Merrimack Station
AR-1209

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Special Report

Standard Models for Variable Generation

5/18/10

to ensure
the reliability of the
bulk power system

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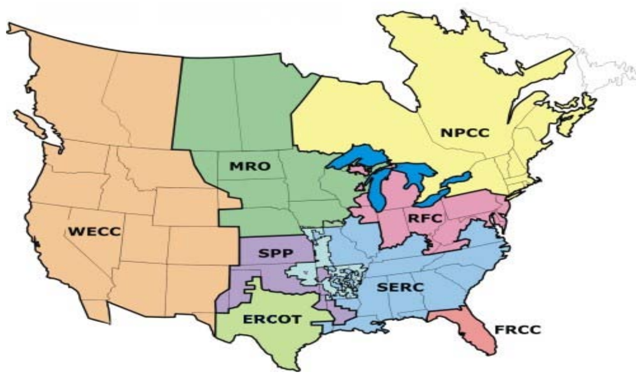
NERC's Mission

The North American Electric Reliability Corporation (NERC) is an international regulatory authority for reliability of the bulk power system in North America. NERC develops and enforces Reliability Standards; assesses adequacy annually via a ten-year forecast and winter and summer forecasts; monitors the bulk power system; and educates, trains, and certifies industry personnel. NERC is a self-regulatory organization, subject to oversight by the U.S. Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada.[1]

NERC assesses and reports on the reliability and adequacy of the North American bulk power system divided into the eight Regional Areas as shown on the map below (See Table A).[2] The users, owners, and operators of the bulk power system within these areas account for virtually all the electricity supplied in the U.S., Canada, and a portion of Baja California Norte, México.



Note: *The highlighted area between SPP and SERC denotes overlapping Regional area boundaries: For example, some load serving entities participate in one Region and their associated transmission owner/operators in another.*

Table A: NERC Regional Entities

ERCOT Electric Reliability Council of Texas	**RFC** Reliability*First* Corporation
FRCC Florida Reliability Coordinating Council	**SERC** SERC Reliability Corporation
MRO Midwest Reliability Organization	**SPP** Southern Power Pool, Inc.
NPCC Northeast Power Coordinating Council, Inc.	**WECC** Western Electricity Coordinating Council

[1] As of June 18, 2007, the U.S. Federal Energy Regulatory Commission (FERC) granted NERC the legal authority to enforce Reliability Standards with all U.S. users, owners, and operators of the BPS, and made compliance with those standards mandatory and enforceable. In Canada, NERC presently has memorandums of understanding in place with provincial authorities in Ontario, New Brunswick, Nova Scotia, Québec and Saskatchewan, and with the Canadian National Energy Board. NERC standards are mandatory and enforceable in Ontario and New Brunswick as a matter of provincial law. NERC has an agreement with Manitoba Hydro, making reliability standards mandatory for that entity, and Manitoba has recently adopted legislation setting out a framework for standards to become mandatory for users, owners, and operators in the province. In addition, NERC has been designated as the "electric reliability organization" under Alberta's Transportation Regulation, and certain reliability standards have been approved in that jurisdiction; others are pending. NERC and NPCC have been recognized as standards setting bodies by the Régie de l'énergie of Québec, and Québec has the framework in place for reliability standards to become mandatory. Nova Scotia and British Columbia also have a framework in place for reliability standards to become mandatory and enforceable. NERC is working with the other governmental authorities in Canada to achieve equivalent recognition.

[2] Note ERCOT and SPP are tasked with performing reliability self-assessments as they are regional planning and operating organizations. SPP-RE (SPP – Regional Entity) and TRE (Texas Regional Entity) are functional entities to whom NERC delegates certain compliance monitoring and enforcement authorities.

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Executive Summary

Existing state and federal energy policies including renewable portfolio standards (RPS) and production tax credits have driven development of wind plants in the U.S. and Canada that presently comprise in excess of 35 GW of installed capacity. This trend is projected to continue with the addition of many other forms of renewable technologies such as photovoltaics. Furthermore, other technologies like plug-in hybrid electric vehicles (PHEV), tidal-power systems, etc. are also on the horizon.

Unlike traditional, non-renewable resources, the output of wind, solar, ocean and some hydro generation resources varies according to the availability of the primary fuel (wind, sunlight and moving water) that cannot be reasonably stored. Therefore, these resources are considered variable, following the availability of their primary fuel source.

The North American Electric Reliability Corporation (NERC) is responsible for ensuring the reliability of the bulk power system in North America. Anticipating the growth of variable generation, in December 2007, the NERC Planning and Operating Committees created the Integration of Variable Generation Task Force (IVGTF), charging it with preparing a report [1] to identify the following:

1) Technical considerations for integrating variable resources into the bulk power system,

2) Specific actions, practices and requirements, including enhancements to existing or development of new reliability standards

One of the identified follow-up tasks from [1] was the need standard, valid, generic, non-confidential, and public power flow and stability models for variable generation technologies, and for a task force to review existing NERC Modeling, Data and Analysis (MOD) Standards to ensure high levels of variable generation can be simulated and appropriately addresses through the existing standards. This document constitutes the results of this review performed by this Task Force. A detailed discussion is provided of model and model validation in general, followed by an account of the current status of models for various variable generation technologies. Then a discussion is provided of the relevant NERC MOD standards and where they will need to be augmented to properly address variable generation.

Thorough out this report reference is made to various forms of models (standard, generic, user-written, 3-phase, etc.). It should be emphasized that the present and imminent need is to have models that are standard (i.e. a defined model structure used by all commercial software tools), publicly available and not specific to any particular design (i.e. “generic” and able to reasonably represent key performance relevant to bulk power system studies) – this is the focus, which is further elaborate in the report. The process and need for model validation, however, applies to any and all levels of modeling.

An earlier draft of this report and recommendations were presented to NERC's Planning Committee at their March, 2010 meeting. The Committee members urged the IVGTF to pursue NERC reliability standard development. Thus, several NERC Standards Drafting Teams undertaking MOD Standard development will be contacted to present the recommendations from this report for their consideration and incorporation in subsequent updates.

