Validation of GE Wind Plant Models for System Planning Simulations

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***Abstract* – GE Energy has an ongoing effort dedicated to the development of models of GE wind turbine generators (WTG) suitable for representing wind plants in system impact studies. This paper documents the present recommendations for dynamic modeling of GE wind plants using either Doubly Fed Asynchronous Generators (DFAG) or Full Conversion (FC) technology. This includes GE's 1.5 and 1.6 MW, as well as 2.5 and 2.75 MW WTGs. The paper presents both the overall model structure and validation results for the non-generic GE equipment models. The assumptions, capabilities and limitations of the plant model will also be discussed.**

I. Introduction

The objective of the work documented in this paper is to describe plant-level models appropriate for bulk power system studies, and to show that these models have been validated against installed equipment. Modeling details are documented elsewhere [1]. The grid performance of the Doubly-Fed Asynchronous Generator (DFAG) and Full Converter (FC) WTGs are similar, since both are dominated by the converter controls. Therefore, the dynamic models are similar. The bulk of the discussion will focus on the DFAG models. The modifications made to represent the full converter WTGs will be described as necessary.

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 fundamental frequency phasor time-domain simulations, e.g. PSLF or PSS/e. Second, the analysis is mainly focused on how the wind plant reacts to disturbances, e.g. faults on the transmission system. Third, 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 or electromagnetic transient studies.

II. Model Overview and Philosophy

A. Fundamentals

A simple schematic representing both the GE Doubly Fed and full converter wind turbines is shown in Fig. 1.

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The Doubly-Fed topology is represented by a power converter that supplies a source of excitation to the generator (bottom right of the figure). Physically, the DFAG 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. Machines of this structure are termed 'doubly fed'. Control of the excitation frequency allows the rotor speed to vary over a wide range, and maximizes power production.

The full converter topology is represented with the converter connected between the stator and the grid (top of the figure). The FC machine is a relatively conventional permanent magnet synchronous generator. With the generator connected to the power grid through a full converter, the generator speed is decoupled from the power system frequency and allows for a wide range of variable speed operation.

For either type of GE WTG, modeling of wind plants with conventional dynamic models for either synchronous or induction machines is, at best, highly approximate and should be avoided.

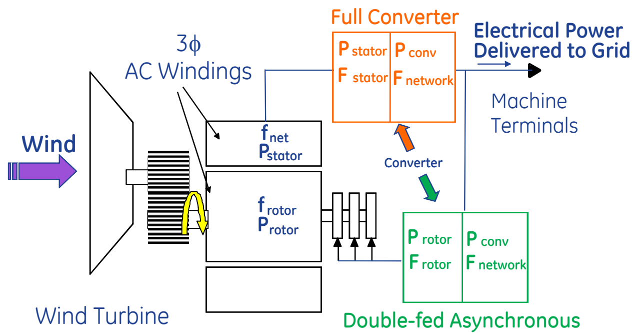

Fig. 1. GE WTG Major Components.

The fundamental frequency electrical dynamic performance of both GE machines is completely dominated by the converter. Conventional aspects of generator performance related to internal angle, excitation voltage, and synchronism are largely irrelevant.

In practice, the DFAG 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 converter will make the WTG behave like a voltage behind a reactance that results in the desired active and reactive current being delivered to the device terminals.

The rotation of the DFAG 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 DFAG machine 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 the bottom portion of Fig. 1. The control of active and reactive power is 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 regarded as instantaneous for simulation of bulk power system dynamic performance.

For the full converter machines, the line-side of the converter corresponds to the WTG terminals. The electrical behavior on the machine side of the converter is of no interest to the AC system. Further, operation (i.e., rotation) of the turbine is not required for the converter to continue reactive operation on the line-side. In the vicinity of rated power, the GE full converter machines will normally operate at a speed selected to give optimum turbine performance. Control of the frequency converter allows the rotor speed to be completely decoupled from the grid frequency, and to be controlled over a wide range.

Broadly stated, the objectives of the turbine control in both DFAG and FC machines 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 the relevant mechanical states and the speed controls. This 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.

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 at the wind plant level and how they interact with the bulk power system. Wind plants with GE WTGs are normally designed with plant-level supervisory control which interacts with the individual WTGs through the electrical controls. Representation of all the individual machines in a large wind farm is inappropriate for most grid stability studies, so provision is made to allow a single aggregate WTG machine model 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.

