 7, is presented at the rectifier terminal for maximum power capture operation. Meanwhile an appropriate dc voltage is maintained at the dc bus to enable the voltage source inverters to perform the optimal real power transfer and reactive power regulation.

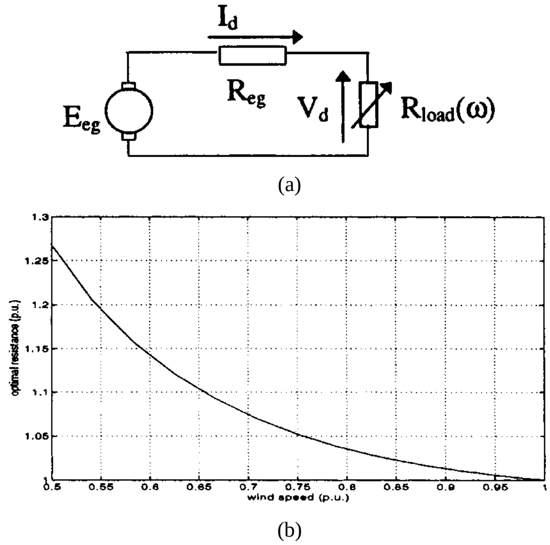


Fig. 10. Optimal resistor loading. (a) Circuit diagram. (b) Characteristics.

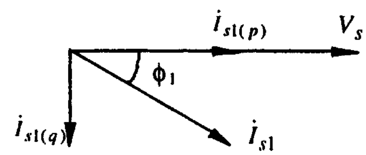


Fig. 11. Inverter-grid phase diagram.

It may be observed that the optimum V_d–I_d characteristic in Fig. 7 can be represented by a variable resistor connected to the PM generator and rectifier terminal. For the purpose of simulating the generator/rectifier therefore, the DC/DC converter and its loading can be represented by an adjustable load resistance. The load resistance value is a function of wind speed as shown in Fig. 10. In practice, the regulation would be implemented by means of a varying PWM switching ratio.

Current-Controlled VSI Control: CC-VSIs can generate an ac current which follows a desired reference waveform and so can transfer the captured real power along with controllable reactive power and with minimal harmonic pollution. The phasor diagram of relevant variables is shown in Fig. 11.

The real and reactive power supplied to the grid is:

$$\begin{aligned} P_s &= P_I = V_s I_{s1} \cos\varphi_1 \\ Q_s &= V_s I_{s1} \sin\varphi_1 \end{aligned} \qquad \text{(pu)} \qquad (5)$$

where V_s is the ac system voltage, I_{s1} is the fundamental component of the inverter ac current and φ_1 is the phase angle between V_s and I_{s1}.With a given ac line voltage, the real power and reactive power can be controlled by regulating the magnitude of I_{s1} and the angle ϕ_1. Equation (5) can be used to represent the CC-VSI for steady state analysis.

In time domain analysis, the inverter simulation model, developed on the basis of switching function concept [9] as shown in Fig. 12, may be used. The desired current and actual current

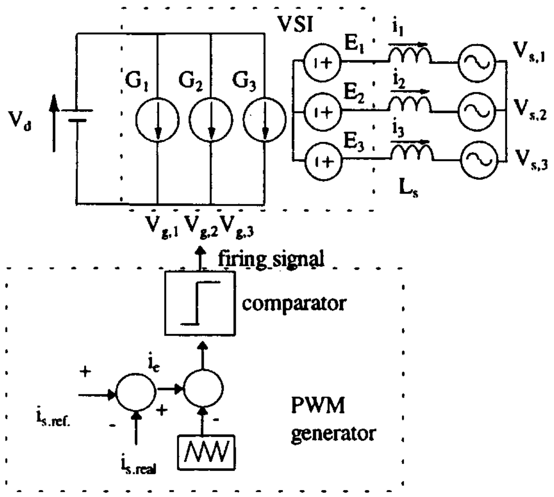


Fig. 12. PWM-VSI grid interface simulation model.

are compared and the error signal is compared with a triangle waveform to generate the inverter firing signals. With this type of control, the inverter is switched at the frequency of the triangle wave and its output current harmonics are well defined.

In a large wind farm, individual machines could experience different wind speed and direction, and therefore give different outputs. However, for the study of the effects of wind power on the grid, the wind farm may be represented with a single equivalent machine, which has the output power equal to that of the whole wind farm. For voltage fluctuation studies, the inverter can then be represented by (5), and for harmonics studies, the model shown in Fig. 12 can be used.