1. Introduction

Existing state and federal energy policies including renewable portfolio standards (RPS) and production tax credits have driven development of wind plants in the U.S. and Canada that presently comprise in excess of 35 GW of installed capacity. This trend is projected to continue with the addition of many other forms of renewable technologies such as photovoltaics. Furthermore, other technologies, like plug-in hybrid electric vehicles (PHEV), are also on the horizon.

Unlike traditional, non-renewable resources, the output of wind, solar, ocean and some hydro generation resources varies according to the availability of the primary fuel (wind, sunlight and moving water) that cannot be reasonably stored. Therefore, these resources are considered variable, following the availability of their primary fuel source. There are two overarching attributes of variable generation that can impact the reliability of the bulk power system if not properly addressed:

1) Variability: The output of variable generation changes according to the availability of the primary fuel resulting in fluctuations in the plant output on all time scales.

2) Uncertainty: The magnitude and timing of variable generation output is less predictable than for conventional generation.

The North American Electric Reliability Corporation (NERC) is responsible for ensuring the reliability of the bulk power system in North America. Anticipating the growth of variable generation, in December 2007, the NERC Planning and Operating Committees created the Integration of Variable Generation Task Force (IVGTF), charging it with preparing a report [1] to identify the following:

3) Technical considerations for integrating variable resources into the bulk power system

4) Specific actions, practices and requirements, including enhancements to existing or development of new reliability standards

One of the identified follow-up tasks from [1] was the need for the models for variable generation technologies. For the purpose of completeness of this document, the proposed action item Task 1-1 from [1] is repeated below.

Item #	Proposed Improvement	Abstract	Lead	Deliverables	Milestones
1.1	Standard, valid, generic, non-confidential, and public power flow and stability models (variable generation) are needed and must be developed, enabling planners to maintain bulk power system reliability	Valid, generic, non-confidential, and public standard power flow and stability (positive-sequence) models for variable generation technologies are needed. Such models should be readily validated and publicly available to power utilities and all other industry stakeholders. Model parameters should be provided by variable generation manufacturers and a common model validation standard across all technologies should be adopted. The NERC Planning Committee should undertake a review of the appropriate Modeling, Data and Analysis (MOD) Standards to ensure high levels of variable generation can be simulated. Feedback to the group working on NERC Standards' Project 2007-09 will be provided.	*Ad Hoc* group: Members from IVGTF - Planning	Make recommendations and identify changes needed to NERC's MOD Standards	• Draft report ready by December 2009 PC meeting • Final report with recommendations to PC for endorsement in February 2010 • Develop SAR with Standards Committee if required.

Therefore, the goal of this document is to address the above action item and to provide:

1. The roadmap for development of valid, generic, non-confidential, and public standard power flow and stability (positive-sequence) models for variable generation technologies. Namely, what is available at present and what is the path forward to developing and deploying these models.

2. The NERC standards implications and feedback on what further NERC action items may be needed, if any, to address model application and validation as it relates to variable generation.

Throughout this report reference is made to various forms of models (standard, generic, user-written, 3-phase, etc.). The present and imminent requirement is to have models that are standard (i.e. a defined model structure used by all commercial software tools), publicly available and not specific to any particular design (i.e. "generic" and able to reasonably represent key performance relevant to bulk power system studies) – this is the focus, which is further elaborated upon this report. The process and need for model validation, however, applies to any and all levels of modeling.

2. The Need for Models for Variable Generation

The planning and operation of large interconnected power systems in diverse regions in the North American continent, is a complex task which requires daily analysis and computer model simulations. System planners and operators use simulation studies to assess the potential impact of credible (and sometimes extreme) contingency scenarios and to assess the ability of the power system to withstand such events while remaining stable and intact (i.e., to avoid cascading outages). When a credible disturbance event is simulated in computer models of the power system and the observed result is unacceptable performance, system planners and/or operators must develop either operating strategies or planned equipment additions (e.g., line re-conductoring, addition of shunt reactive compensation devices, etc.) to mitigate the potential problem. To help ensure proper assessment of reliable performance and to minimize (as much as possible) capital investment, models are required that reasonably represent actual equipment performance in simulations.

The NERC Modeling, Data, and Analysis (MOD) Reliability Standards require Registered Entities to create procedures needed to develop, maintain and report on models to analyze the steady-state and dynamic performance of the power system (MOD-011 and MOD-013). Equipment owners are required to provide steady-state and dynamic models (MOD-012) to the Regional Entities. This information is required to build a reasonable representation of the interconnected system for planning purposes, as stated in MOD-014 and MOD-015.[3] Specifically, models are required to perform powerflow, short circuit, and stability studies necessary to ensure bulk power system reliability.

Therefore, system models are required for generation equipment at three levels:

1. Models for assessing the steady-state behavior of the units and their fault current contributions for protection system analysis.
2. Models for emulating the dynamic behavior of the units for bulk power system time-domain stability analysis.
3. Detailed, equipment-specific (3-phase) models for specialized studies.

In this chapter, the aforementioned three categories of models are described in detail focused on variable generation technologies.

[3] http://www.nerc.com/page.php?cid=2|20

2.1. Steady-State and Fault Current Analysis

Steady-state analysis in the context of bulk power system studies is primarily associated with power flow, which determines the flow of power on transmission lines and transformers and the voltages at power system nodes (substations). Accurate calculations are essential in the planning and design of the interconnected power system to ensure that all equipment will be operated within its rated capability under various credible scenarios (including contingencies). These calculations are performed under various base-case conditions (i.e., all equipment generally in service) and contingency conditions that impact one or more power system elements such as a line, generating unit, or transformers out of service (e.g., for different system load conditions including peak load, light load, different seasons, or different power transfer).

To assess the adequacy of protection system settings, faults on transmission equipment are simulated and the settings for protection relays are evaluated, as well as the calculated fault currents are compared to the current rating of circuit-breakers.

Both these analyses are critical to the reliable operation of the power system. To perform these analyses, adequate models are needed for simulating the steady-state power flow and the fault current characteristics of generation equipment.

2.2. Time-Domain Positive Sequence Dynamic Models for Bulk Power System Stability Analysis

Time-domain simulations are a key tool for assessing the reliability of the bulk power system assessing the stability of the system.[4]

> "Reliability of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period.
>
> Stability of a power system refers to the continuance of intact operation following a disturbance. It depends on the operating condition and the nature of the physical disturbance."