B. Overall Model Structure

From a load flow perspective, conventional generator and transformer models are used for initialization of the dynamic simulation program. The dynamic models presented here are specific to the GE WTG, and are widely available in commercially available power system simulation packages, such as PSLF, PSS/e, DigSilent PowerFactory, etc. The implementation is structured in a fashion that is somewhat similar to other conventional generators. To construct a complete WTG model, three main device models are used, as shown in Fig. 2:

- Generator and Converter, which includes the high/low voltage ride through capability, and network interface
- Electrical Control, which includes closed loop voltage and reactive power controls as well as current limits
- Turbine and Turbine Controls, which includes the blade pitch and torque controls, as well as optional features for active power control and WindINERTIA™

A fourth Wind Profile model can be used to emulate wind disturbances such as gusts and ramps by varying input wind speed to the wind power module which determines mechanical power. The user can also input wind speed vs. time sequences, derived from field measurements or other sources.

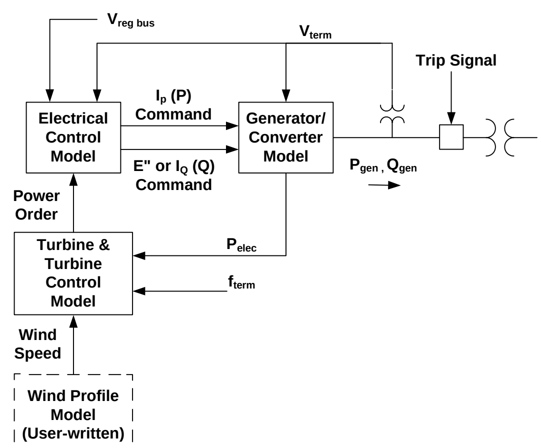

Fig. 2. GE WTG Basic Dynamic Models and Data Connectivity.

III. LOAD FLOW MODEL

The modeling for load flow analysis is relatively simple. A single WTG is represented by a conventional generator connected to an explicitly represented PV bus, which is connected to the power system collector through a step-up transformer. Specifically, for the 60 Hz 1.5 WTG, each individual machine is connected to a 575 V or 690 V 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 (12.5kV and 34.5kV are typical). The unit transformer will typically have 5-6% leakage reactance.

For a plant model of a wind farm consisting of *n* 1.5 MW WTGs, a single generator and transformer with MVA ratings equal to *n* times the individual device ratings gives a reasonable equivalent for bulk system studies. The generator real power output, maximum and minimum reactive power output are input as *n* times the unit capabilities.

An equivalent impedance to reflect the aggregate impact of the collector system can be included, together with the substation step-up transformer(s). The total charging capacitance of the collector system should also be included. The charging capacitance can be significant since underground cables are often used for the collector system. The substation transformer would be suitably rated for the number of WTGs, with an impedance typically around 10%. Several papers have been published on the topic of aggregation [2,3].

The supervisory control would typically be structured to regulate the collector bus voltage to a specified level, possibly with additional voltage droop or line drop compensation to provide effective regulation of the point-of-common coupling (PCC) bus or to coordinate multiple wind plants in one area.

The load flow provides initial conditions for dynamic simulations. 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 load flow must be initialized in accordance with those customized rules. For example, if the active power controls are set to curtail power to 95% of that available in the wind, then the real power at the load flow generator must be set accordingly. Similarly, it is possible to inject or absorb reactive power (e.g., regulate voltage) at zero real power with a full converter WTG. Therefore, the real power at the generator in the power flow must be zero for this type of simulation.

Inconsistencies between the power flow and the dynamic model will result in an unacceptable initialization.

IV. Dynamic Model

A. Generator/Converter Model

Fig. 3 shows the structure of the Generator/Converter model for both the double fed and full converter machines. This model is the physical equivalent of the generator and converter hardware and provides the interface between the WTG electrical controller 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 reduced to their algebraic equivalents. The flux dynamics are too fast to have significant impact on system stability. The net result is an algebraic, controlled current source that injects the active and reactive power specified by the WTG electrical control model into the network.

The generator model also includes over/under voltage protective functions. In particular, the low voltage tripping can be set to meet so-called “low-voltage ride through” LVRT) or “zero-voltage ride through” (ZVRT) requirements.

