GE Power Systems

Dynamic Modeling of GE 1.5 and 3.6 Wind Turbine-Generators

Prepared by:

Nicholas W. Miller
William W. Price
Juan J. Sanchez-Gasca

October 27, 2003

Version 3.0

GE-Power Systems Energy Consulting

Foreword

This document was prepared by General Electric International, Inc. through its Power Systems Energy Consulting (PSEC) in Schenectady, NY.

Technical and commercial questions and any correspondence concerning this document should be referred to:

Nicholas W. Miller
Power Systems Energy Consulting
General Electric International, Inc.
Building 2, Room 605
Schenectady, New York 12345
Phone: (518) 385-9865
Fax: (518) 385-5703
E-mail: nicholas.miller@ps.ge.com

Legal Notice

This report was prepared by General Electric International, Inc.'s Power Systems Energy Consulting (PSEC) as an account of work sponsored by GE Wind Energy (GEWE). Neither GEWE nor PSEC, nor any person acting on behalf of either:

1. Makes any warranty or representation, expressed or implied, with respect to the use of any information contained in this report, or that the use of any information, apparatus, method, or process disclosed in the report may not infringe privately owned rights.

2. Assumes any liabilities with respect to the use of or for damage resulting from the use of any information, apparatus, method, or process disclosed in this report.

Table of Contents

1. Introduction

GE Power Systems Energy Consulting has an ongoing effort dedicated to development of models of GE wind turbine generators (WTG) suitable for use in system impact studies. This report documents the present recommendations for dynamic modeling of the GE 1.5 and 3.6 WTG for use in studies related to the integration of GE wind turbines into power grids. This report includes recommended model structure and data, as well the assumptions, capabilities and limitations of the resulting model.

The model provided is as simple as is appropriate for bulk power system dynamic studies. It is valuable to put the model limitations in the context of what analysis is required. First and most important, this model is for positive sequence phasor time-domain simulations – e.g. PSLF or PSS/e. Second, this assumes that the analysis is mainly focused on how the WTGs react to grid disturbances, e.g. faults, on the transmission system. Third, the model provides for calculation of the effect of wind speed fluctuation on the electrical output of the WTG. Details of the device dynamics have been substantially simplified. Specifically, the very fast dynamics associated with the control of the generator converter have been modeled as algebraic (i.e. instantaneous) approximations of their response. Representation of the turbine mechanical controls has been simplified as well. The model is not intended for use in short circuit studies.

2. Model Overview and Philosophy

2.1 Fundamentals

A simple schematic of an individual GE Wind Turbine-Generator (WTG) is shown in Figure 2-1.

The GE WTG generator is unusual from a system simulation perspective. Physically, the machine is a relatively conventional wound rotor induction (WRI) machine. However, the key distinction is that this machine is equipped with a solid-state voltage-source converter AC excitation system. The AC excitation is supplied through an ac-dc-ac converter. For the GE 3.6 machine the converter is connected as shown. For the GE 1.5 machine it is connected directly at the stator winding voltage. Machines of this structure are termed ‘double fed’, and have significantly different dynamic behavior than either conventional synchronous or induction machines. Modeling of the GE 1.5 and 3.6 machines with conventional dynamic models for either synchronous or induction machines is, at best, highly approximate and should be avoided.

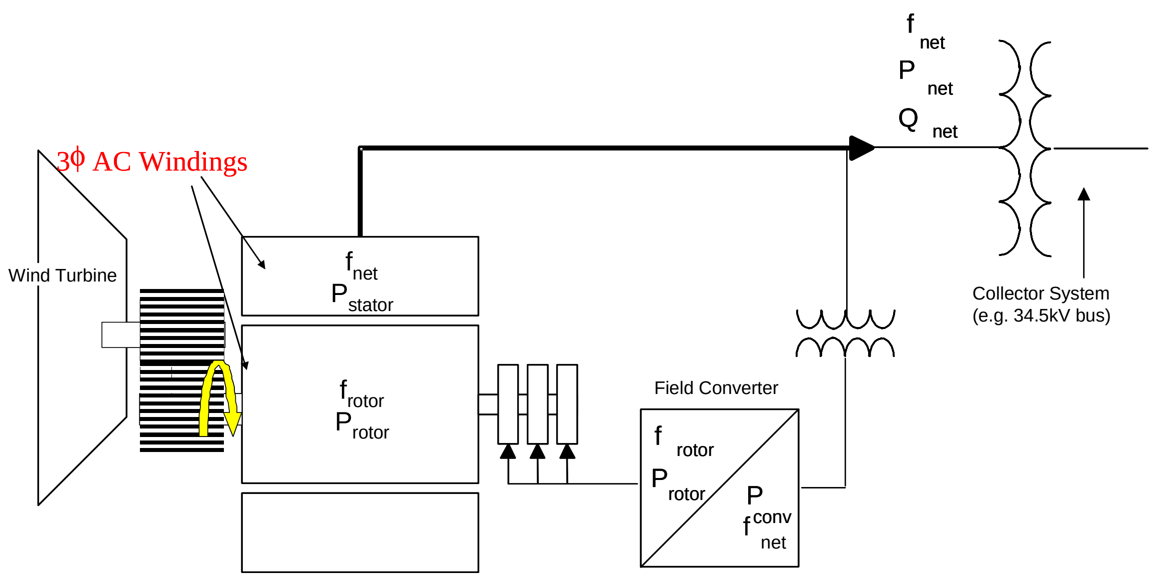

Figure 2-1. GE WTG Major Components.

The fundamental frequency electrical dynamic performance of the GE WTG is completely dominated by the field converter. Conventional aspects of generator performance related to internal angle, excitation voltage, and synchronism are largely irrelevant. In practice, the electrical behavior of the generator and converter is that of a current-regulated voltage-source inverter. Like other voltage-source inverters (e.g. a BESS or a STATCOM), the WTG converter synthesizes an internal voltage behind a transformer reactance which results in the desired active and reactive current being delivered to the device terminals. In the case of the WTG, the machine rotor and stator windings are primary and secondary windings of the transformer.

The rotation of the machine means that the ac frequency on the rotor winding corresponds to the difference between the stator frequency (60Hz) and the rotor speed. This is the slip frequency of the machine. In the vicinity of rated power, the GE 1.5 and

3.6 machines will normally operate at 120% speed, or -20% slip. Control of the excitation frequency allows the rotor speed to be controlled over a wide range, ±30%. The rotation also means that the active power is divided between the stator and rotor circuits, roughly in proportion to the slip frequency. For rotor speeds above synchronous, the rotor active power is injected into the network through the converter. The active power on the rotor is converted to terminal frequency (60Hz), as shown in Figure 2-1. The variation in excitation frequency and the division of active power between the rotor and stator are handled by fast, high bandwidth regulators within the converter controls. The time response of the converter regulators are sub-cycle, and as such can be greatly simplified for simulation of bulk power system dynamic performance.

Broadly stated, the objectives of the turbine control are to maximize power production while maintaining the desired rotor speed and avoiding equipment overloads. There are two controls (actuators) available to achieve these objectives: blade pitch control and torque order to the electrical controls (the converter). The turbine model includes all of the relevant mechanical states and the speed controls. The implementation of the turbine model, while relatively complex, is still considerably simpler than the actual equipment. Losses are not considered throughout the model, since “fuel” efficiency is not presently a consideration. These simplifications are examined in the detailed model discussion in Section 4.

The model presented here describes the relevant dynamics of a single GE WTG. However, the primary objective of this model is to allow for analysis of the performance of groups of WTGs and how they interact with the bulk power system. Wind farms with GE WTGs are normally designed with supervisory control using GE’s Wind Volt-Ampere-Reactive control system, called WindVAR which interacts with the individual WTGs through the electrical controls. (Earlier versions of the supervisory control were called “DVAR”). Representation of all the individual machines in a large wind farm is inappropriate for most grid stability studies. Therefore, we have made provision within the model structure to allow a single WTG machine model (suitably sized) to provide a realistic approximation to the way that an integrated system will behave. The model implementation allows the user access to parameters that might reasonably be customized to meet the particular requirements of a system application. These parameters all reside in the WTG electrical control model, and are discussed in more detail below.