Similarly, NERC defines stability as, "The ability of an electric system to maintain a state of equilibrium during normal and abnormal conditions or disturbances."[5]

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[4] The definitions listed are quoted from: P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem and V. Vittal, "Definition and classification of power system stability: IEEE/CIGRE joint task force on stability terms and definitions", IEEE Transactions on Power Systems, Volume 19, Issue 3, Aug. 2004, pp: 1387 – 1401. (http://ieeexplore.ieee.org)

Stability analysis is traditionally performed using positive-sequence models. This includes models that focus on system simulation under assumed perfect balanced conditions (i.e., no imbalance in the 3-phase system voltages and currents). Furthermore, the primary stability issues that are investigated (angular stability, voltage stability, frequency control/stability) for bulk power systems tend to be bounded within a small frequency band around the system fundamental frequency. Positive sequence models are typically required to be valid in a range of roughly 0.1 Hz to about 3 Hz, with the control system having validity up to 10 to 15 Hz to allow for investigating general control loop stability. With these simplifying assumptions, it has been historically easy to establish generic, non-proprietary models for representing conventional generation and its controls. Functional models that are non-proprietary and generic (i.e., applicable to any vendors equipment, simply by changing the model parameters) are needed for the various variable generation technology. A library of models to deal with each family of variable generation technology is required to support reliability assessment. What is presently available, and what must be further developed is discussed in the next chapter.

Aside: *There are many cases were extended term analysis may be necessary, in which case wind speed variations may be a needed input to the model. For the purposes of typical stability analyses, however, where the study period spans over only several seconds, wind speed is typically assumed to be constant.*

2.3. Detailed Three-phase Equipment Level Models

There are a number of potential interaction issues that may occasionally require detailed analysis [2]. To perform this analysis, detailed three-phase equipment models are required.

Subsynchronous resonance (SSR) is a phenomenon whereby series compensation of a transmission line results in electrical resonance frequencies in the subsynchronous frequency range that can lead to destabilizing modes of mechanical torsional vibration on the turbine-generator shaft that fall in the frequency range of the electrical resonance.[6] These resonance phenomena are only of concern to generation technologies with a mechanical turbine-generator shaft that is coupled to the electrical system. Type 1, 2 and 3 Wind-Turbine Generation (WTG) may be susceptible.[7] Clearly, Type 4 (where the unit is decoupled from the electrical system) and technologies like PV have no such concerns. SSR is less likely to affect wind turbines compared

[5] Glossary of Terms Used in Reliability Standards, http://www.nerc.com/files/Glossary_2009April20.pdf, Updated April 20, 2009,

[6] P. M. Anderson, B. L. Agrawal and J. E. Van Ness, Subsynchronous Resonance in Power Systems, IEEE Press, New York, 1990.
P.M. Anderson and R. G. Farmer, Series Compensation of Power Systems, ISBN 1-888747-01-3, 1996

[7] See Appendix I for more information on these WTG configurations.

to large conventional synchronous generators since the typical torsional mode for a wind turbine is quite low (around 1 to 4 Hz). Accordingly, it would be quite unlikely that the level of series compensation in a system would be high enough to result in an electrical resonance that would interact with a low mechanical frequency.[8] A larger concern is induction machine self-excitation.[9] Some detailed 3-phase analysis and discussions with the wind turbine manufacturer on a case by case basis is prudent when installing wind near series compensated lines.

Another potential phenomenon related to torsional mechanical modes is device dependant subsynchronous oscillations, often referred to in the literature as subsynchronous torsional interaction (SSTI). This was first observed at the Square Butte HVDC project in 1976.[10] SSTI is a phenomenon by which controls associated with power electronic based transmission equipment (e.g., SVC or HVDC) may introduce negative damping torques in the frequency range associated with the torsional mechanical modes of oscillation of nearby thermal turbine-generating units. Again, due to the relatively low frequency range for torsional modes of wind turbine, this may not be a concern in most cases; however, where wind plants are closely coupled to a HVDC system, analysis is prudent to ensure that control and/or torsional interaction do not occur. This analysis will typically require detailed three-phase models for both the wind plant and the HVDC system. Also, SSTI is not necessarily detrimental[11] because, in some cases, torsional damping can be markedly improved through the application of power electronic devices. One thermal power plant in the Western U.S. grid uses a dedicated SVC for this purpose as a means of mitigating the effects of SSR. [12] A practical example of this is the Taiban Mesa wind plant located in New Mexico. This wind plant is located electrically adjacent to a back-to-back HVDC station – Blackwater. The detailed interconnection studies performed by ABB during the design of the wind plant showed that there was little risk of torsional interaction between the HVDC controls and the wind turbine generators. This analysis required detailed equipment level (3-phase) models of the wind turbines, the HVDC and transmission network.

[8] Note: The electrical resonance needs to be in the range of 56 to 59 Hz on a 60 Hz system found in North America.

[9] P.M. Anderson and R. G. Farmer, Series Compensation of Power Systems, ISBN 1-888747-01-3, 1996
C. F. Wagner, "Self-Excitation of Induction Motors with Series Capacitors", AIEE Transactions, pp.1241-1247, Vol. 60, 1941. (http://ieeexplore.ieee.org)

[10] M. Bahrman, E. Larsen, R. Piwko, H. Patel, "Experience with HVDC – Turbine Generator Torsional Interaction at Square Butte", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, pp. 966-975, May/June 1980. (http://ieeexplore.ieee.org)

[11] D. Dickmander, P. Pourbeik, T. Tulkiewicz and Y. Jiang-Häfner, "SSTI Characteristics of HVDC Light", White paper by ABB Inc., December, 2003

[12] Pourbeik, A. Boström and B. Ray, "Modeling and Application Studies for a Modern Static VAr System Installation", IEEE Transactions on Power Delivery, Vol. 21, No. 1, January 2006, pp. 368-377. (http://ieeexplore.ieee.org)

Other phenomena that may expose the shaft of a WTG to cyclical and significant transient torque pulsations may also be a concern. For example, nearby arc furnaces, or high-speed re-closing on a transmission line emanating from the wind plant substation, or repeated commutation failures on a nearby conventional line-commutated HVDC. As a first step, some simple transient stability analysis may be performed to estimate the expected step change in the electrical torque on a wind turbine generator due to the electrical event, and the wind turbine manufacturer consulted to identify if the observed level of transient torque is a concern. Based on consultation with the wind turbine manufacturer, more detailed analysis may be required to assess if a potential problem exists and how it may be remedied.