III. Power System Modeling

A. System Modeling for Voltage Fluctuation Studies

The voltage fluctuation problem is closer to a steady state problem such as load varying, which is well defined by the real and reactive power distribution. The harmonics effects may be ignored with PWM switching inverters and appropriately designed filters. Therefore, the conventional power flow equations are sufficient for voltage fluctuation study. The node voltage and node injected power are related by

$$\begin{aligned} P_k &= \sum_{m \notin k} V_k V_m (G_{km}\cos\theta_{km} + B_{km}\sin\theta_{km}) \\ Q_k &= \sum_{m \notin k} V_k V_m (G_{km}\sin\theta_{km} - B_{km}\cos\theta_{km}) \\ \theta_{km} &= \theta_k - \theta_m \\ k &= 1, \ldots, n. \end{aligned} \tag{6}$$

Where

- n is the node number of the power network,
- $\dot{V}_i(V_i\angle\theta_i)$ is the voltage of bus i,
- θ_i is the voltage phase angle with respect to the reference bus,
- P_k and Q_k are the real and reactive power injected at bus k,
- G_{km} and B_{km} are respectively the real and imaginary parts of the node admittance.

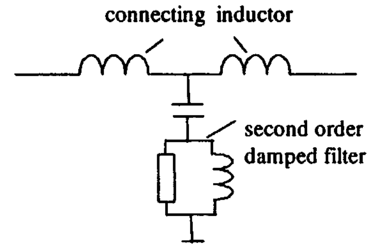


Fig. 13. Harmonic filter arrangement (single phase).

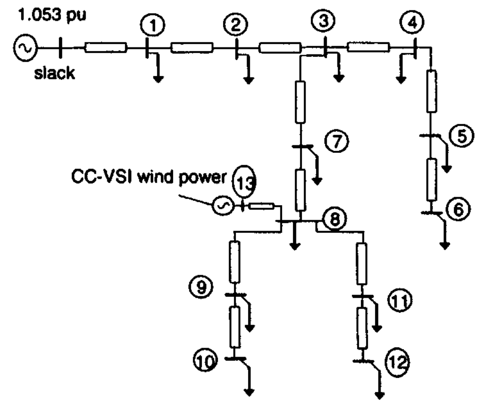


Fig. 14. Power system for the case study.

The wind farm may be considered as a PQ bus. The real power, P_e, injected by the wind farm will be the captured real power and the reactive power, Q_e, can be regulated to meet the system reactive power or voltage regulation requirements.

B. System Modeling for Harmonics Studies

The time domain simulation method is used for power system current harmonic studies. The wind farm is represented by an equivalent PWM current-controlled voltage source inverter as shown in Fig. 12. The inverter operating point is determined by a power flow analysis.

The distribution network is represented by its three phase circuits and the system load is represented by constant resistance and inductance elements. The values of these elements are also determined by the analysis of power flow.

The VSI is a voltage harmonic source in the point view of ac system and a harmonic filter has to be located appropriately to remove the voltage harmonics it creates [10]. In this study, the inductor connecting the VSI to the network is split, a damped second order harmonic filter is placed at the midpoint as shown in Fig. 13.

IV. Case Study

A. Power Network Configuration

A radial distribution system [11] has been chosen for the study. Fig. 14 shows the network configuration.

The slack bus keeps a voltage of 1.053 pu. An equivalent CC-VSI (which, in practice, would be a number of CC-VSIs) at bus 13 connects the wind farm to bus 8 of the grid. It is assumed that the loading at each node is kept constant during the analysis and the multi-machine wind farm has a total capacity of 32% system loading.

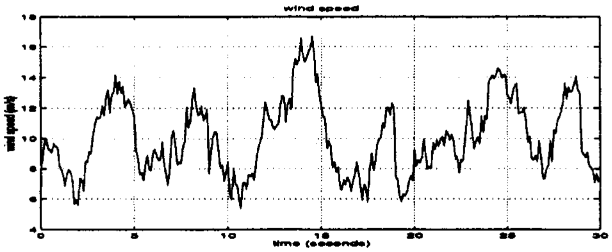


Fig. 15. Wind speed data for case study.

