Simplified Wind Turbine Generator Aerodynamic Models for Transient Stability Studies

W. W. Price , J. J. Sanchez-Gasca
GE Energy
Schenectady, NY, 12345 USA

Abstract - **This paper presents the results of an investigation to establish the feasibility of using a simple aerodynamic model for wind turbine generators, suitable for application in transient stability studies.**

Index Terms - **Wind turbine generator, wind power coefficient.**

I. Introduction

The development of wind turbine generator models for the study of bulk power system dynamic performance is an area of intense activity in the power industry. The high level of interest is in response to the rising prominence of wind power as a viable source of electric power.

The current trend of increasing wind power is not likely to abate in the near future. Rather, large wind power plants and high levels of wind power penetration are likely to characterize numerous power systems [1]. This trend underscores the need to understand the effect that wind power plants have on the dynamic performance of power systems - an understanding that is typically obtained by means of transient stability analyses.

A transient stability analysis associated with wind power integration typically requires a large number of time-domain simulations and often involves several interested parties such as developers, manufacturers, technical consultants, and system operators, who may require access to pertinent models and/or data. It is thus highly desirable to develop simplified models that facilitate the exchange of information while providing the required level of accuracy associated with transient simulations.

For the past several years, GE Energy has been involved in the development of wind turbine generator models suitable for use in transient stability studies. This effort involves several related activities that include the implementation and testing of wind turbine models in production grade software.

A model suitable for representing 1.5 and 3.6 MW GE wind turbines was initially described in [2]. However, the continuous development of wind power technologies dictates that such models be updated. Recent updates to the model and associated block diagrams are documented in [3], a more extensive description will be published in an upcoming CIGRE brochure on "Modeling and Dynamic Performance of Wind Generation as it Relates to Bulk Power System Control and Dynamic Performance." Although the model responds to grid disturbances with satisfactory fidelity compared with validated, electromagnetic transient (EMTP-type) models, its aerodynamic model exhibits a significant level of complexity.

This paper documents the development and evaluation of a simplified aerodynamic model for GE's 1.5 and 3.6 MW wind turbines suitable for transient stability studies. The simplified model is intended for typical transient stability simulations spanning ten to twenty seconds, with the assumption that the wind speed remains constant. The ultimate objective of this work is to develop a simplified model that can be readily implemented and evaluated in projects that involve GE's wind turbines.

The study approach consists of comparing the dynamic performance of a wind turbine using three different aerodynamic models. The most accurate (and complex) aerodynamic model includes a detailed three-dimensional representation of the power coefficient curve. This model is used for the assessment of two simpler models. One of the simpler models is currently used in production-grade software and is based on a two-dimensional representation of the power coefficient; the other is based on a linear relation between the rate of change of mechanical power with respect to the blade pitch angle and the pitch angle. The latter model is the focus of this work.

The work reported here was performed as a contribution to the work of the Western Electricity Coordinating Council's Wind Generator Modeling Group. This group, with broad participation of utilities, wind turbine vendors, and software vendors, is working to develop simplified, generic models appropriate for each of the major wind turbine technologies.

The rest of the paper is organized as follows: Section II summarizes the wind turbine model. Section III describes the different representations of the aerodynamic model considered in this work. Section IV, presents the analysis results, and Section V the conclusions reached in this investigation.

II. Wind Turbine Model Overview

The wind turbine model used in this paper was developed specifically for the GE's 1.5 and 3.6 MW wind turbines. The model is based on presently available design information, test data, and engineering judgment. The model is not designed to serve as a general-purpose model; there are substantial

W. W. Price and J. J. Sanchez-Gasca are with GE Energy, Schenectady NY 12345. e-mails: william.price@ps.ge.com and juan.sanchez@ps.ge.com.

variations between models and manufacturers. Subsequent paragraphs describe the relevant dynamics of a single wind turbine. However, the primary objective of the model is to allow for the analysis of the dynamic performance of groups of wind turbines and their interactions with the bulk power system. Wind power plants with GE wind turbines normally include a wind power plant management system - WindCONTROL.