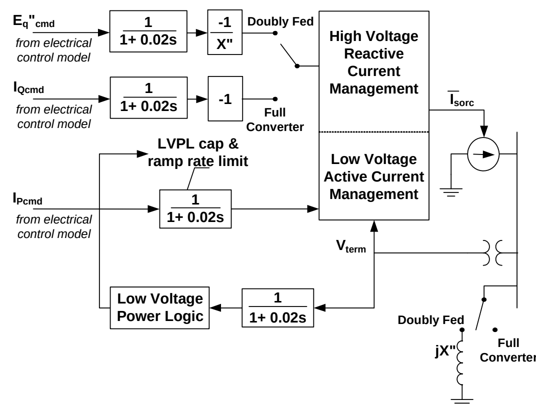

Fig. 3. GE WTG Generator/Converter Model.

B. Electrical Control Model

This 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 control (Qord).

The real power path is shown in Fig. 4. The real current command signal, I_{Pcmd}, , is developed from the wind turbine model power order (P_{ord}) and the terminal voltage (V_{term}).

The block diagram for the reactive power control, including both WindCONTROL™ emulation and turbine-level volt/var control, is shown in Fig. 5. Q_{ord} comes from the WindCONTROL emulation function. This emulation function represents a simplified equivalent of the supervisory control for the entire wind power plant. Q_{ord} can also be held constant, or determined by a power factor regulator, or come from a separate, user-written model.

The WindCONTROL Emulation function monitors a specified bus voltage, V_{reg}, and compares it against the reference voltage, $V_{ref\ reg}$. The regulator itself is a PI controller with proportional and integral path gains, K_{pv} and K_{iv}, respectively. The time constant, T_c, reflects the delays associated with cycle time, communication, and additional filtering in the machine controls. The voltage measurement lag is represented by the time constant T_r.

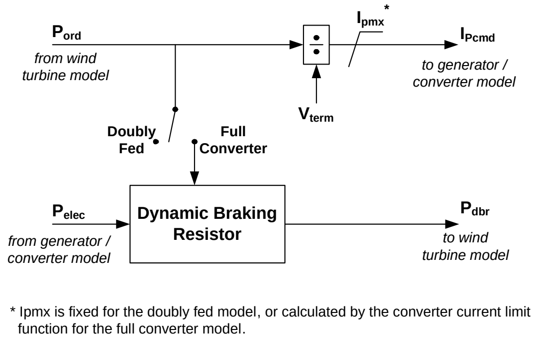

Fig. 4. Real Power Path in Electrical Control Model.

The WindCONTROL plant-level regulator sends a reactive power command, Qord, to the intermediate turbine-level reactive power regulator. The Q_{ord} signal is compared to the reactive power generated by the converter, and the resulting error is integrated with a gain of K_{qi}, to generate a voltage reference, V_{ref} term. This terminal voltage reference is sent to the fast turbine-level voltage regulator. This regulator computes the DFAG voltage command, $E_{q''cmd}$, or FC current command, I_{Qcmd}, required to meet the voltage reference.

Thus, the WindCONTROL reactive power command is implemented via a slowly changing terminal voltage reference. The subsequent voltage control block is significantly faster. The voltage reference is compared to the actual terminal voltage, and the resulting voltage error is multiplied by a gain and integrated to compute the commands $E_{q''cmd}$ or I_{Qcmd}. Thus, a drop in terminal voltage, e.g., in response to a system fault, results in an immediate large voltage error and an increased reactive command. The magnitude of the gain determines the effective time constant associated with the voltage control loop.

While the WindCONTROL reactive power control remains unchanged for the full converter machine, the turbine-level voltage regulator is slightly different than that of the DFAG machine. The primary philosophical change to the model was to generate a reactive current command rather than a flux command. Additional functions include a dynamic braking resistor, as shown in Fig. 4, and a converter current limit, as shown in Fig. 5.

The objective of the dynamic braking resistor is to minimize the WTG response to large system disturbances, such as extended periods of low voltage. This is accomplished by absorbing energy in the braking resistor when the power order is significantly greater than the electrical power delivered to the grid. The energy capability of the resistor is respected. The model does not include thermal reset, so simulations with multiple events may result in limited dynamic braking resistor response.

The full converter model also contains converter current limit logic that prevents the combination of the real and reactive currents from exceeding converter capability. Depending upon the value of a user-specified flag, either real or reactive power has priority. This flag is dependent upon the equipment features selected, and is normally dictated by the host system grid code.

An auxiliary test signal can be injected into the terminal bus voltage regulator for both DFAG and full converter electrical controls as shown in Fig. 5. This is especially useful when validating the response of the electrical control model to field test results of the same step stimulus in real equipment.