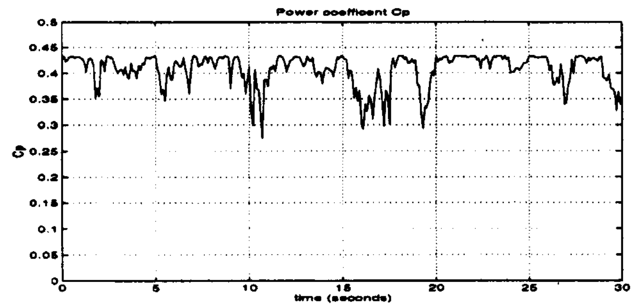


Fig. 16. C_p traces.

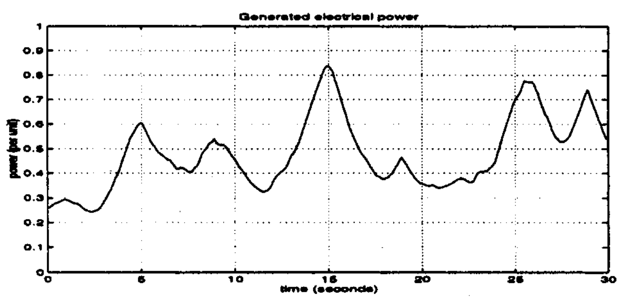


Fig. 17. Output electrical power.

B. Voltage Fluctuation Analysis

The wind speed curve used for the study is shown in Fig. 15. The C_p trace of the equivalent machine is shown in Fig. 16. Fig. 17 shows the corresponding electrical power generated by the wind farm. Inertia smoothing effects are apparent.

A series of power flow analyzes have been carried out using the generated electrical power shown in Fig. 17 as the real power input at bus 13.

Fig. 18 shows the bus voltages under the following conditions:

i) wind power not connected,
ii) wind power converter operating at $P_{\min}$ and unity power factor,
iii) wind power converter operating at $P_{\max}$ and unity power factor.

$P_{\min}$ and $P_{\max}$ are respectively the minimum and maximum electrical power shown in Fig. 17.

It can be seen that unity power factor operation of the wind farm can increase the network voltage level. It is also noted that the injection of varying power can result in bus voltage fluctuation, although the voltage variation is less than 2% in this case. If the wind power varied over a wider range and if the load variation is taken into account, then voltage fluctuations may become

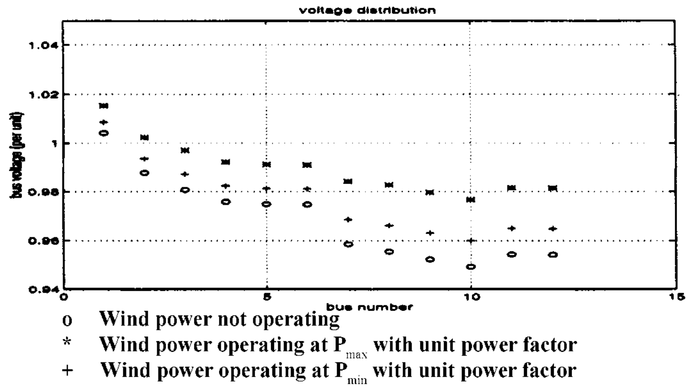


Fig. 18. Bus voltage distribution—1.

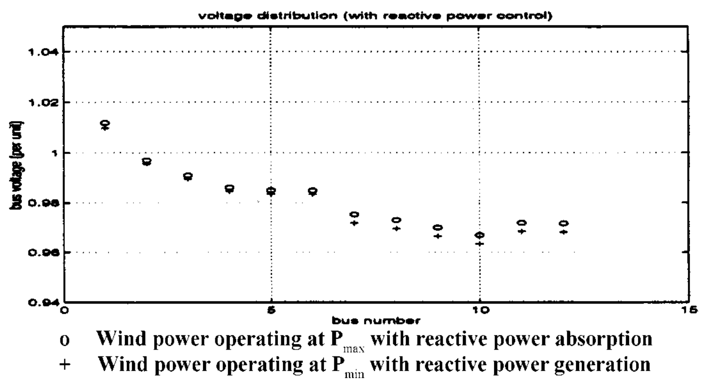


Fig. 19. Bus voltage distribution—2.

unacceptable for loads connected on some buses even though the wind power generation is maintained at unity power factor.

However, the bus voltage fluctuation can be reduced if the wind farm inverters are used to generate reactive power during system low voltage periods and to absorb reactive power during system high voltage periods. In this way, the inverters also work as Var compensators. A simple example of wind power converter operating under such control scheme is shown in Fig. 19. It can be seen that the bus voltage fluctuation has been greatly reduced.