A simple schematic of the wind turbine major components is shown in Figure 1. The generator is unusual from a system simulation perspective. Physically, the machine is a relatively conventional technology wound rotor induction machine. However, the key distinction is that this machine is equipped with a solid-state AC excitation system. The AC excitation is supplied through an AC-DC-AC converter. The fundamental frequency electrical dynamic performance of the wind turbine generator is completely dominated by the field converter. In practice, the electrical behavior of the generator and converter is that of a current-regulated voltage source inverter. The wind turbine behaves like a voltage behind a reactance that results in the desired active and reactive current being delivered to the device terminals. Conventional aspects of generator performance related to internal angle, excitation voltage, and synchronism are largely irrelevant. These characteristics have significant implications from the standpoint of power-swing performance.

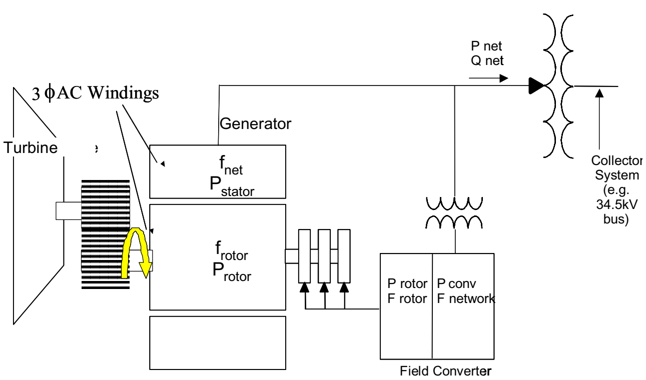

Figure 1. GE Wind Turbine Major Components

The overall wind turbine model consists of four major components, as shown in Figure 2: i) Generator/Network Interface, ii) Electrical Control, iii) Wind Turbine, and iv) Aerodynamic Model. These components have been described in [3]. In this Section, only the turbine model is described; Section III deals with the aerodynamic model.

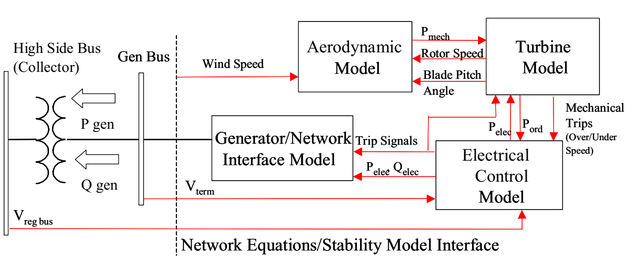

Figure 2. GE Wind Turbine Basic Dynamic Models and Data Connectivity

A. *Wind Turbine*

The wind turbine model provides a simplified representation of a very complex electro-mechanical system. The turbine control is designed to deliver power over a range of wind conditions, taking advantage of the variable speed capability of the machine. The controller enforces the power-speed relationship shown in Figure 3. Above about 75% rated power, the power levels of primary interest for stability studies, the controller works in two distinct regions. When the available wind power is above the equipment rating, the blades are pitched to reduce the mechanical power (P_{mech}) delivered to the shaft down to the equipment rating (1.0 p.u.), thereby returning the machine to the reference speed for full power operation, 120% of synchronous speed. When the available wind power is less than rated, the blades are fixed to maximize the mechanical power, and speed control is accomplished by adjusting the generator electrical power. The dynamics of the pitch control are moderately fast, and can have significant impact on dynamic simulation results. The block diagram is shown in Figure 4.

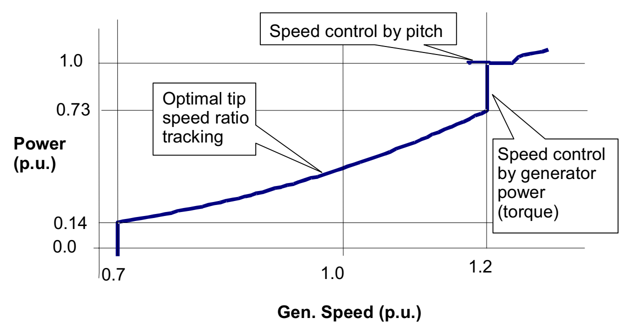

Figure 3. Power vs. Speed Steady State Curve.