2.2 Overall Model Structure

From a loadflow perspective, there are two standard components that need to be included in the loadflow setup and are required for initialization of the dynamic simulation program:

- Generator
- Transformer

These two components use conventional loadflow device models, and can be represented in any loadflow program. Details are presented in Section 3.

The dynamic models presented here are specific to the GE WTGs. The implementation is structured in a fashion that is similar to other conventional generators. To construct a complete WTG model, three device models are used:

- Generator/converter model (interfaces with network and models several hardware-related constraints.)
- Electrical control model (includes closed and open loop reactive power controls and provides for other system level features, e.g. governor function, for future applications)
- Turbine and turbine control model (mechanical controls, including blade pitch control and power order to converter; over/under speed trips; rotor inertia equation; wind power as a function of wind speed, blade pitch, and rotor speed.)

A fourth, user-written model can be used to simulate a wind gust by varying input wind speed to the turbine model. The user can also input wind speed vs. time sequences, derived from field measurements or other sources.

The overall connectivity of the models is shown in Figure 2-2.

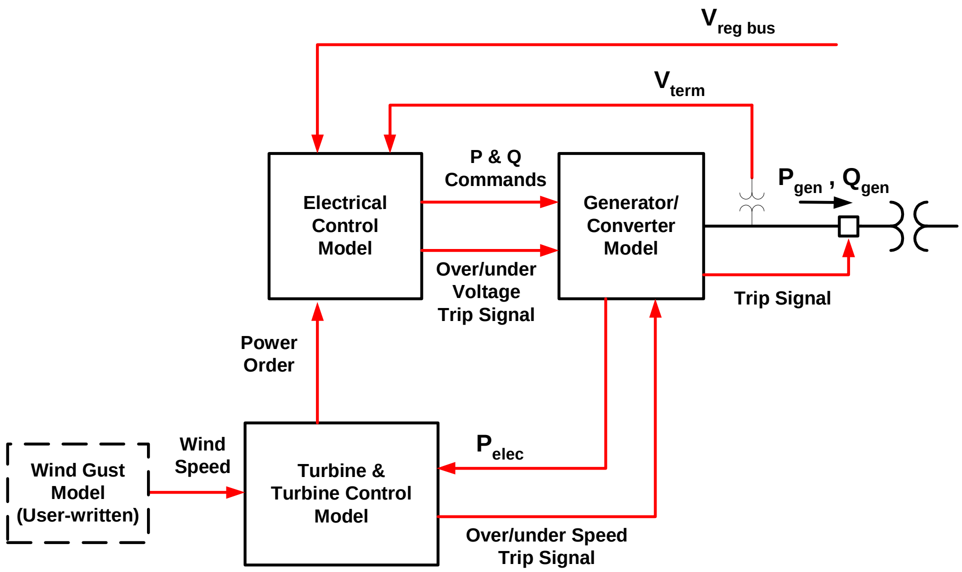

Figure 2-2. GE WTG Dynamic Models and Data Connectivity

3. Modeling for Loadflow

The modeling for load flow analysis is relatively simple, as shown in Figure 3-1. A conventional generator is connected to a (PV) bus. For the 60Hz GE 1.5, each individual WTG is connected to a 575V bus, and for the 60Hz GE 3.6, each individual WTG is connected to a 4160V bus. The generator terminal bus is then connected to the collector system bus through a suitably rated transformer. Typical collector system voltages are at distribution levels (12.5 kV and 34.5 kV are common). For GE 3.6 applications, the transformer will typically be 34.5kV/4160V, rated 4 MVA with a 6% leakage reactance.

Each GE 1.5 machine has a rated power output of 1.5 MW. The reactive power capability of each individual machine is +0.95/-0.90 pf, which corresponds to Qmax = 0.49 MVAr and Qmin = -0.73 MVAr, and an MVA rating of 1.67 MVA. The minimum steady-state power output for the WTG model is 0.2 MW.

Each GE 3.6 machine has a rated power output of 3.6 MW. The reactive power capability of each individual machine is ±0.9 pf, which corresponds to Qmax = 1.74 MVAr and Qmin = -1.74 MVAr, and an MVA rating of 4.0 MVA. The minimum steady-state power output for the WTG model is 0.5 MW.

Wind farms normally consist of a large number of individual WTGs. The wind farm model may consist of a detailed representation of each WTG and the collector system. Alternatively, a simpler model, which may be adequate for many bulk transmission system studies, consists of a single WTG and transformer with MVA ratings equal to ***n*** times the individual device ratings. Some equivalent impedance to reflect the aggregate impact of the collector system can be included. A third alternative is to model groups of WTGs by a single model, with a simplified representation of the collector system.

The supervisory control (WindVAR) is typically structured to measure the voltage at a particular bus, often the point of interconnection (POI) with the transmission system, and regulate this voltage by sending a reactive power command to all of the WTGs. Line drop compensation may be used to regulate the voltage at a point some distance from the voltage measurement bus. For loadflow modeling of the WindVAR, each WTG should be set to regulate the same remote bus, located at the desired voltage regulation point.

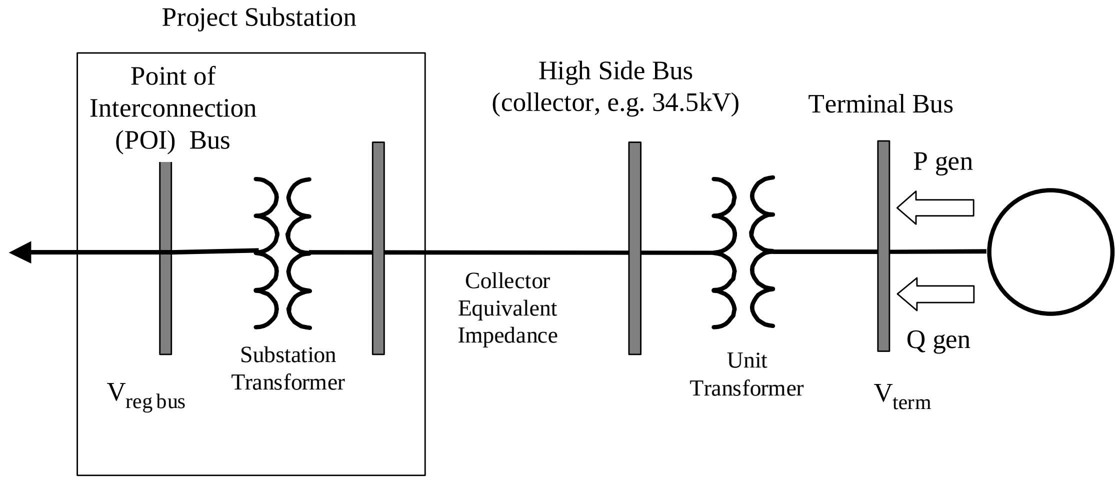

Figure 3-1 Loadflow Details

3.1 Initial conditions for dynamic simulation

The loadflow provides initial conditions for the dynamic simulations. The conditions outlined above are generally applicable to the dynamic model presented below. The maximum and minimum active and reactive power limits must be respected in order to achieve a successful initialization. If the WTG electrical control or additional substation controls are customized to meet a particular set of desired performance objectives, then the loadflow must be initialized in accordance with those customized rules.

4. Dynamic Model

This section presents the engineering assumptions, detailed structure, and data for each of the component models.

4.1 Generator/Converter Model

This model is the physical equivalent of the generator and provides the interface between the WTG and the network. Unlike a conventional generator model it contains no mechanical state variables for the machine rotor – these are included in the turbine model. Further, unlike conventional generator models, all of the electrical/flux state variables have been modified to reflect to the effective response to the higher level commands from the electrical controls (i.e. the converter). The net result is an algebraic, controlled-current source that computes the required injected current into the network in response to the flux and active current commands from the excitation (converter) model. For a given time step, the model holds the in-phase (active power) component of current constant and holds constant q-axis voltage (d-axis flux) behind the subtransient reactance (X”). The model includes two small time constants (20 msec) to represent converter action. This is a reasonably accurate model of the combined behavior of the doubly-fed generator and its rotor converter. The model is shown in Figure 4-1.

Several limits and trip functions related to the hardware capabilities are included in the model. The generator will be tripped if the terminal voltage deviates from nominal (1 p.u.) by more than the voltage trip levels specified in Table 4-1, for more than the corresponding trip times, also listed in Table 4-1. These levels may be different for some projects. In addition, trip signals from the excitation (converter) model and turbine model can also cause the generator to trip.