C. Grid Current Harmonic Distortion

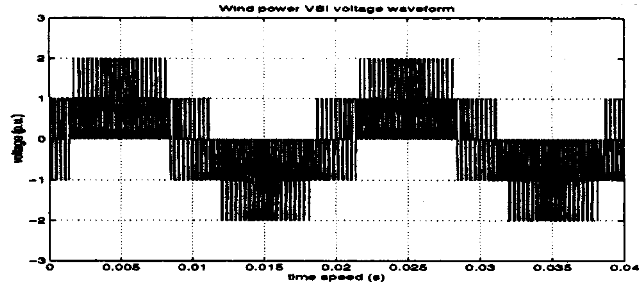
The time domain harmonic analysis has been performed with the operating points obtained by power flow analysis.

The switching frequency of the grid interface inverter is 3.15 kHz. It is assumed that the system operates in a balanced condition. The voltage waveform and harmonic spectra of VSI wind power (bus 13) and bus 8 are shown in Figs. 20 and 21. Fig. 22 shows the total voltage harmonic distortion at each bus. These results correspond to the operating condition of $P_{\max}$ as shown in Fig. 17.

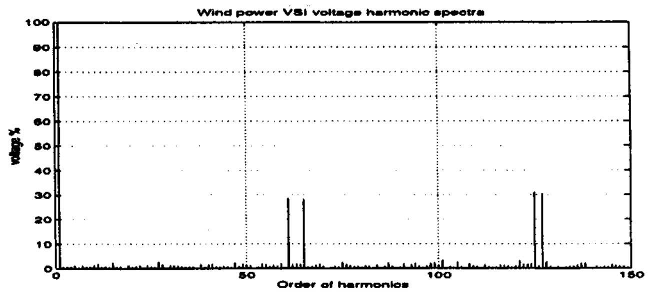
It can be seen clearly that the harmonic distortion can be reduced sufficiently to meet modern standards for the discussed type of distribution systems.

V. Discussions

The estimated overall efficiency of the wind electrical power system (generator and power electronic converters) is about

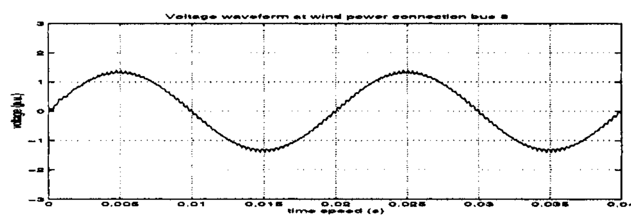


(a)



(b)

Fig. 20. Voltage waveform and harmonic spectra at VSI bus. (a) Voltage waveform. (b) Voltage harmonic spectra.



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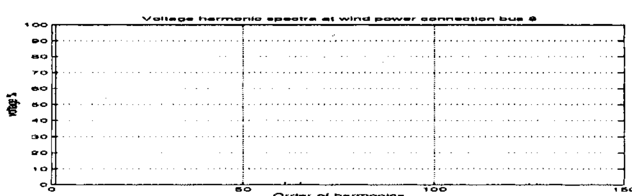

(b)

Fig. 21. Voltage waveform and harmonic spectra at bus 8. (a) Voltage waveform. (b) Voltage harmonic spectra.

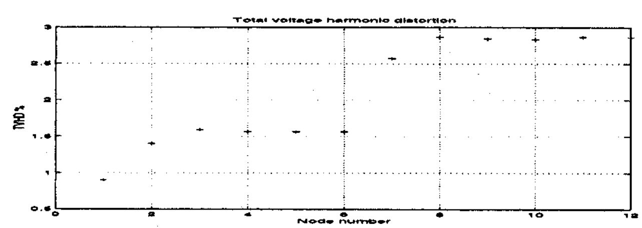

Fig. 22. Total voltage harmonic distortions at bus 1–12.

82%. The average efficiencies of generator and power electronic conversion system are about 85% and 96%, respectively. A detailed study of the technical feasibility and economic performance of various power electronic conversion systems can be found in [1], [2], [12].

VI. Conclusion

The modeling and simulation techniques of a wind power converter and connected power system have been described. The voltage fluctuations and harmonic distortion of a distribution network supplied with a high proportion of its input from wind power sources have been studied.

Significant voltage fluctuations may occur when a large amount of power is generated from direct drive variable speed wind turbines and supplied to a relatively small network. However, the reactive power regulation ability of an advanced power electronic interface, such as the CC-VSI, can be used to minimize the fluctuations to acceptable levels. The system harmonic requirements can be met by the high frequency PWM switching technique together with a relatively low cost harmonic filter.

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