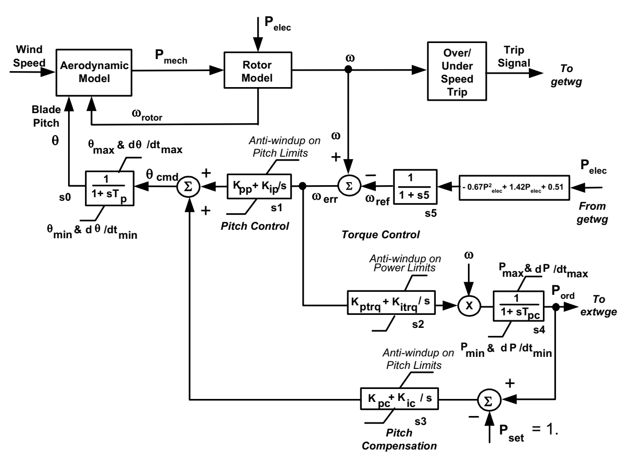

Figure 4. Wind Turbine Model Block Diagram.

The wind turbine model represents the relevant controls and mechanical dynamics of the wind turbine. The model accepts the machine terminal active power from the electrical control model and the mechanical power calculated by the aerodynamic model. The turbine model sends a power order to the electrical control for the converter to deliver the requested power to the grid. The electric power actually delivered to the grid is returned to the turbine model for use in the calculation of rotor speed.

The speed controller does not differentiate between shaft acceleration due to increase in wind speed or due to system faults. In either case, the response is appropriate and relatively slow compared to the electrical control.

The turbine control acts so as to smooth out electrical power fluctuations due to variations in shaft power. By allowing the machine speed to vary around its rated value (120%), the inertia of the machine functions as a buffer to mechanical power variations.

III. AERODYNAMIC MODEL

The function of the aerodynamic model is to compute the wind turbine mechanical power, P_{mech}, from the energy contained in the wind. The inputs to the aerodynamic model are the wind speed, v, in [m/sec], the blade pitch angle, θ, in degrees, and the rotor speed, ω_t, in pu. The well-known relationship:

$$P = \frac{\rho}{2} A_r v^3 C_p(\lambda, \theta) \qquad (1$$

is used to compute the mechanical power extracted from the wind (ρ is the air density in kg/m^3, A_r is the area swept by the rotor blades in m^2, v is the wind speed in m/sec, and C_p is the is the power coefficient). C_p and is a function of λ and θ, and λ is the ratio of the rotor blade tip speed and the wind speed (v_{tip}/v). The model computes λ from the relation

$$\lambda = K_b (\omega_t / v_w) \qquad (2$$

K_b is a constant, for GE's wind turbines the parameters listed in Table 1 result in P_{mech} in p.u. on the unit's MW base.

Table 1. Wind Power Coefficients

	1.5 MW	3.6 MW
½ρ A_r	0.00159	0.00145
K_b	56.6	69.5

The aerodynamic model also computes the initial value for the pitch angle such that the mechanical power provided by the wind turbine is equal to the generated power computed by the power flow.

The complexity of the aerodynamic model depends on the level of detail used to represent the power coefficient, C_p. Subsequent paragraphs describe C_p representations in decreasing level of detail beginning with a three-dimensional representation.

A. Three-Dimensional Model

A representative three-dimensional curve for C_p is shown in Figure 5. The use of a three-dimensional C_p curve requires the interpolation of λ and θ to compute C_p - a time consuming process. Although this representation is very accurate, this level of detail is not required for transient stability analyses. Perhaps more important, from a practical standpoint, is that such detailed representation for C_p is seldom available to system analysts. For the purposes of this work, a three-dimensional representation of C_p is used to validate simpler models.

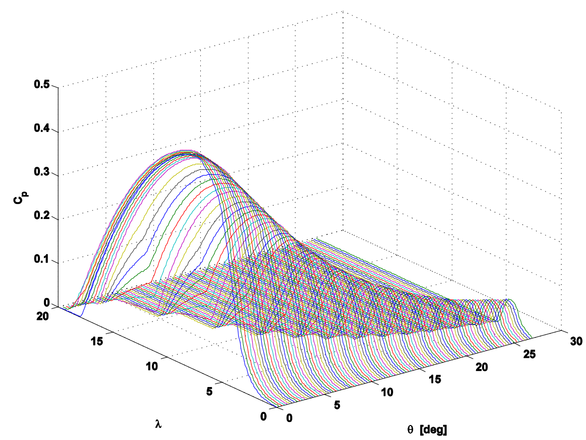

Figure 5. Wind Power Cp Curve

B. Two-Dimensional Model

C_p is a characteristic of the wind turbine and is usually provided as a set of curves relating C_p to λ, with θ as a parameter. Representative C_p curves for the GE's 1.5 and 3.6 MW wind turbines are shown in Figure 6. Curve fitting was performed to obtain the following mathematical representation of the C_p curves for the transient stability model in GE's production software, PSLF:

$$C_p(\theta, \lambda) = \sum_{i=0}^{4} \sum_{j=0}^{4} \alpha_{i,j}\, \theta^i \lambda^j \qquad (3$$