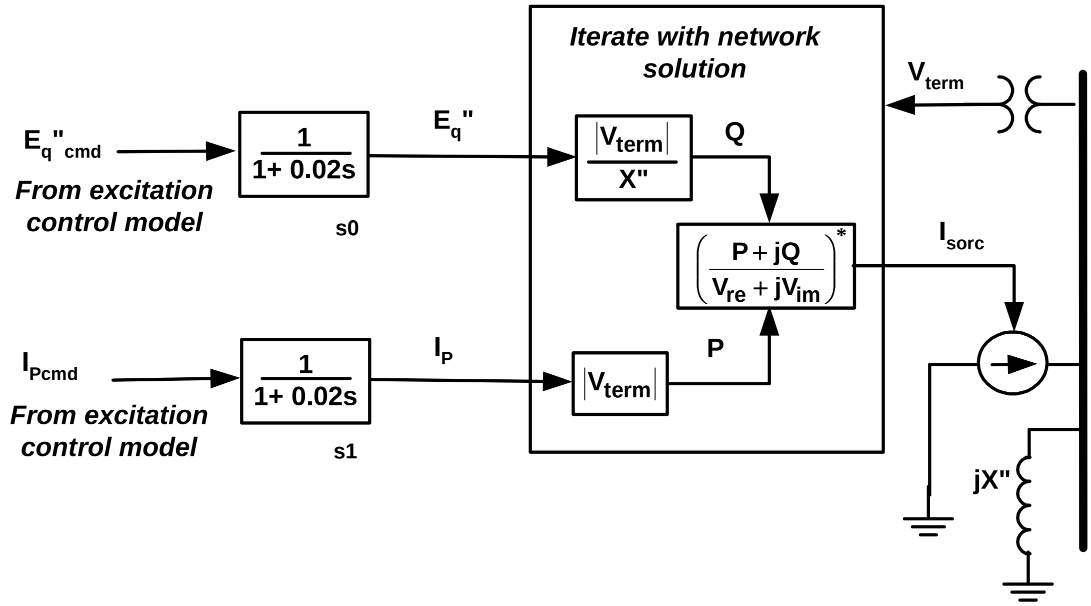

Figure 4-1 Generator/Converter Model (X"= 0.20 pu)

Table 4-1 WTG Generator/Converter Trip Levels and Times

		[pu]	[sec]
ΔV_{trip}	T_{trip}	-0.15	10.0
ΔV_{trip}	T_{trip}	-0.25	1.0
ΔV_{trip}	T_{trip}	-0.30	0.10[1]
ΔV_{trip}	T_{trip}	-0.70	0.02[2]
ΔV_{trip}	T_{trip}	+0.10	1.0
ΔV_{trip}	T_{trip}	+0.15	0.10
ΔV_{trip}	T_{trip}	+0.30	0.02[2]

[1] Machines equipped with low voltage ride through (LVRT); else 0.02 sec

[2] Nominally instantaneous trip; 20 ms delay is recommended to improve simulation numerical behavior

4.2 Excitation (Converter) Control Model

The Excitation Control Model dictates the active and reactive power to be delivered to the system based on inputs from the turbine model (P_{ord}) and from the supervisory VAR controller (Q_{ord}). Q_{ord} can either come from a separate model or from the DVAR Emulation function included in the Excitation Control Model. The design philosophy has been to greatly simplify the model relative to the actual implementation used within the equipment, while maintaining those aspects that are crucial to capturing the system dynamic performance of interest. The model consists of the following control functions:

WindVAR Emulation

Open Loop Control Logic

Electrical Controller

The overall block diagram for the Electrical Control model is shown in Figure 4-2; Figure 4-3 shows a more detailed representation.

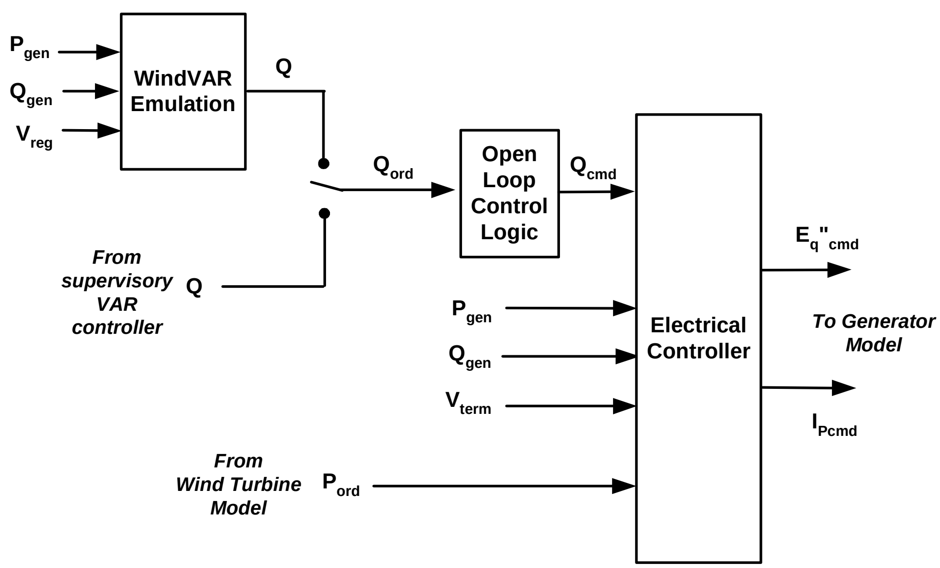

Figure 4-2 Overall Excitation (Converter) Control Model

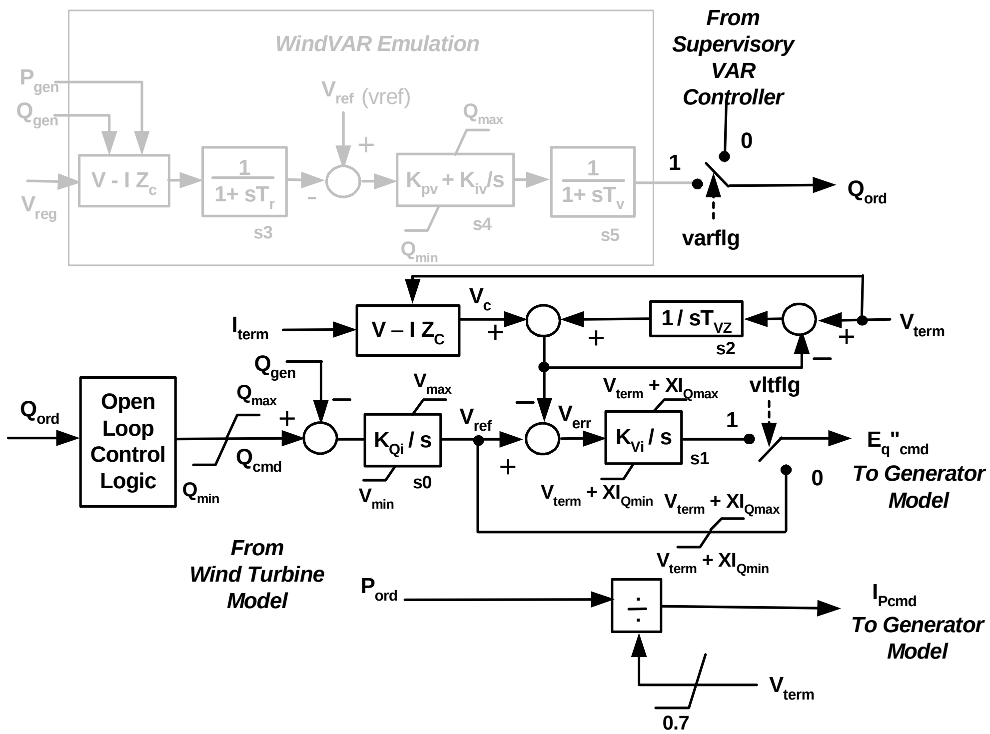

Figure 4-3   Electrical Control Model

WindVAR Emulation

The WindVAR Emulation function represents a simplified equivalent of the supervisory VAR controller for the entire wind farm. The function monitors a specified bus voltage, with optional line drop compensation, and compares it against the reference voltage. The regulator itself is a PI controller plus a time constant, T_v. The time constant reflects the delays associated with cycle time, communication delay to the individual WTGs, and additional high frequency attenuation needed to maintain stability. The measurement lag is represented by the time constant T_r. Table 4-3 includes suggested settings for the WindVAR Emulation model. All settings are given in terms of rated MVA.