Another issue that may be of concern is the stability and behavior of variable generators in extremely weak short-circuit nodes of the power system and regions of the system that may be highly susceptible to islanding. Again, more detailed models than positive sequence stability representations may be needed to study these scenarios (e.g., to accurately review the potential for temporary over voltages upon islanding, etc.). Also, in some cases and designs (e.g., Type 3 WTG), the behavior of the unit as it pertains to voltage-ride through during fault scenarios can be more onerous on the controls (i.e., controlling the DC bus voltage in the Type 3 WTG) for unbalanced fault scenarios as opposed to a balance 3-phase faults. Thus, 3-phase detailed equipment models are needed to assess these phenomena.

Finally, transient stability studies should be completed to ensure that basic control loops in the variable generation plants (e.g., central voltage control systems often deployed in doubly-fed and full-converter based wind plants that regulate voltage at the interconnecting substation by adjusting the reactive output of all wind turbines in the wind plant) do not interact or interfere with other nearby transmission and generation controls. This often requires proper tuning of the controls.

This brief section illustrates the need for the availability of detailed 3-phase equipment level models, which cannot be generic. These models are likely to be proprietary and may need to be used under non-disclosure agreements between the vendor and the plant developer/utility. Therefore, it is important to recognize the need for these models so that they are developed and available to be easily deployed and used when such specialized studies are needed.

2.4. Summary

This chapter has outlined the basic power generation plants models required power system analysis related to reliability assessment. In addition, these models need to be generic (i.e., the model structure applicable to any vendor’s equipment, with only the variation of the model parameters to represent various vendor equipment) and non-proprietary (i.e., publicly available to all stakeholders). Adequate models readily exist for conventional synchronous generators, but, until recently, have been unavailable for any variable generation technology. In the next chapter the current status of models for all variable generation technologies is discussed.

3. Present Status of Modeling Variable Generation

This chapter provides an overview of the models and modeling capability presently available. In the summary of this chapter the gaps are identified and areas requiring further work are identified. The modeling and model development discussed here is primarily for power system power flow, short-circuit and stability analysis.

Time-domain stability analysis is concerned with phenomena in the tens of milliseconds to several minutes time frame (see Figure 3.1).

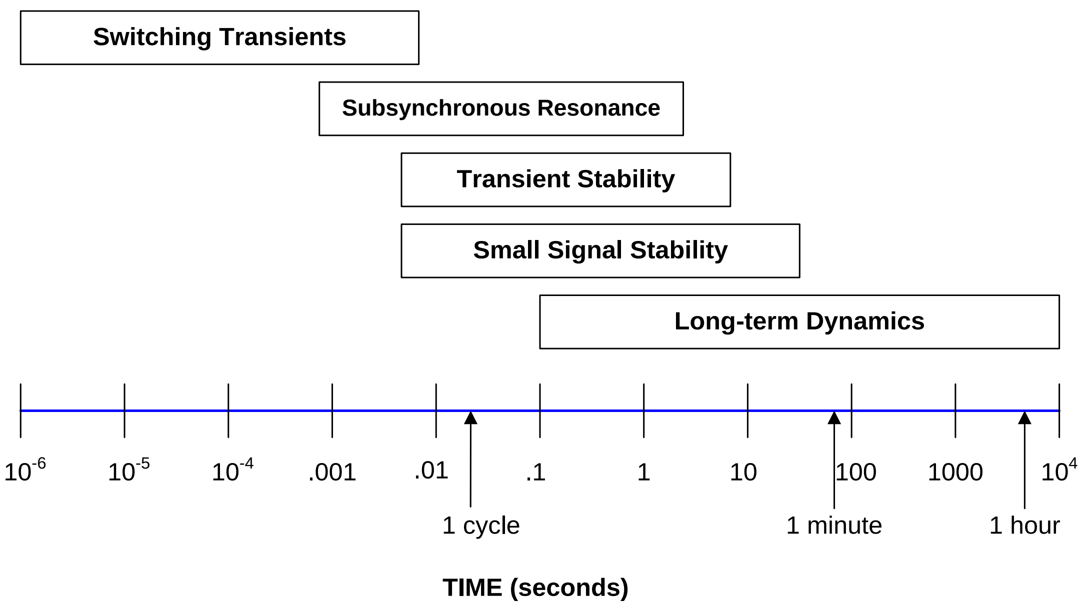

Figure 3.1: Times of various phenomena of interest in power system studies (GE).

3.1. Wind Generation

3.1.1 WECC/IEEE Effort for Generic Models

The size of individual WTGs has increased dramatically from several hundred kilowatts to multi-megawatt turbines. The size of individual wind power plants has also increased significantly. In the past, a typical wind power plant consisted of several turbines. Presently, wind power plants of several 100 MW and larger are being proposed. By some projections,[13] as much as 300 GW (20% penetration) of wind generation capacity is forecast in the U.S. by 2030 and NERC projects an increase of 229 GW of new wind generation installed capacity by 2018.[14] The increased penetration of renewable energy generation poses significant questions concerning the ability of the power system to maintain reliable operation.

Presently, most wind turbine technologies use power electronics and advanced reactive power compensation as an integral part of wind turbine generator and wind power plant. Under dynamic transients, the behavior of modern wind turbines must be accurately simulated to predict the response of the wind power plant. Misrepresentation of WTGs in transmission studies may threaten the reliability of power systems by either resulting in excessive overbuild of transmission systems due to pessimistic models, or in deficient transmission system investment based on optimistic models.

Turbine manufacturers have developed dynamic models for their wind turbines. These dynamic models are typically user-written models in commercially available power system simulation software platforms (e.g., Siemens PTI PSS™E, GE PSLF™, DigSILENT PowerFactory, etc.). Detailed three-phase equipment level models of WTGs used for internal design purposes are also often developed by manufacturers in either their own simulation platforms or commercial software tools including PSCAD® or Matlab® Simulink.