The curve fit is a good approximation for values of $2 < \lambda < 13$, which are a suitable for stability simulations. These curves should not be used for energy production or other economic evaluation. Values of λ outside this range represent very high and low wind speeds, respectively, that are outside the continuous rating of the machine.

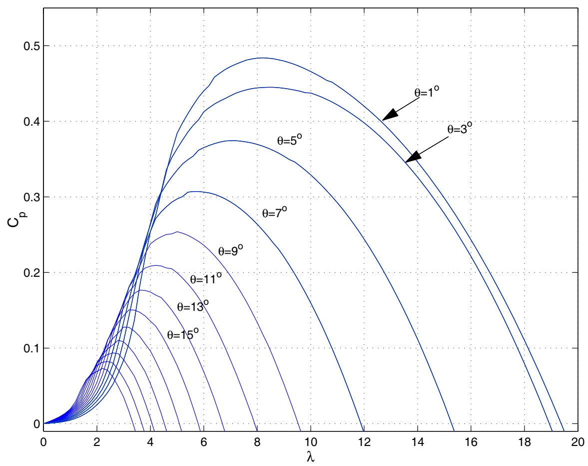

Figure 6. Cp Curves

Initialization of the aerodynamic model recognizes two distinct states: 1) initial electrical power (from the load flow) is less than rated, or 2) initial electrical power equal to rated. In either case, $P_{mech} = P_{elec}$ is known from the load flow and $\omega = \omega_{ref}$ is set at the corresponding value (1.2 p.u. if $P > 0.75$ pu). Then, using the C_p curve fit equation, the wind speed v_w required to produce P_{mech} with $\theta = \theta_{min}$ is determined. (Notice from Figure 6, that two values of λ will generally satisfy the required C_p for a given θ. The wind speed v_w, corresponding to the higher λ is used.) If P_{mech} is less than rated, this value of wind speed is used as the initial value. If P_{mech} is equal to rated and the user-input value of wind speed is greater than the $\theta = \theta_{min}$ value, then θ is increased to produce rated P at the specified value of wind speed.

The two-dimensional model is relatively complex, albeit considerably simpler than the actual equipment. The next section shows how a simpler representation can be obtained assuming that the wind speed is constant.

C. One-Dimensional (Linear) Model

For power system simulations involving grid disturbances, it is reasonable to assume that wind speed remains uniform for the 5 to 30 seconds typical of such cases. For a constant wind speed, an inspection of the relation between C_p, λ, and θ, shows an approximate linear relation between the rate of change of power, $dP/d\theta$, with respect to the pitch angle, θ (Figure 7).

Figure 7 shows values for $dP/d\theta$ versus θ derived from the two-dimensional model described in the previous section (denoted by "o"), and a linear approximation according to the relation:

$$\frac{\Delta P}{\Delta \theta} = -\frac{1}{100} \qquad (4$$

This relation between the mechanical power and the pitch angle suggests that the computation of the power can be significantly simplified by an expression of the form $Pmech = Pmech_0 - \Delta P$, where $\Delta P = \theta\,(\theta - \theta_o)\,/100$, where $Pmech_0$ and θ_o are the initial values of the power and pitch angle.

The initialization of the wind turbine model can also be simplified by observing that the power versus the wind speed, for wind speeds below nominal (Figure 8), and the pitch angle versus the wind speed, for wind speeds above nominal (Figure 9) are approximately linear relations. In these figures, the markers "o" correspond to data from the two-dimensional aerodynamic model and the solid lines represent linear fits.

Similar to the standard model, initialization of the aerodynamic model recognizes two distinct cases: 1) initial electrical power (from the power flow) is less than rated, or 2) initial electrical power equal to rated. In either case, $P_{mech} = P_{elec}$ is known from the power flow and $\omega = \omega_{ref}$ is set at the corresponding value (1.2 p.u. if $P > 0.75$ p.u.). Then, using the linear relation in Figure 8 the wind speed v_w required to produce P_{mech} with $\theta = \theta_{min}$ is determined. If P_{mech} is less than rated, this value of wind speed is used as the initial value. If P_{mech} is equal to rated and the user-input value of wind speed is greater than the $\theta = \theta_{min}$ value, then θ is computed using the linear relation in Figure 9. The validity of this approach is confirmed in Section IV.