Open Loop Control Logic

The Open Loop Control Logic is responsive to large variations in system voltage, and is inactive whenever the terminal voltage is within its normal range. The Open Loop Control Logic is described by Table 4-2. The functions in this table represent the type of *optional* open loop controls than were implemented to improve system performance for large voltage deviations resulting from systems events. This feature was used in some wind farms with GE WTGs before the implementation of present local closed loop electrical controller described below. The Open Loop Control Logic forces the reactive power to pre-specified levels as voltage deviations persist. As with all open loop controllers of this type, hysteresis is needed to avoid hunting. Once the voltage thresholds are crossed and the open loop reactive power command is issued, the threshold voltage is shifted up (or down for high voltage events) by a specified amount, V_{hyst}. For future projects with GE WTGS, this feature is not expected to be required. However, representative values from earlier projects for the open loop control parameters are given in Table 4-3.

Table 4-2 Open Loop Reactive Power Control Logic

Voltage Condition	For time duration	Open Loop Reactive Power Command
$V_{term} < V_{L1}$	$t < T_{L1}$	Q_{L1}
	$T_{L1} < t < T_{L2}$	Q_{L2}
	$t > T_{L2}$	Q_{L3}
$V_{term} > V_{H1}$	$t < T_{H1}$	Q_{H1}
	$T_{H1} < t < T_{H2}$	Q_{H2}
	$t > T_{H2}$	Q_{H3}

Electrical Controller

The electrical controller model is a simplified representation of the converter/excitation system. This controller monitors the generator reactive power, Q_{gen}, and terminal voltage, V_{term}, (or a remotely compensated voltage), to compute the voltage and current commands $E_q''{}_{cmd}$ and I_{Pcmd}.

The model allows for the control of V_{term} or Q_{gen}. If the flag vltflg is set to 1, the terminal voltage is compared against the reference voltage V_{ref}, to create the voltage error V_{err}. This error is then multiplied by a gain and integrated to compute the voltage command $E_q''{}_{cmd}$. The magnitude of the gain determines the effective time constant associated with the voltage control loop. If the flag vltflg is set to 0, the integral of the error between Q_{cmd} and Q_{gen} is used directly to compute the voltage command $E_q''{}_{cmd}$ to regulate Q_{gen}. In both cases $E_q''{}_{cmd}$ is limited according to a time-varying limit that reflects hardware characteristics and prevents unrealistic high or low values.

The current command I_{Pcmd} is computed by dividing the power order, P_{ord}, from the wind turbine model over the generator terminal voltage V_{term}.

Table 4-3 includes recommended settings for the Electrical Control model. All settings are given in terms of rated MVA.

Table 4-3 WTG Electrical Control Parameters
(all power quantities are per unit on MVA base – 1.67MVA or 4.0 MVA)

Parameter Name	Recommended Value
T_r	0.05
T_v	0.05
K_{pv}	20
K_{iv}	2.0
K_{Qi}	0.05
K_{Vi}	20.0
T_{vz}	1.0
Q_{max}	0.29 (1.5) /0.432 (3.6)
Q_{min}	-0.432
XI_{Qmax}	0.07
XI_{Qmin}	-0.07
V_{max}	1.05
V_{min}	0.95
V_{L1}	0.9
V_{H1}	1.1
T_{L1}	0.1
T_{L2}	0.5
T_{H1}	0.1
T_{H2}	1.0
Q_{L1}	Q_{cl} *
Q_{L2}	Q_{cl} * (0.45 for older projects)
Q_{L3}	Q_{cl} *
Q_{H1}	Q_{cl} *
Q_{H2}	-0.245
Q_{H3}	Q_{cl} *
V_{hyst}	0.05
Z_c	0.0

* Qcl – closed-loop Q command is passed without modification. (can be indicated by setting parameter to 0.)

4.3 Wind Turbine & Turbine Control Model

The wind turbine model provides a simplified representation of a very complex electro-mechanical system. The block diagram for the model is shown in Figure 4-4. In simple terms, the function of the wind turbine is to extract as much power from the available wind as possible without exceeding the rating of the equipment. The wind turbine model represents all of the relevant controls and mechanical dynamics of the wind turbine. The block labeled "Wind Power Model" is a moderately complex algebraic relationship governing the mechanical shaft power that is dependent on wind velocity, rotor speed and blade pitch. This model is described in Section 4.3.3.

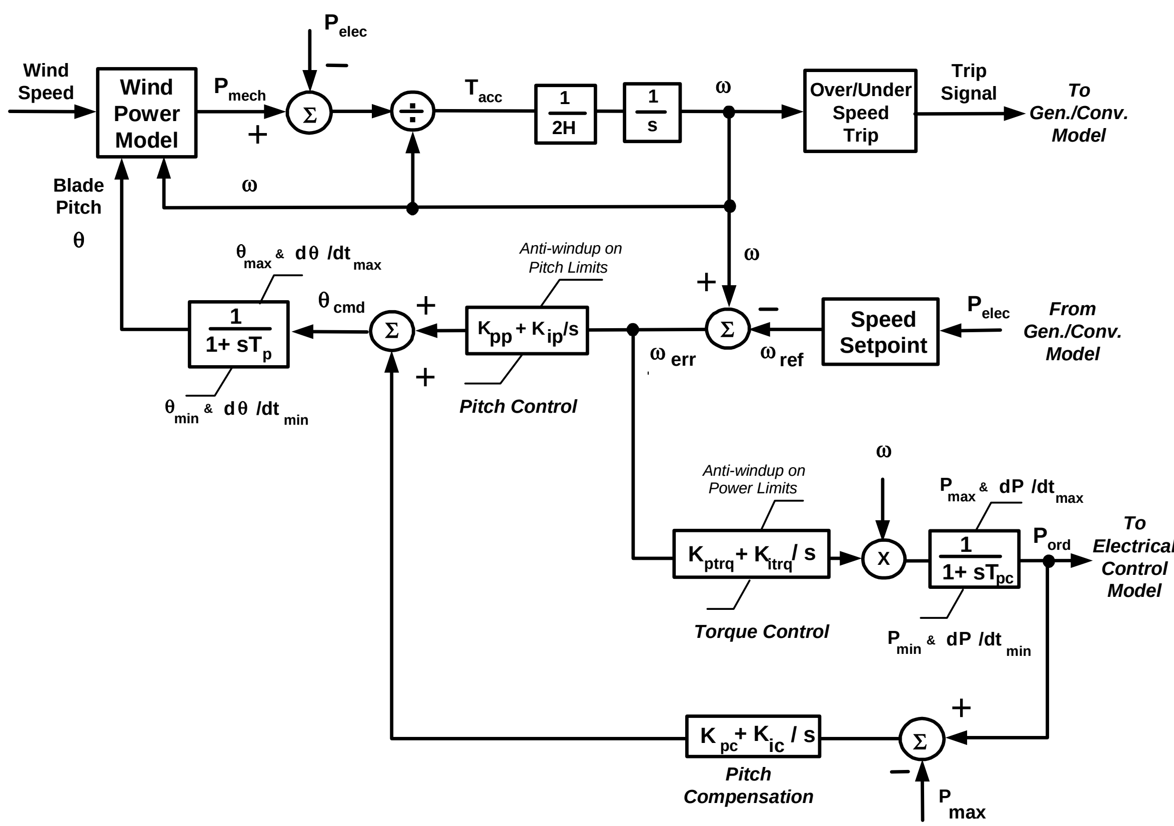

Figure 4-4. Wind Turbine Model Block Diagram

4.3.1 Rotor Mechanical Model

The upper part of Figure 4-2 includes the rotor inertia equation for the WTG rotor. This equation uses the mechanical power from the Wind Power Model and the electrical power from the Generator/Converter model to compute the rotor speed. This part of the model can be extended to include a two-mass rotor model, with separate masses for the turbine and generator. The relatively low natural torsional frequencies typical of wind systems make this extension possible. Figures 4-5 and 4-6 show the two-mass rotor model using physical and modal parameters, respectively.