Unfortunately, both these categories of models (the user-written positive-sequence models and the three-phase detailed equipment models) require significant input data/parameters considered to be proprietary by the turbine manufacturers and therefore are not freely available to the general public. Access to these models usually requires a non-disclosure agreement (NDA) between the dynamic model user and the turbine manufacturers. This agreement is only valid for a specific turbine model, for a given period of time.

In many cases, it takes months to negotiate and to finalize the NDA. Furthermore, in some cases there are incompatibilities among turbine models developed by different turbine manufacturers which results in numerical interactions if multiple user-written models are incorporated into a single power system model for system analysis. This makes the work of power system planners almost impossible. The NDA are also usually bilateral, which renders it impossible to share the information among the manufacturers to help resolve incompatibility problems. Finally, the NDAs make it difficult, at best, and impossible, in some cases, to share the models thereby potentially violating the NERC requirements for submitting models for system planning studies.

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[13] http://www.nrel.gov/docs/fy07osti/40482.pdf
[14] http://www.nerc.com/files/2009_LTRA.pdf

With this back drop, the WECC Wind Generator Modeling Group (WGMG) initiated the development of generic wind turbine models of the four (4) different types of wind turbines (see Appendix I for these four WTG designs). These four types of turbines currently hold the largest market share throughout the world. WECC is interested in providing accurate and validated models of standard wind turbines that will be available in their database, including the datasets to be used for testing the models, and the methods for representing a wind power plant in power system studies. These goals are being accomplished through the development and validation of standard models. The standard models must be generic in nature – that is, they must not require nor reveal proprietary data from the turbine manufacturers. These improved standard (generic, non-proprietary) dynamic models enable planners, operators and engineers to perform the necessary transmission planning studies required to ensure system reliability.

Currently, the first generation of these generic WTG models, for all four turbines types, have been developed and are available as part of the main model library for the two most widely used commercial power system simulation tools in North America (i.e., Siemens PTI PSS™E, GE PSLF™)[15]. As a continuation of, and in parallel with, the WECC effort, the Institute of Electronic and Electrical Engineers (IEEE), Power & Energy Society (PES) has also established a Working Group to investigate WTG modeling issues: The IEEE Working Group on Dynamic Performance of Wind Power Generation, under the Power System Dynamic Performance Committee. This Working Group is actively expanding the efforts of generic dynamic modeling for wind power plants, focusing on modeling specifications, disseminating methods and model validation.

To date, the first generation of generic models developed and released have focused on capturing the response of the units to electrical voltage disturbances on the transmission grid (grid faults). One deficiency, particularly for the Type 1 and 2 models, is the proper representation of unit responses to large system frequency excursions. These models have not been verified due to the lack of data on actual turbine behavior under such circumstances and will require further development, in consultation with turbine manufacturers.

Finally, as with all modeling exercises, model development and validation are iterative processes, requiring:

- Generic wind turbine models are to be made available to the public.

[15] PSS®E-32.0 Program Application Guide: Volume II, Chapter 21.
PSS®E-32.0 Model Library, Chapters 17 through 21
GE PSLF User's Manual. v.17.0_04. October, 2009.

- Generic wind turbine models must be validated before release and public dissemination, which is being pursued in WECC, IEEE, International Electrotechnical Commission (IEC) and other forums.
- Models should evolve and be revalidated as the technology progresses.
- Data from field measurement and monitoring for model validation can be a vital resource.

A somewhat unique need in modeling variable generation (e.g., wind) is the need for methods required to develop equivalent models for large wind power plant. In contrast to conventional fossil fuel and hydro power plants, where plants are constituted by either a single large unit or, at most, a few large units, a wind power plant can be made up of tens to more than a hundred WTGs. For large scale power system simulations, particularly in North America where the power system models are quite large, it is often preferred to reduce the wind power plant to a single equivalent unit. Accordingly, techniques are needed for model aggregation and testing their validity – some significant progress has been made in this regard. For example, Figure 3.2 shows the technique developed for reducing the impedance of the wind power plant collector system into a single, equivalent feeder impedance for representation of the wind power plant (WPP) by an aggregated single equivalent unit in power system studies.

From	To	R	X	B	n	$R n^2$	$X n^2$
1	2	0.0035	0.0263	0.0000	1	0.0035	0.0263
2	3	0.0018	0.0254	0.0013	2	0.0071	0.1015
3	4	0.0080	0.0226	0.0008	3	0.0722	0.2030
4	5	0.0023	0.0193	0.0005	4	0.0364	0.3080
5	51	0.0074	0.0248	0.0000	5	0.1861	0.6200
6	7	0.0031	0.0171	0.0014	1	0.0031	0.0171
7	8	0.0061	0.0143	0.0015	2	0.0244	0.0572
8	9	0.0069	0.0107	0.0004	3	0.0617	0.0965
9	51	0.0070	0.0033	0.0004	4	0.1113	0.0525
10	11	0.0078	0.0371	0.0003	1	0.0078	0.0371
11	12	0.0001	0.0005	0.0004	2	0.0005	0.0021
12	52	0.0083	0.0259	0.0004	3	0.0747	0.2330
13	14	0.0049	0.0349	0.0004	1	0.0049	0.0349
14	15	0.0041	0.0483	0.0008	2	0.0163	0.1931
15	16	0.0059	0.0116	0.0002	3	0.0528	0.1040
16	17	0.0079	0.0002	0.0003	4	0.1262	0.0029
17	18	0.0089	0.0146	0.0007	5	0.2224	0.3656
18	53	0.0018	0.0342	0.0008	6	0.0664	1.2302
51	52	0.0074	0.0034	0.0011	9	0.5957	0.2778
52	POI	0.0049	0.0456	0.0002	12	0.7102	6.5633
53	POI	0.0003	0.0338	0.0012	6	0.0125	1.2177
				0.0132		2.3962	11.7438
						0.0074	0.0362

Sum = B_{EQ} R_{EQ} X_{EQ}

← Partial sum

← Partial sum divided by total number of WTG (18 in this case) squared

NOTES:

Branch R, X and B parameters are random numbers in this example.

Parameters should be in per-unit at 100 MVA and collector system kV.