C. Wind Turbine and Turbine Control Model

The wind turbine model provides a simplified representation of a very complex electro-mechanical system. The turbine control is designed to deliver as much power as the wind will allow without exceeding equipment ratings, taking advantage of the variable speed capability of the machine. The wind turbine model represents the relevant controls and mechanical dynamics of the wind turbine. This model is used for both the DFAG and full converter WTG models. However, not all features (i.e., dynamic braking resistor) are applicable to the DFAG machines. 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 for the model is shown in Fig. 6.

The wind turbine model represents all of the relevant controls and mechanical dynamics of the wind turbine. The model is based on power calculations, rather than torque, for simplicity.

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 a 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 may be of interest. The turbine model depends on the Wind Power Model to provide this mapping. This function computes the wind turbine mechanical power from the energy contained in the wind.

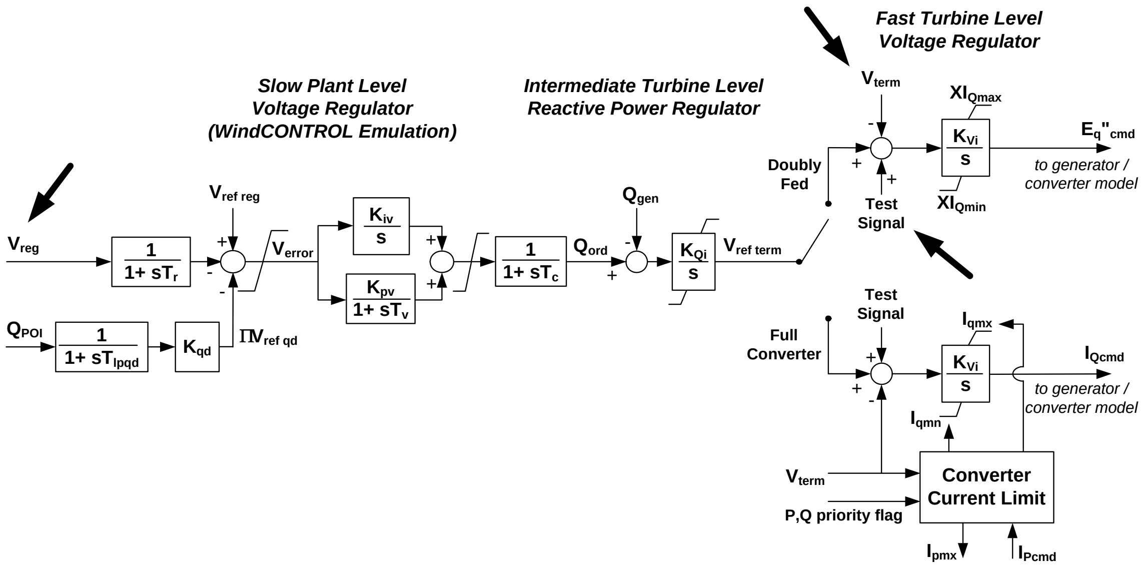

Fig. 5. Plant Reactive Power Control Model.

The turbine model directly accepts the machine terminal active power from the Generator/Converter Model and the mechanical power calculated by the Wind Power Model. The turbine control model simultaneously sends a power order to the electrical control, requesting that the converter deliver this power to the grid. The electrical control may or may not be successful in meeting 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. The dynamics of the electrical control are extremely fast.

Dynamically, the combination of blade pitch control and electric power order results in the two distinct operating conditions. For power levels significantly below nominal (~75%), the power is controlled by a reduction in turbine speed. This is approximated by adjusting the speed reference. The model does not allow for motoring of the turbine.

The turbine control modifies the blade pitch. In this model the blade position actuators are rate limited and there is a short time constant associated with the translation of blade angle to mechanical output. The Pitch Control and Torque Control respond to speed error, without differentiating 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 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 also includes high and low wind speed cut-out for the turbine. For machines without WindFREE™ reactive power capability, this results in a generator trip. All of the wind speed thresholds and timers are internal to the model and can not be changed by the user. The high wind speed threshold is currently set at 25 m/sec. An inverse time function is implemented, such that the more excessive the wind speed, the faster the unit is tripped. The low wind speed threshold is set at 3 m/sec. For this function, the decrease in rotor speed and power is approximated with a pseudo drag term. The unit is tripped, via a low rotor speed tripping function, when the rotor speed falls below 0.10 pu. Once a WTG has tripped, it can not be started again. The model is neither applicable nor appropriate for simulating start-up scenarios.