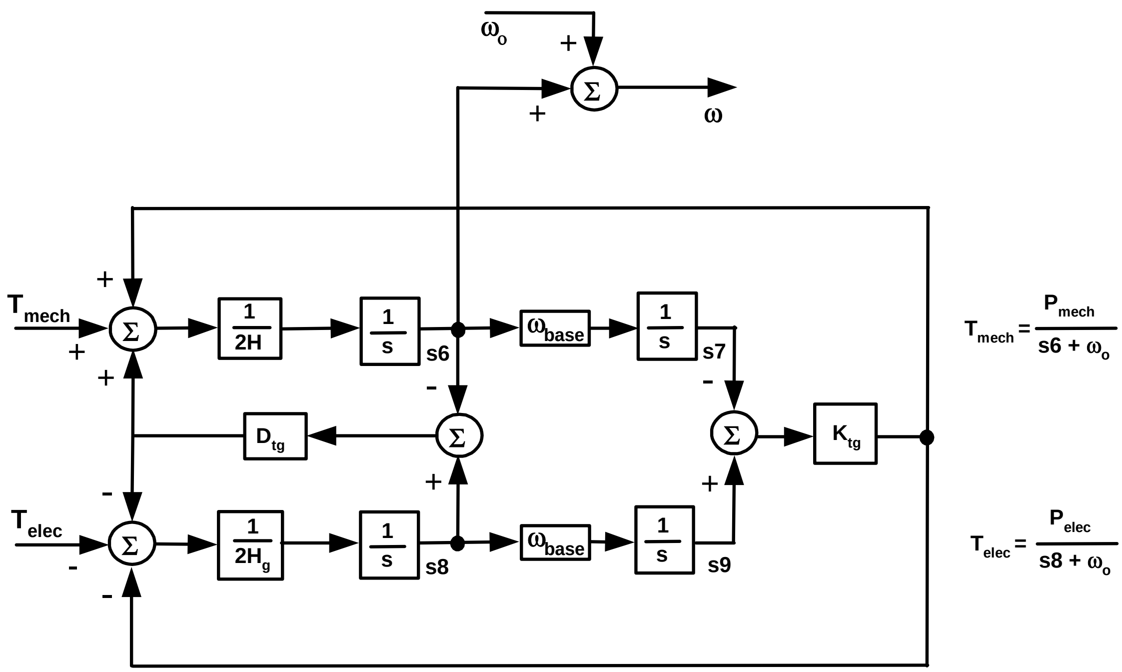

Figure 4-5. Two-Mass Rotor Model – Physical Parameters Model

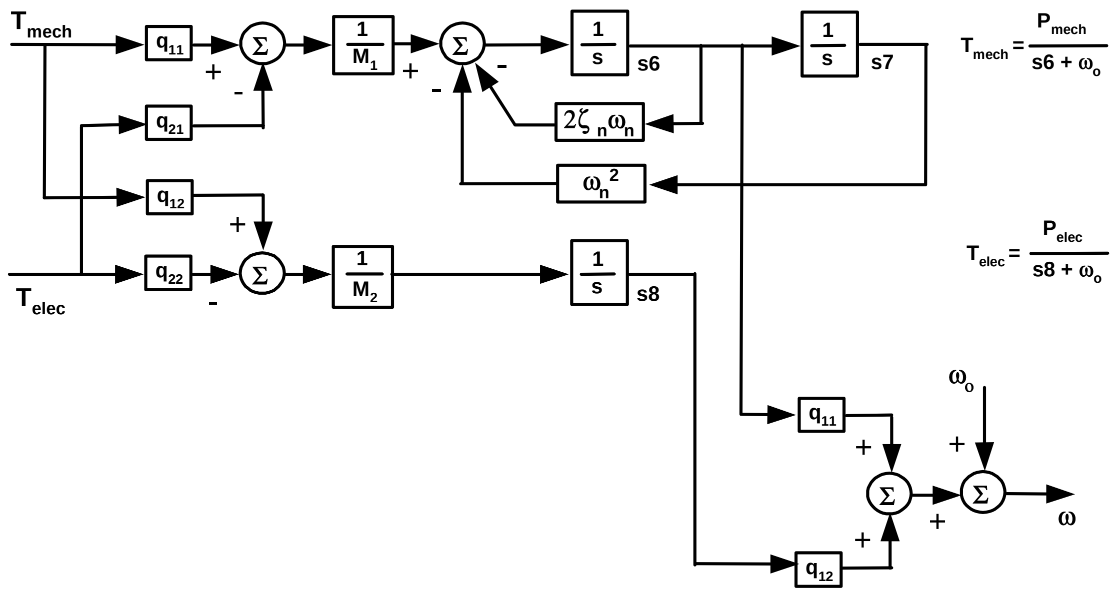

Figure 4-6. Two-Mass Rotor Model – Modal Parameters Model

The data for the rotor mechanical model are given in Table 4-4.

Table 4-4 WTG Rotor Mechanical Model Parameters

	GE 1.5	GE 3.6
One-Mass Model		
H (pu on turbine MW base)	4.64	5.19
Two-Mass Model - Physical Parameters		
H	4.32	4.29
H_g	0.62	0.90
K_{tg}	80.27	296.7
D_{tg}	1.5	1.5
ω_{base}	1.745	1.335
Two-Mass Model - Modal Parameters		
M_1	0.791	1.562
M_2	5.661	7.775
ζ_n	0.0610	1.575
ω_n	11.4	16.32
q_{11}	0.1411	0.2053
q_{12}	1.0	1.0
q_{21}	-0.990	-0.979
q_{22}	1.0	1.0

Overspeed and underspeed tripping logic is also included in the model. The related data are listed in Table 4-5.

Table 4-5 Overspeed and Underspeed Tripping Thresholds

	GE 1.5	GE 3.6
Overspeed trip	1.3 pu	1.3 pu
Underspeed trip	0.7 pu	0.7 pu

4.3.2 Turbine Control Model

The lower part of Figure 4-2 is the model of the turbine control. The practical implication of the turbine control is that 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 pu). When the available wind power is less than rated, the blades are set at minimum pitch to maximize the mechanical power. In either case, the turbine control senses the shaft speed and tries to return the machine to nominal speed. The dynamics of the pitch control are moderately fast, and can have significant impact on dynamic simulation results.

The turbine control model sends a power order to the electrical control, requesting that the converter deliver this power to the grid. The electrical control, as described in Section 4.2, may or may not be successful in implementing this power order. The electric power actually delivered to the grid is returned to the turbine model, for use in the calculation of rotor speed setpoint. As discussed above, the dynamics of the electrical controller are extremely fast.

Dynamically, the combination of blade pitch control and electric power order results in two distinct operating conditions. For power levels below rated, the turbine speed will be controlled primarily by the electric power order to the specified speed reference. For power levels above rated, the rotor speed will be controlled primarily by the pitch control, with the speed being allowed to rise above the reference transiently.

In this model, the blade position actuators are rate limited and there is short time constant associated with the translation of blade angle to mechanical output. The pitch control 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 reference speed is normally 1.2 pu but is reduced for power levels below 75%. This behavior is included in the model by using the following equation for speed reference when the power is below 0.75 pu:

$$\omega_{ref} = -0.67\,P^2 + 1.42\,P + 0.51$$

The speed reference slowly tracks changes in power with a time constant of approximately 5 seconds.

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 reference speed, the inertia of the machine functions as a buffer to mechanical power variations.

The model does not include high and low wind speed cut-out for the turbine. In situations where system performance questions hinge on this behavior, the user can simply trip the machine.

Parameter values for the wind turbine control model are shown in Table 4-6. None of these values should be modified by the user unless advised to by the manufacturer.