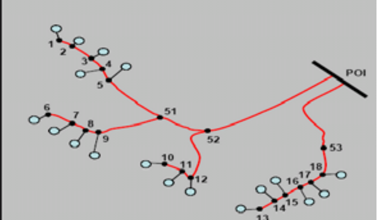

Figure 3.2: Example shows the method for reducing the impedance of a wind power plant collector system into a single equivalent impendence.[16]

[16] "WECC Wind Generator Power Flow Modeling Guide" (http://www.wecc.biz/library/WECC%20Documents/Documents%20for%20Generators/Generator%20Testing%20Program/Wind%20Generator%20Power%20Flow%20Modeling%20Guide.pdf)

Figure 3.3 shows an example for dynamic simulations of aggregating the WPP into a single equivalent unit and an equivalent single impedance representing the entire collector system as compared to a detailed model representing the whole WPP unit-by-unit – the example shown assumes that all WTGs in the WPP are identical, in cases where this is not true multiple equivalent units may be needed one for each WTG type. As can be seen in this figure, the results from the two simulations compare very well at the point of interconnection (which is what is shown); thus, the equivalent aggregate is adequate for power system studies.[17]

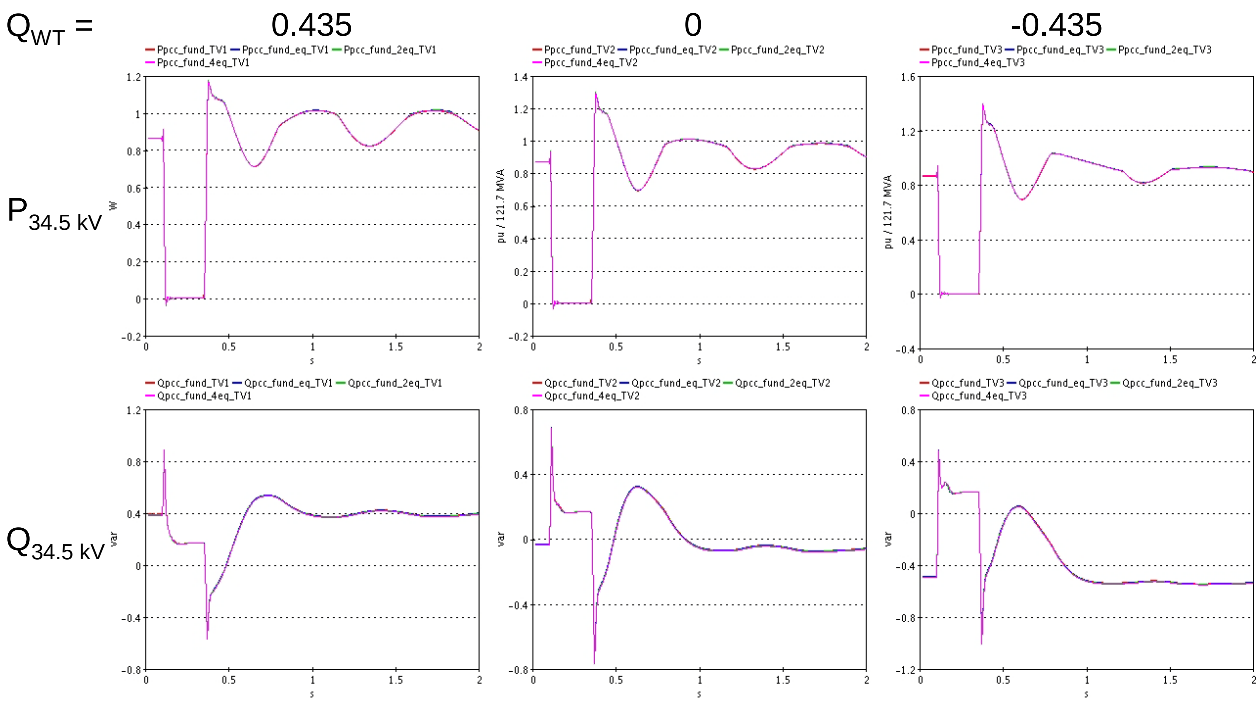

Figure 3.3: Example of time-domain simulations comparing a detailed model of a Wind Power Plant (i.e., representing the complete collector system and each WTG individually), versus a single-machine equivalent aggregate (i.e. the entire plant is represented by one equivalent unit and an equivalent impedance to represent the whole collector system).

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[17] Figure is from J. Brochu, R. Gagnon and C. Larose, "Validation of the WECC Single-Machine Equivalent Power Plant", Presented at the IEEE PES DPWPG-WG Meeting at IEEE PSCE, March 2009.

3.1.2 UWIG Generic Model Documentation and Validation Effort

The Utility Wind Integration Group (UWIG),[18] under a U.S. Department of Energy grant, will be launching an effort to provide the basic documentation, application, and validation of generic models for wind turbines. The goal of this project is to accelerate the appropriate use of generic wind turbine models for transmission network analysis.

The objectives of the project, which will commence in early 2010 and run for a period of two years, are to:

- Complete characterization and documentation of the four generic models developed through an outgrowth of a WECC activity begun in 2005;
- Defining proposed enhancements to the generic wind turbine model structures that would allow representation of more advanced features including power control, automatic curtailment, inertial and governor response;
- Comparative testing of the generic models against more detailed (and sometimes proprietary) versions developed by turbine vendors;
- Developing recommended parameters for the generic models to best mimic the performance of specific commercial wind turbines;
- Documenting results of the comparative simulations in an application guide for users;
- Acquiring test data from all available sources for the purpose of validating the performance of the appropriately specified generic models in actual case studies;
- Conducting technology transfer activities in regional workshops for dissemination of knowledge and information gained, and to engage electric power and wind industry personnel in the project while underway.

[18] The UWIG was established in 1989 to provide a forum for the critical analysis of wind technology for utility applications and to serve as a source of credible information on the status of wind technology and deployment. The group's mission is to accelerate the development and application of good engineering and operational practices supporting the appropriate integration of wind power into the electric system. It currently has more than 150 members spanning the United States, Canada, and around the world including investor-owned, public power, and rural electric cooperative utilities; transmission system operators; and associate member corporate, government, and academic organizations http://www.uwig.org/aboutuwig.htm

Maintaining communication and coordination with other ongoing activities and agencies engaged in this topic is another objective of the effort which will be critical for success.