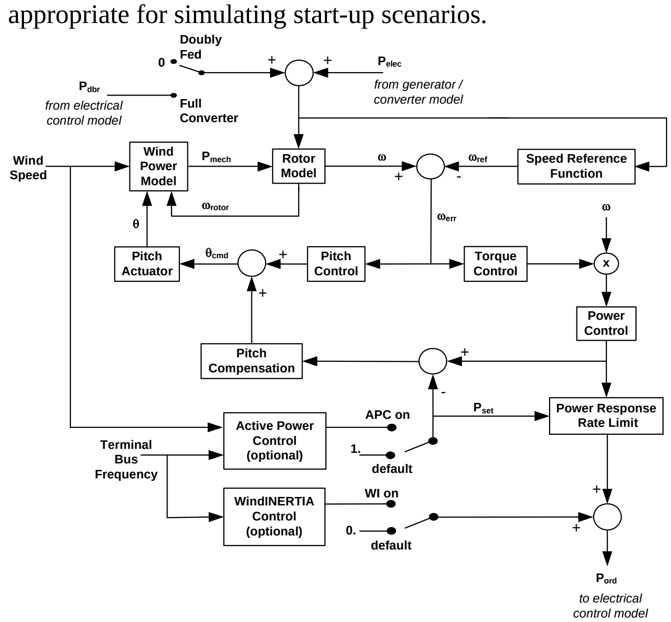

Fig. 6. Wind Turbine Model Block Diagram.

The turbine model also contains a module that represents the optional active power control of the wind turbine. Under normal operating conditions with near nominal system frequency, the control is either enforcing a maximum plant output (i.e., P_{set}) or providing a specified margin by generating less power than is available from the wind (e.g., actual power generated is 95% of the available power).

In response to frequency excursions, the control switches into another mode and calculates a plant power order as a function of system frequency. This path requests a higher than usual power order for low frequency events, and lower than usual power order for high frequency events. Thus, the wind plant will generate additional power in response to the loss of other generating facilities or less power in response to the loss of load. The turbine model also contains a module representing the optional WindINERTIA function. System disturbances that include the loss of generation normally result in transient depressions of system frequency. The rate of frequency decline, the depth of the frequency excursion, and time required for system frequency to return to normal are affected by the dynamic characteristics of generation connected to the grid. In the first few seconds following the loss of a large generating plant, the frequency dynamics of the system are dominated by the inertial response of the generation. Conventional synchronous generation inherently contributes some stored inertial energy to the grid, reducing the initial rate of frequency decline and allowing slower governor actions to stabilize grid frequency.

Most modern MW-class wind generation does not exhibit this inertial response. However, GE's WindINERTIA feature provides an inertial response capability for wind turbines, similar to that of conventional synchronous generators, for large under-frequency grid events. Note that this control is asymmetric: it only responds to low frequencies. High frequency controls are handled separately by the APC described above. Fast supplemental controls, added to the fast power electronics and mechanical controls of the WTG, take advantage of the inertia in the rotor. For these large underfrequency events, this feature temporarily increases the power output of the wind turbine in the range of 5% to 10% of the rated turbine power. The duration of the power increase is on the order of several seconds. This benefits the grid by allowing other non-wind power generation assets time to increase their power production during under-frequency events.

The power delivery of the wind turbine-generator is limited not only by the available wind, but by the physical limitations of the components of the WTG. Most critical are aero-mechanical ratings and speed limits. A key point is that slowing the turbine tends to reduce the aerodynamic lift, thereby reducing the delivered mechanical shaft torque and exacerbating the speed decline caused by increased generator electrical torque. This positive feedback tends to push the blade towards aerodynamic stall, which must be avoided. The inertial control must provide margin above stall, and is consequently limited when the initial rotor speed is low. The power and energy of the inertial response declines below about 50% rated power, dropping to zero at below about 20%. Inertial energy extracted by slowing the rotation of the turbine must ultimately be recovered. After the initial increase in electrical power, it must temporarily drop below the mechanical power to allow the energy to recover, reaccelerating the rotor [4,5].

V. Dynamic Model Validation via Field Tests

This section demonstrates results from a subset of field tests performed at a 70MW wind plant in Canada using GE DFAG wind turbines. Similar performance would be expected from a plant consisting of FC machines.