Table 4-6 Turbine Control Parameters
(all quantities are per unit. on MW base)

Parameter Name	**Recommended Value**
K_{pp}	150.
K_{ip}	25.
T_p (second)	0.01
Θ_{max} (degrees)	27.
Θ_{min} (degrees)	0.0
$d\theta/dt_{max}$ (degrees/second)	10.0
$d\theta/dt_{min}$ (degrees/second)	-10.0
P_{max} (pu)	1.0
P_{min} (pu)	0.1
dP/dt_{max} pu/second)	0.45
dP/dt_{min} (pu/second)	-0.45
K_{pc}	3.0
K_{ic}	30.0
K_{ptrq}	3.0
K_{itrq}	0.6
T_{pc}	0.05

4.3.3 Wind Power Model

For power system simulations involving grid disturbances, it is a reasonable approximation to assume that wind speed remains uniform for the 5 to 30 seconds typical of such cases. However, the mechanical power delivered to the shaft is complex function of wind speed, blade pitch angle and shaft speed. Further, with wind generation, the impact of wind power fluctuations on the output of the machines is of interest. The turbine model depends on the wind power model to provide this mapping.

The function of the wind power module is to compute the wind turbine mechanical power (shaft power) from the energy contained in the wind, using the following formula:

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

P is 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_w is the wind speed in m/sec, and C_p is the is the power coefficient, which is a function of λ and θ. λ is the ratio of the rotor blade tip speed and the wind speed (v_{tip}/v_w), θ is the blade pitch angle in degrees. For the rigid shaft representation used in this model, the relationship between blade tip speed and generator rotor speed, ω, is a fixed constant, K_b. The calculation of λ becomes:

$$\lambda = K_b\ (\omega/v_w)$$

For the GE WTGs, parameters given in Table 4.4 will result in P_{mech} in pu on the unit's MW base.

Table 4-6. Wind Power Coefficients

	GE 1.5	GE 3.6
$\frac{1}{2}\rho\ A_r$	0.00159	0.00145
K_b	56.6	69.5

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. The C_p curves for the GE wind turbine are shown in Figure 4-3. Curve fitting was performed to obtain the mathematical representation of the C_p curves used in the model:

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

The coefficients $\alpha_{i,j}$ are given in Table 4-7. The curve fit is a good approximation for values of $2 < \lambda < 13$. Values of λ outside this range represent very high and low wind speeds, respectively, that are outside the continuous rating of the machine.

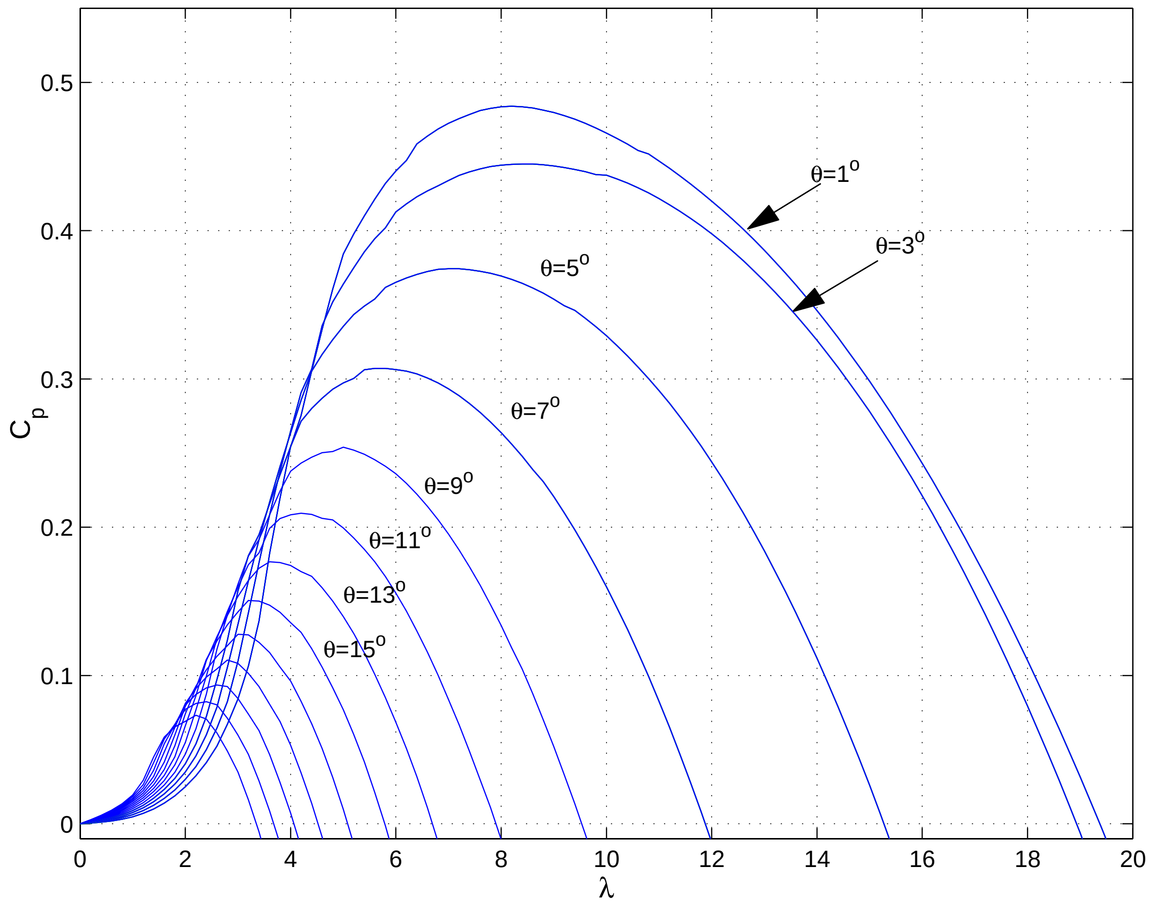

Figure 4-7. Wind Power C_p Curves

Initialization of the wind power model recognizes two distinct states: 1) initial electrical power (from the loadflow) is less than rated, or 2) initial electrical power equal to rated. In either case, $P_{mech} = P_{elec}$ is known from the loadflow and $\omega = \omega_{ref}$ is set at the corresponding value (1.2 pu 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 4-3, 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.

Table 4-7. Cp coefficients $\alpha_{i,j}$

i	j	a_{ij}
4	4	4.9686e-010
4	3	-7.1535e-008
4	2	1.6167e-006
4	1	-9.4839e-006
4	0	1.4787e-005
3	4	-8.9194e-008
3	3	5.9924e-006
3	2	-1.0479e-004
3	1	5.7051e-004
3	0	-8.6018e-004
2	4	2.7937e-006
2	3	-1.4855e-004
2	2	2.1495e-003
2	1	-1.0996e-002
2	0	1.5727e-002
1	4	-2.3895e-005
1	3	1.0683e-003
1	2	-1.3934e-002
1	1	6.0405e-002
1	0	-6.7606e-002
0	4	1.1524e-005
0	3	-1.3365e-004
0	2	-1.2406e-002
0	1	2.1808e-001
0	0	-4.1909e-001

4.4 Wind Speed

Wind power fluctuations are relatively complex and stochastic in nature. The wind speed variable is accessible to a user-written model that can be designed to apply various wind fluctuations, including the following:

- Step of wind speed
- Wind gust following a (1 – cos A t) shape
- Wind speed variations derived from measurements

5. Sample Simulation Results

This Section illustrates the performance of the GE PSLF model. The following three simulations are included: i) comparison of the model response versus measured field data; ii) simulation of a three-phase fault; and iii) simulation of an abrupt change in wind speed.

5.1 Comparison with Measured Data

Figure 5-1 compares the generator reactive power of the wind turbine model versus measured data, for a up/down step in the reactive power order, Q_{ord}. The discrete points correspond to the measured data; the model response is the continuous trace. The model response closely matches the field measurements.