3.1.3 IEC Effort for Generic Models

The International Electrotechnical Commission (IEC) recently started a Working Group in October 2009 to address the development of generic and "standard" models for wind turbine generators.[19] The goal of this Working Group is to define standard dynamic simulation models for wind turbines and wind plants, which are intended for use in power system and grid stability analyses, and should be applicable for dynamic simulations of power system events including short circuits (low voltage ride through), loss of generation or loads, and system separation. The group is approaching this work in two parts. Part 1 will focus on specifying dynamic simulation models for the generic wind turbine topologies/concepts/configurations presently in the market, as well as specifying how these models may be modified as future technologies/concepts are introduced. The standard should also include procedures for validation of the models specified. Another goal is that the models should be developed and specified at a fundamental level so they are independent of any specific software platform and can be adopted by any software vendor.

Part 2 of this work will be focused on extending the modeling to allow for modeling of the entire wind power plant, including wind power plant control and auxiliary equipment.

Several members of this IEC Working Group are also members of the WECC and IEEE Working Groups (and this NERC Task Force). The three groups are clearly working in close collaboration to ensure maximum benefit to the industry globally and maximum sharing of knowledge already gained through the WECC and IEEE efforts.

[19] http://www.iec.ch/dyn/www/f?p=102:14:0::::FSP_ORG_ID:5613

3.2. Photovoltaic Solar Generation

Photovoltatic (PV) systems for power generation are quickly increasing becoming a significant portion of generation in some regions in North America. PV or solar arrays are composed of a large number of solar cells connected in series and parallel. These cells produce a DC voltage when they are exposed to sunlight due to the photo-voltaic effect[20]. Figure 3.4 shows the I-V characteristics of a cell at a constant temperature and various sun intensity or *insolation* levels.

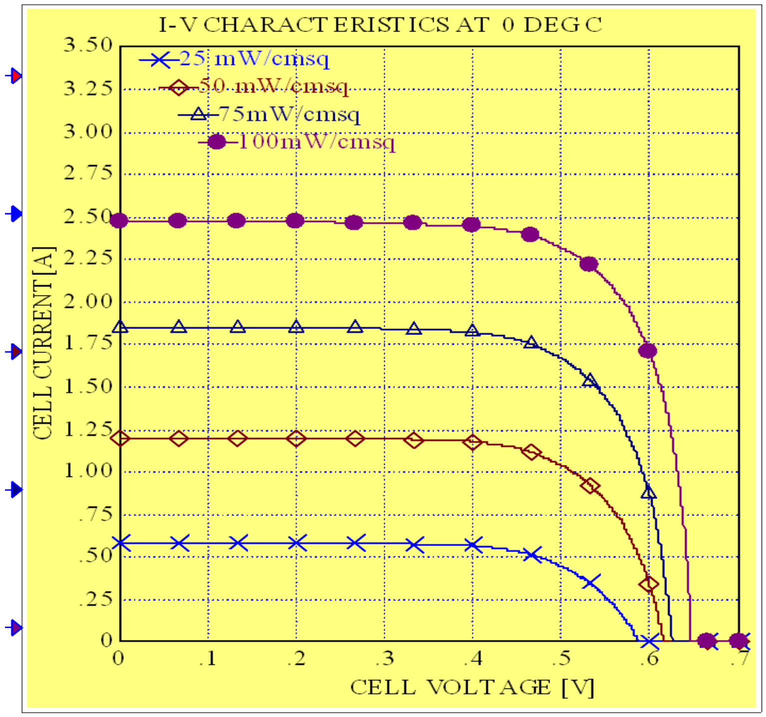

Figure 3.4: Current-Voltage characteristics of a solar cell for various insolation levels at a constant temperature (source [11][21]).

[20] The photo-voltaic effect is the process by which an electric potential difference (voltage) is created in a material exposed to light (electromagnetic radiation), which then leads to the flow of electric current. This process is directly related to the photo-electric effect, but distinct from it in that in the case of the photo-electric effect electrons are ejected from the material surface upon being exposed to high enough frequency (energy) light, whereas in the photo-voltaic effect the generated electrons are transferred across a material junction (e.g., PN junction in a photo-diode) resulting in the buildup of a voltage between two electrodes and the flow of direct current electricity.

[21] Solar Radiation Research Laboratory at the National Renewable Energy Laboratory (http://www.nrel.gov/midc/srrl_rsp/)

Figure 3.5 shows that the current is limited when the cell is short-circuited (Voltage=0).