The test plant is configured as shown in Fig. 7, where multiple feeders are collected at one main 25 kV bus at the plant substation. This plant uses GE 1.5MW SLE wind turbine-generators and the WindCONTROL plant management system. The WindCONTROL system allows coordination of all on-line turbine-generators for plant-level voltage regulation at the point of interconnection (POI), located contractually at the 25 kV substation bus.

The intent of testing at this plant is for model validation. Field tests were performed, data captured, results analyzed and then compared to simulation results from a model of the plant and interconnecting grid built in GE's PSLF simulation software. Two tests are performed: a control stimulus test via a step change in voltage reference, and an external physical stimulus by switching the plant capacitor bank.

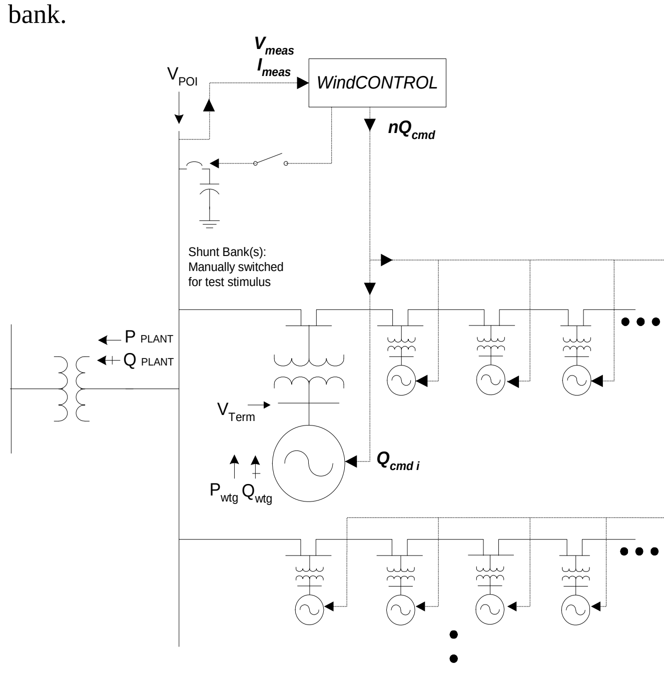

Fig. 7. Wind Plant Layout.

A. Control Stimulus Test

The fastest dynamic response in the wind plant model is the turbine-level voltage regulator loop. This control loop senses the terminal voltage of the individual WTG, compares it to the local dynamically modified voltage reference, and instructs the generator converter to deliver reactive current to the collector system of the plant.

To test the fast regulator loop, a step change to the reference signal is injected at the test signal input as shown in Fig. 5. The resulting change in reactive power and voltage at the terminals of the machine is measured. In this test, the WTG communication with the plant-wide WindCONTROL is shut down, so the reactive power command from the plant-level regulator (Q_{ord}) is held constant.

The top portion of Fig. 8 shows a comparison between measured wind turbine generator reactive power response and simulated response in PSLF. Notice that the initial response of reactive power is extremely fast, rising to full output for this stimulus in about 200msec – a response similar to that of an SVC.

When the WTG is isolated from the plant level supervisory control, the gain Kqi is reduced and the turbine operates in a constant reactive power mode. This is accounted for both in the actual response of the WTG control as well as in the model. The bottom portion of Fig. 8 shows the results of the voltage step test when one WTG is isolated. In this case, since reactive power command (Q_{ord}) is held constant, the initial rapid increase in reactive power output is slowly compensated for by the WTG reactive control as shown in Fig. 5.

B. External Physical Stimulus Test

In the case of our example system, a 10MVAr capacitor bank, located at the 25kV wind plant collector bus, is switched offline for the external physical stimulus. Fig. 9 shows the detailed WindCONTROL response to capacitor switching.

In the bottom plot of Fig. 9, the red curve (Q_ACTUAL) shows that total plant reactive power initially drops after the switching action. The fast autonomous controls on each turbine generator, however, quickly and stably respond to increase reactive power generated by individual turbines, as shown by the orange curve (Q_TURBINES). The WindCONTROL reactive power command (Q_COMMAND) distributed to the individual turbines is shown in blue. The response of Q_COMMAND is dominated by the gains of the voltage regulator portion of the WindCONTROL, specifically the proportional gain, K_{pv}, and integral gain, K_{iv}.