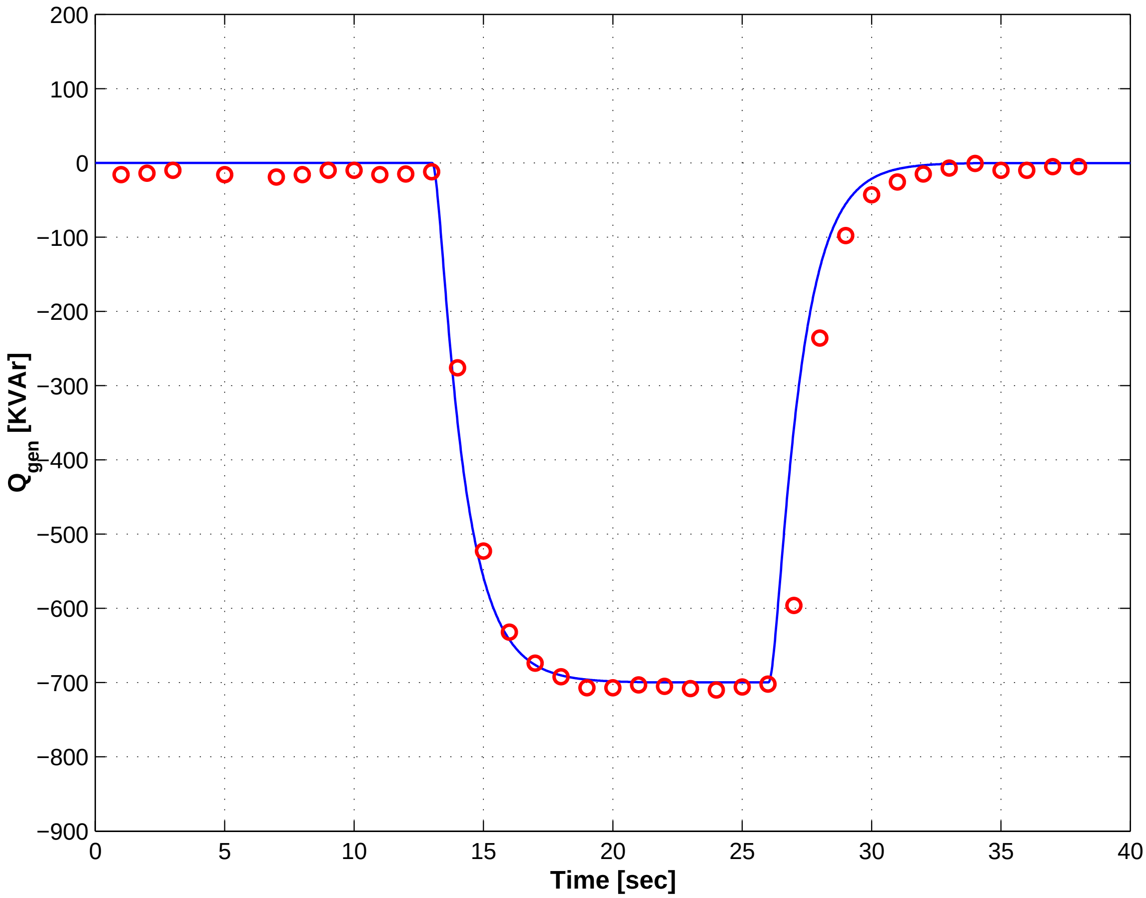

Figure 5-1. Generator Reactive Power – Response to a Step in Q Order

5.2 Response to Fault

The wind farm for this case consists of six wind turbines, WT1…WT6, connected to a large power system with a single transmission line as shown in Figure 5.2. Each wind turbine represents the aggregate of several 1.5 MW machines. The turbine-generator sets are represented with a single mass model. A 30 cycle fault is applied at the point of interconnection bus (POI). The low voltage trip point at 0.7 pu was reduced for this case to demonstrate the control response. For this case, the wind speed, V_w, is kept constant at 11.3 m/sec during the simulation.

Pertinent model variables are plotted in Figure 5-3. Following the fault, the speed (spd) tends to increase. In response, the WT controller increases the pitch to reduce the mechanical power provided by the wind turbine (Pmech). The generator terminal voltage drops to 0.23 pu during the fault-on time and returns to 1.015 pu when the fault is cleared. Its steady state value of 1 pu is reached at 4 sec. In response to a high voltage following the removal of the fault, the reactive power order, Q_{ord}, hits its Q_{min} limit when the fault is cleared.