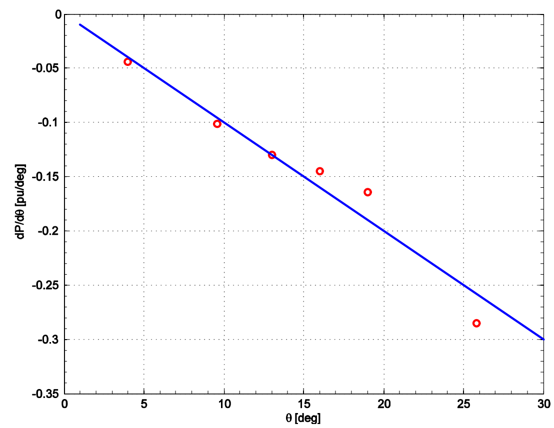

Figure 7. Rate of Change in Mechanical Power vs. Pitch Angle

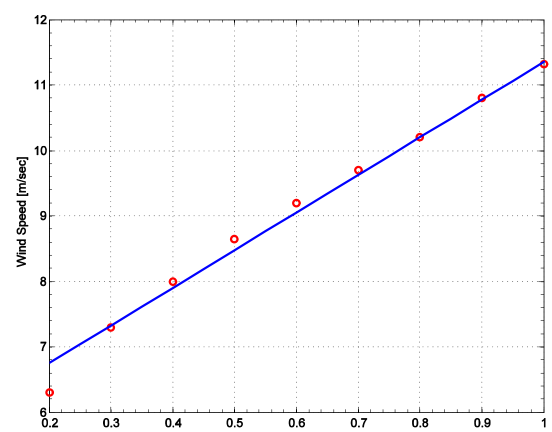

Figure 8. Wind Speed vs. Mechanical Power
Solid Line: Linear Fit Vw = 5.75*Pmech + 5.60

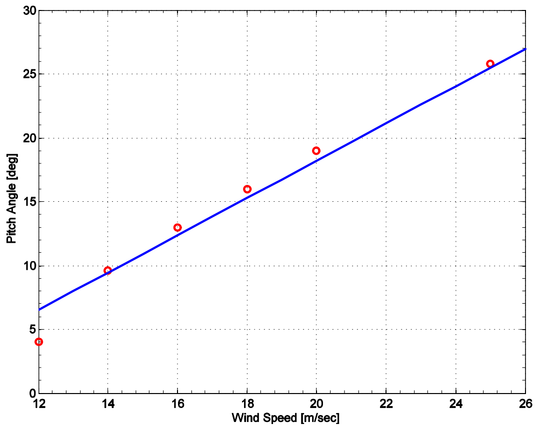

Figure 9. Pitch Angle vs. Wind Speed
Solid Line: Linear Fit θ = 1.46*Vw – 11.0

Table 2. Simulation Cases

Case	System SCR (Pre/Post Fault)	Fault Location	Fault Clearing Time (Cycles)
1 [1]	10 / 5	bus 2	9
2 [2]	10 / 5	Bus 2	9
3 [3]	10 / 5	Bus 2	9
4 [1]	20 / 10	Bus 2	9
5 [1]	10 / 5	Bus 2	5
6 [1]	20 / 10	Bus 2	5
7 [1]	10 / 5	Mid line 1	9
8 [1]	20 / 10	Mid line 1	9
9 [1]	10 / 5	Mid line 1	5
10 [1]	20 / 10	Mid line 1	5

[1]: 100% power output, rated wind speed (12 m/sec)
[2]: 50% power output, rated wind speed (12 m/sec)
[3]: 100% power output, 125% wind speed

IV. Analysis Results

A. Simple Test System

The test system is the benchmark system proposed by the Western Electricity Coordinating Council's Wind Generator Modeling Group:

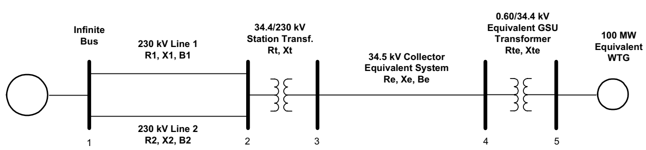

Figure 10. Test System

The wind turbine is rated at 100 MW, the machine connected at the infinite bus is modeled as a classical generator with infinite inertia. The system data are given on p.u. of 100 MW.