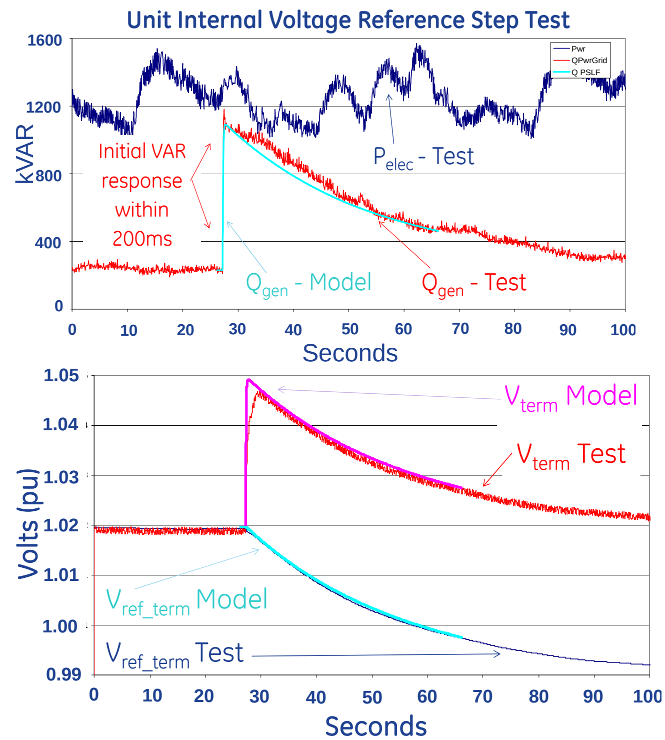

Fig. 8. Wind Turbine Generator Voltage Step Test Response.

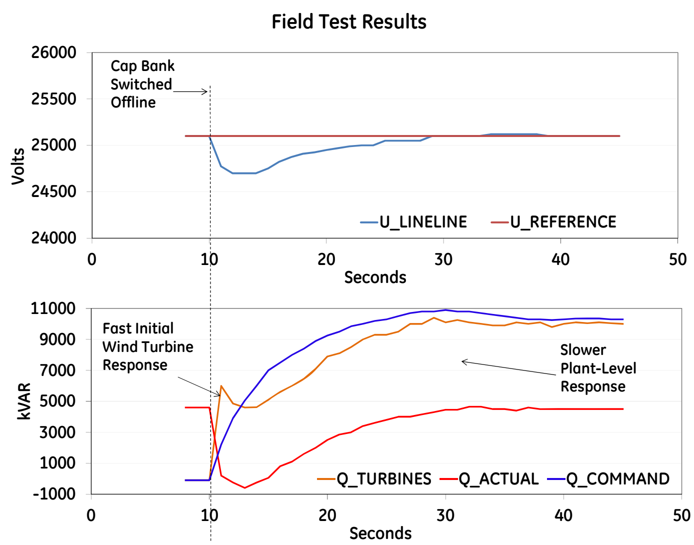

Fig. 9. 10MVAr Capacitor Removal Response from WindCONTROL.

The difference between the response of the individual turbines (Q_TURBINES) and the WindCONTROL command (Q_COMMAND) is due to the dynamics of the individual wind turbines. Thus, the coordinated response of the wind plant and the individual turbines is multi-modal: a fast initial response to address severe perturbations as well as a slower, grid friendly refinement.

The very fast initial response will dominate and saturate the controls for big events. The wind plant will do everything as quickly as it can to mitigate a large disturbance. In this case, the fast response took approximately 200ms. The slow, refined control then takes over to allow for coordination with other equipment and to maintain post-disturbance stability.

The blue curve in the top plot in Fig. 9 (U_LINELINE) represents the measured voltage at the POI. When the capacitor is switched offline, the voltage decreases due to reduced reactive power flowing into the grid. As noted above, the response of the individual WTGs is to rapidly increase reactive output to make up for the loss of reactive power supplied by the shunt capacitor. The plant level control then responds to this initial under-voltage condition and attempts to restore the POI voltage by increasing each wind generator's reactive output by equal amounts until the plant voltage settles to the voltage reference (U_REFERENCE).

Fig. 10 shows a comparison between these measured values and the simulation results of the PSLF model. Model outputs Qgen, QPOI, and Qord are compared to measured Q_TURBINES, Q_ACTUAL, and Q_CMD, respectively. This plot shows that the model performance adequately represents actual performance. The response matches closely, with a difference immediately following the switching operation due to the lower sampling rate in the measurement than in the PSLF simulation [6,7].