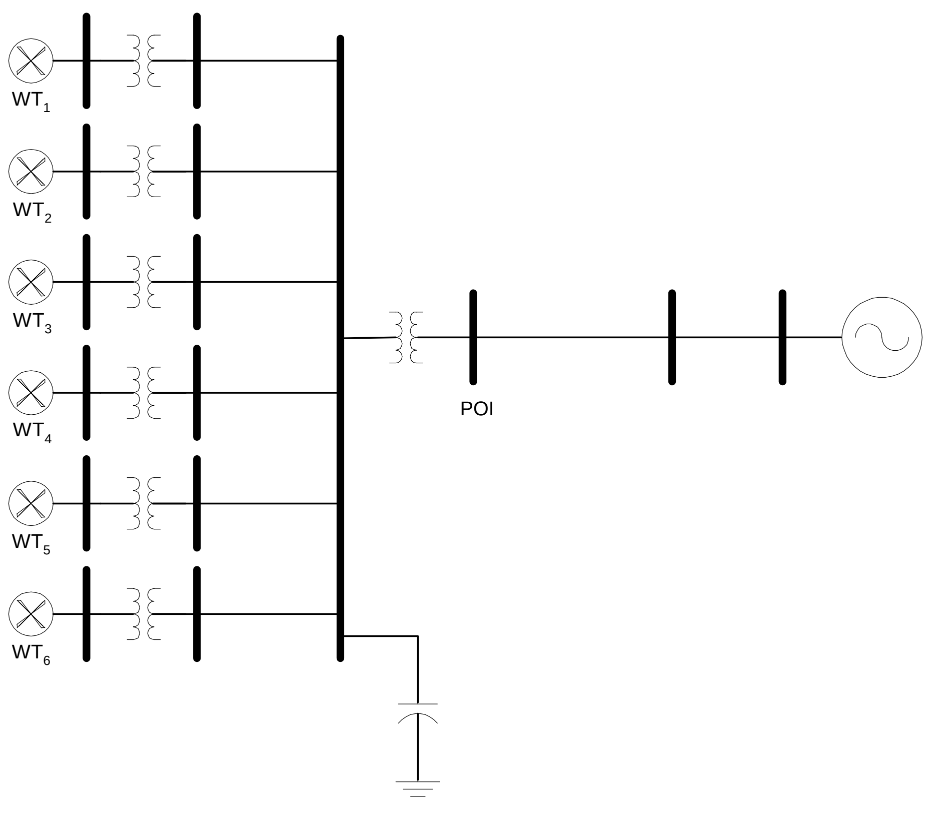

Figure 5-2. Power System Model

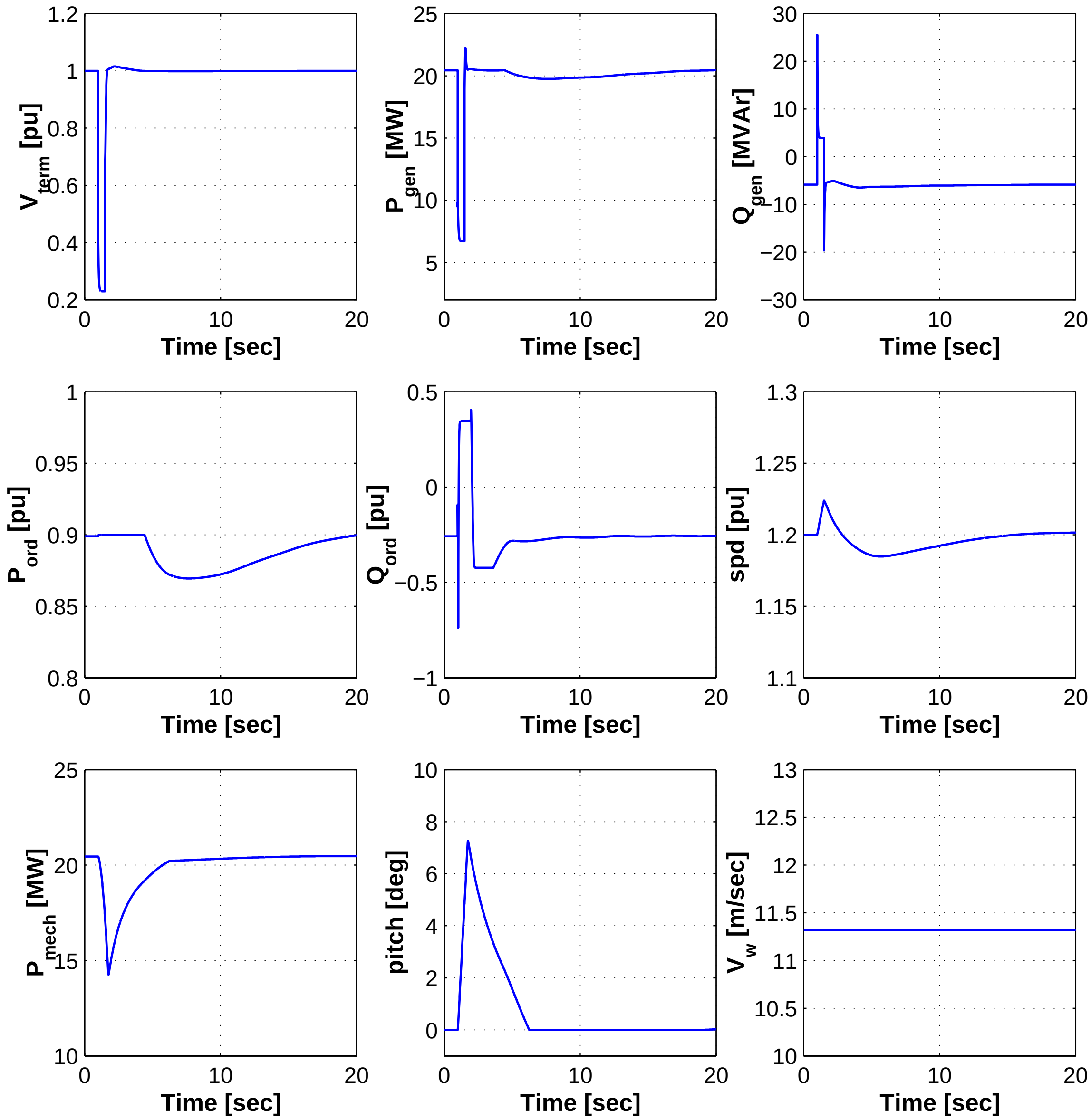

Figure 5-3. Response to a 30 cycle system fault

5.3 Response to Wind Step

Figure 5-4 shows the response of the system shown in Figure 5-1 to a change in wind speed, V_w, of 3 m/sec in a time span of 1 second. The WT controller adjusts the pitch to 10.4^o to keep the speed, spd, at 1.2 pu.

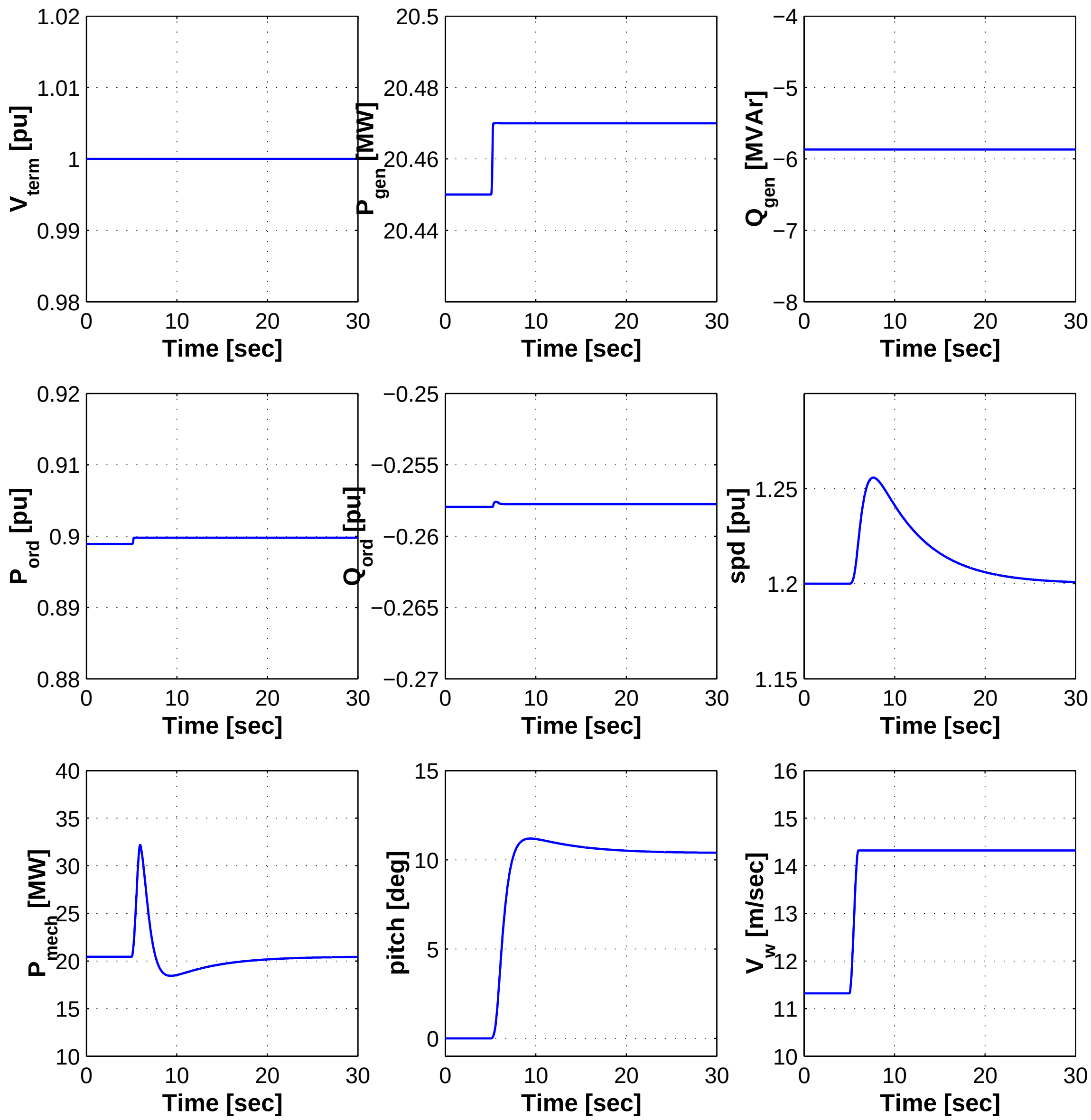

Figure 5-4. WTG Electrical Variables: Response to Wind Gust

6. Other Technical Issues

6.1 Equivalencing

In practice, a wind farm has a local grid collecting the output from the machines into a single point of connection to the grid. Since the wind farm is made up of many identical machines, it is a reasonable approximation to parallel all the machines into a single equivalent large machine behind a single equivalent reactance. This approach is consistent with the model presented in this report. This approach is reasonable - up to a point. Disturbances within the local collector grid cannot be analyzed, and there is some potentially significant variation in the equivalent impedance for the connection to each machine. A single machine equivalent requires the approximation that the power output of all the machines will be the same at a given instant of time. For grid system impact studies, simulations are typically performed with the initial wind of sufficient speed to produce rated output on all machines. Under this condition, the assumption that all machines are initially at the same (rated) output is not an approximation. Otherwise, this assumption presumes that the geographic dispersion is small enough that the wind over the farm is uniform. Simulations of bulk system dynamics using a single machine equivalent is adequate for most planning studies.

Detailed modeling of the WTG collector system is possible. The inclusion of the supervisory (WindVAR) control in each WTGs electrical control model provides an emulation of the action of a single centralized control. An intermediate level of modeling detail can also be used in which groups of WTGs, e.g. those on a single collector feeder, are represented by a single equivalent model.

6.2 Applicability of Model to Other WTGs

This model was developed specifically for the GE 1.5 and 3.6 MW WTGs. The model is applicable, with care, to other recent vintage GE WTGs and other WTGs, as long as the basic principals of power conversion and control are the same. Just as with the equivalencing, changing the MVA and MW bases for the device models will allow for other machines to be represented.

In the broader sense, this model is not designed for, or intended to be used as, a general purpose WTG. There are substantial variations between models and manufacturers.

7. Conclusions

The wind turbine model presented in this report is based on presently available design information, test data and extensive engineering judgment. The modeling of wind turbine generators for bulk power system performance studies is still in a state of rapid evolution, and is the focus of intense activity in many parts of the industry. More important, the GE equipment is being continuously improved, to provide better dynamic performance. These ongoing improvements necessitate continuing changes and improvements to these models. This model is expected to give realistic and correct results when used for bulk system performance studies. It is expected that as experience and additional hard test data is obtained, these models will continue to evolve, in terms of parameter values and structure.