The cases studied included two different levels of generated power (100% and 50%), two system strengths (SCR 10 and SCR 20), and two wind speeds (100% and 125%). Table 2 summarizes the cases. The data for Line 1 and Line 2, are as follows:

SCR 10: R1 = R2 = 0.025; X1 = X2 = 0.25; B1 = B2 = 0.05

SCR 20: R1 = R2 = 0.010; X1 = X2 = 0.10; B1 = B2 = 0.02

Other system data are as follows:

Rt = 0.0; Xt = 0.10

Re = 0.015; Xe = 0.025; Be = 0.01

Rte = 0.0; Xte = 0.05

B. Simulation Results

Figure 11 documents the results obtained for the first case listed in Table 2. Similar results were obtained for other cases. The variables plotted are the following: V_2 = p.u. high side substation bus; V_5 = p.u. wind turbine generator terminal voltage; P_g = p.u. wind turbine generator power; Q_g = p.u. wind turbine generator reactive power, ω_g = p.u. generator speed; ω_t = p.u. turbine speed; P_m = p.u. mechanical power; θ = pitch angle in degrees. Each set of axes in Figure 11 contains three traces: Blue/solid for the three-dimensional model; red/dashed for the two-dimensional model; and black/dot-dashed for the linear model.

The simulation results show that, following the clearing of the fault, the wind turbine generator voltage returns to its setpoint of 1.05 pu. The oscillations observed in the terminal voltage and other variables are due to the two-mass model used to represent the turbine and the generator and have an amplitude of only 0.0025 pu. The turbine and generator speeds, and the real and reactive powers reach steady state within ten seconds. Overall, the response of the wind turbine generator is well-behaved and typical for this type of events, i.e., faults either at the point of interconnection or beyond where the overall system is stable. The same performance has been observed on larger networks as evidenced in Section IV.C.

Of particular significance is that the interface variables between the wind turbine generator and the network (V_5, P_g and Q_g) are similar for the three models. The mechanical power and pitch angle for the two-dimensional and linear models exhibit a small deviation from the three-dimensional model (notice that the time scale for the pitch angle is twenty seconds; it is ten seconds for all the other variables).

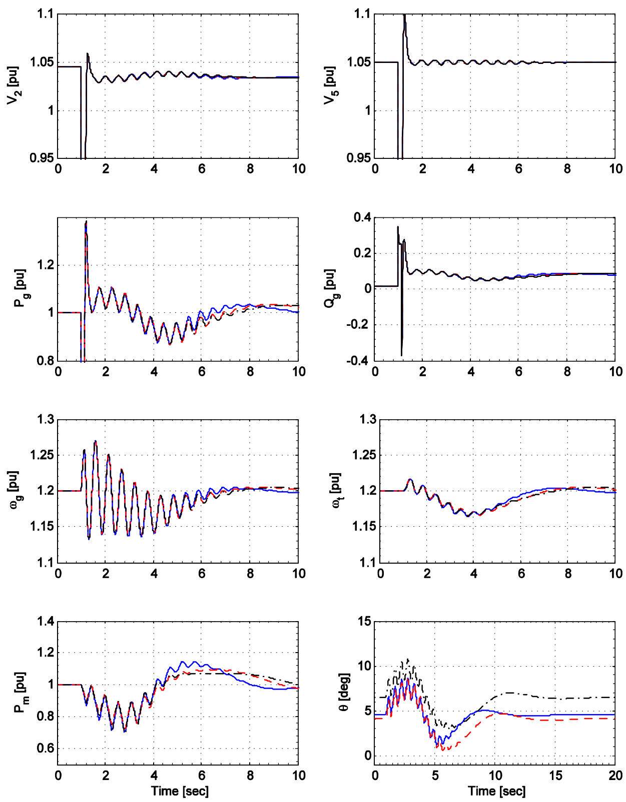

Figure 11. Simulation Results

Figure 12 shows C_p as a function of time. C_p for the linear model was obtained from Equation 1 using known values for all the other variables in the equation. This figure shows, as expected, that the linear model exhibits the larger deviation from the three-dimensional model. Most of this difference can be attributed to the computation of the initial conditions based on Figures 8 and 9. A better match is likely to be obtained by refining the computation of the initial values; however, since the proposed model gives acceptable results in transient stability simulations, further refinements have not been pursued.