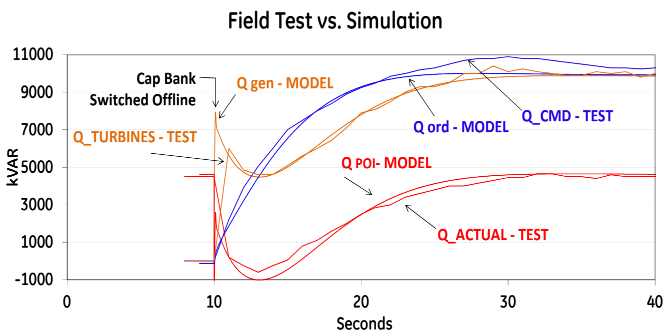

Fig. 10. 10MVAr Capacitor Removal Field Test vs. Simulation Results.

VI. Conclusions

Modeling of wind plants for bulk power system stability studies is the focus of intense activity in many parts of the industry. The wind plant model presented in this paper is based on presently available design information, test data and extensive engineering judgment. It was developed specifically for the GE WTGs, and has been validated against installed and operating equipment. As such, it is expected to give realistic and correct results when used for bulk system performance studies. It is also expected that these model components will continue to evolve, in terms of parameter values and structure, as experience and additional test data are obtained.

VII. References

[1] K. Clark, N.W. Miller, J. J. Sanchez-Gasca, "Modeling of GE Wind Turbine-Generators for Grid Studies," version 4.5, April 16, 2010. Available from GE Energy.

[2] E. Muljadi, S. Pasupulati, A. Ellis, D. Kosterov, "Method of Equivalencing for a Large Wind Power Plant with Multiple Turbine Representation", 2008 IEEE PES General Meeting

[3] A. Ellis, E. Muljadi "Wind Power Plant Representation in Large-Scale Power Flow Simulations in WECC"2008 IEEE PES General Meeting

[4] 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.

[5] W.W.Price and J. J. Sanchez-Gasca, "Simplified wind turbine generator aerodynamic models for transient stability studies," in PROC IEEE PES 2006 Power Systems Conf. Expo. (PSCE), Atlanta, GA, Oct. 1, 2006, p. 986-992

[6] R.J. Piwko, N.W. Miller, J.M. MacDowell, "Field Testing & model validation of wind plants," in Proc. IEEE PES General Meeting, Pittsburg, PA, Jul 2008.

[7] N. Miller, K. Clark, J. MacDowell and W. Barton, "Experience with field and factory testing for model validation of GE wind plants," in Proc. Eur. Wind Energy Conf. Exhib., Brussels, Belguim, Mar./Apr. 2008

VIII. Biographies

Jason MacDowell is a Senior Engineer for GE Energy Consulting in NY. His current focus is on performance and interconnection of wind generation into the bulk transmission system, modeling and model validation of wind plants and power system protection, and has authored many technical papers on these subjects. He was chairman of IEEE std. 551-2006 (the Violet Book) and is a balloting member of NERC Generator Verification Standards Drafting Team (GVSDT). He has lectured and provided consultation on Wind Power interconnection to governments, grid companies and generation owners in North America and Asia.

Kara Clark (M '84, S '95) is a Principal in GE's Energy Consulting group, a registered Professional Engineer, and author of many technical papers. Her current focus is on the control of wind-turbine generators and wind plants, model development, and analyzing the impact of significant levels of wind and solar generation on power system performance. She was a principal contributor to the New York, California, and Western US wind and solar integration studies, and received the 2007 American Wind Energy Association (AWEA) Technical Achievement Award and the 2010 Utility Wind Industry Group (UWIG) Achievement Award.

Nicholas Miller is a Director for GE Energy Consulting in NY. He leads analytical developments for large scale wind generation. He is an IEEE Fellow; was chairman of the IEEE TF on Dynamic Performance of Wind Generation. He has lectured and provided consultation on Wind Power integration to governments and institutions in more than two dozen countries. He holds eight patents for wind technology and power control devices.

Juan Sanchez-Gasca is a member of the engineering staff of GE Energy - Energy Consulting Department and has worked extensively in the areas of dynamic simulation and control of power systems. Dr. Sanchez-Gasca has been involved in the development of generic wind turbine generator models suitable for transmission planning studies. He is an IEEE Fellow and currently chairs the IEEE Power System Dynamic Performance Committee.