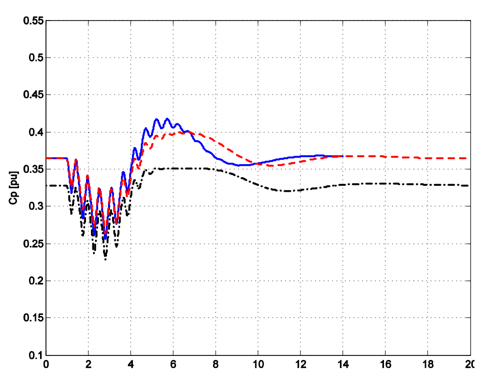

Figure 12. Power Coefficient. (Solid: 3D Model, Dashed: 2D Model, Dot-Dashed: 1D Model)

C. Simulation Results for a Large System

The simulation results reported here correspond to a large system comprising over 30,000 buses and approximately 2,000 generators; a wind power plant consisting of 130 3.6 MW wind turbines is included in the model. The simulated event is a three-phase, 0.1 second fault at a 345 kV bus in the vicinity of the wind power plant. No attempt was made to refine the linear relation in Equation 4.

The variables plotted in Figure 13 correspond to a single wind turbine generator, and are the following: V_g = terminal voltage; P_g = p.u. generated power; Q_g = p.u. reactive power; ω_g = p.u. generator speed.

Each set of axes in Figure 13 contains two traces: Blue/solid for the two-dimensional model, and red/dashed for the linear model. The key point in these results is that interface variables between the wind turbine generator and the network (V_g, P_g, and Q_g) are similar for the two models.

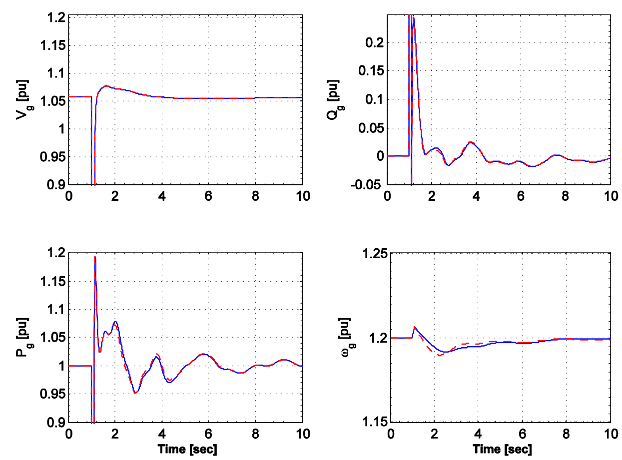

Figure 13. Simulation Results

V. Conclusions

The results obtained demonstrate the feasibility of using a simplified aerodynamic model for transient stability simulations. In all cases, the interface variables between the wind turbine generator and the network, i.e., active and reactive power, and terminal voltage are, for all practical purposes, the same. This simple model can be used to obtain results compatible with the level of approximation inherent in transient stability simulations of bulk power systems.

The wind turbine model used in this investigation is expected to give realistic and correct results when used for bulk system performance studies. Given the rapidly changing nature of this field of modeling and analysis, it is reasonable to assume that the model components will continue to evolve, in terms of parameter values and structure, as experience and additional test data are obtained.

VI. REFERENCES

[1] N. Hatziargyriou, A. Zervos, "Wind Power Development in Europe," *Proceedings of the IEEE*, Vol. 89, No. 12, Dec. 2001, pp. 1765-1782.

[2] N. W. Miller, J. J. Sanchez-Gasca, W. W. Price, R. W. Delmerico, "Dynamic Modeling of GE 1.5 and 3.6 MW Wind Turbine-Generators for Stability Simulations," *Proc. IEEE Power Engineering Society General Meeting*. Toronto, Ontario. July 2003.

[3] J.J. Sanchez-Gasca, R.J. Piwko, N. W. Miller, W. W. Price, "On the Integration of Wind Power Plants in Large Power Systems", *Proc. X Symposium of Specialists in Electric and Expansion Planning (SEPOPE)*, Florianopolis, Brazil, May, 2006.