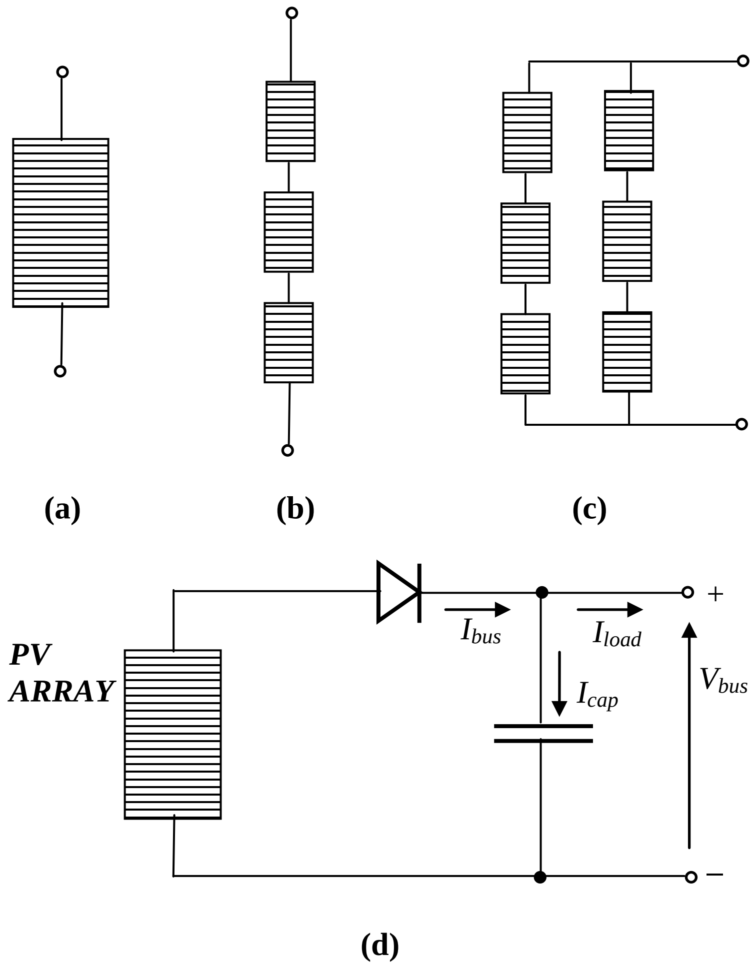

Figure 3.5: The concept of a solar array: (a) a single solar cell, (b) a series connection of solar cells (N_{ser} = 3 and N_{par} = 1), and (c) a solar array (N_{ser} = 3 and N_{par} = 2). The solar cell array(s) is then connected to a DC bus (d).

Figure 3.5 shows the concept of the solar cell up to the solar array. To use the DC power generated by the PV array in an AC power system, the DC power must be converted to 60 Hz AC in North America (50 Hz in some other regions in the world, like Europe). There are several power electronic based converter concepts that can achieve this, which can be classified into two general categories: line-commutated converters (LCC) and self-commutated or more commonly referred to as voltage-source converters (VSC). These technologies have been applied for decades and are well understood. LCC use thyristors as their controlled switching device. The switching on of a thyristors can be controlled, while the turn-off time cannot be controlled and happens at the next AC waveform current zero crossing. LCC systems must be operated in a network with an AC source and cannot operate to serve an isolated load. In contrast, VSC systems are self-commutating, that is the power electronic switching devices used (e.g., integrated gate-commutated thyristors or IGCTs and insulated-gate bipolar transistors or IGBTs) are able to be completely controlled for both turn-on and turn-off and allow the VSC to completely control the AC waveform produced and adjust the power factor as seen on the AC side to within the current rating of the device. Due to advances in the technology, most power electronic converters employed in PV systems are of the VSC type.[22]

From a modeling standpoint for power system studies, there are some user-written manufacturer-specific models in existence as developed by various PV manufacturers. Presently, no generic or standard models exist.

The WECC Working Group, which has been addressing the development of generic WTG models, will be extending its effort in 2010 to review developing generic PV models for dynamic simulations in stability studies. As a starting point, the grid side structure of the Type 4 WTG model may be used since it represents a VSC. This is because PV is typically connected to the grid with a VSC and it will behave electrically similar to a Type 4 WTG that has a similar electrical interface with the grid—this is from a grid perspective looking at the electric response and neglects any of the effects of the energy source.

From a steady-state, power flow and short-circuit analysis perspective, the behavior of the PV technologies will behave in a similar fashion to a Type 4 WTG because of the VSC interface, and because its power factor can be controlled based on the control functionality of the VSC design. Its short-circuit response will be limited to the current limit effected by the VSC under grid fault conditions.

The development of generic and standard PV models is presently a topic for further research. This should be pursued imminently and much of what has been learnt from the WTG model development process should be leveraged.

[22] IEA-PVPS: Grid-Connected Photovoltaic Power Systems: Survey of Inverter and related Protection Equipment; Report IEA PVPS T5-05: 2002, December 2002 (http://www.iea-pvps.org/products/download/rep5_05.pdf).

3.3. Solar Thermal

Solar thermal energy is based on harnessing the radiated heat of the sun for the purpose of producing electricity. In broad terms, there are presently two main ways of achieving this:

1. Concentrating Solar Power (CSP) plants – in this case solar radiation is typically collected through a large number of mirrors (thus a large amount of solar radiation) which is then focused on a small area – the mirrors have tracking systems to follow the Sun. The concentrated solar radiation heats a high temperature working fluid, which then feeds a conventional steam-turbine generator. From an electrical grid perspective, the models needed to simulate the steady-state, short-circuit and transient time-domain dynamics of such a generating unit, are typically no different than standard synchronous generating units for fossil fuel plants.

2. The Stirling Engine concept[23] – in this design a parabolic mirror assembly concentrates the collected solar radiation on a sterling engine that sits at the focal point of the mirror assembly. A Stirling engine is a reciprocating heat engine that operates based on the concept of cyclical compression and expansion of a working fluid. As the working fluid expands/contracts it drives a piston that then turns a generator. The engine is connected to an electrical generator that produces electric energy. Once again for power system studies the units may be modeled using standard generator models. However, in this case a power plant would be constituted by a large number of small units (the typical Stirling engine is about 25 kW) in a large electrical collector system that collects the power and injects it into the utility grid – much like the collector system of a wind power plant. Thus, modeling the collector system (e.g. see Figure 3.2 for an aggregate model of a wind collector system) and any other devices in the collector system, such as shunt reactive devices etc. must be properly modeled

3.4. Tidal Generation

Tidal power generation derives energy directly from the motion of oceanic tides. The gravitational pull of the Moon and Sun, combined with the Earth's rotation result in the generation of tides. Tides generally occur with a period of roughly twelve hours, and so most coastal areas experience two high and two low tides within every twenty-four hour period. Tidal generation uses this phenomenon to generate energy. Clearly, the stronger the tides are, either in tidal current velocity or the height/level of water, the greater the potential amount of energy generation.

[23] http://www.stirlingenergy.com/ Y. Zhang and B. Osborn, "Solar Dish-Stirling Power Plants and Related Grid Interconnection Issues", *IEEE PES General Meeting*, 24-28 June 2007.

Presently, in North America tidal power is not a significant source of power in any region. Some pilot programs exist for introducing the technology. In April 2009, one was announced in Snohomish County Public Utility District in Washington State.[24]

There are several options for harnessing tidal power. One method is the use of turbines similar to wind turbines; however the fluid (water) is much denser and requires a turbine with smaller and bulkier blades, as shown in Figure 3.6. Most of these technologies typically use AC/DC/AC converter technology, similar to a Type 4 wind turbine, to convert the low frequency generated electricity to grid frequency AC electricity and interface with the power system. Once this technology becomes more prevalent a starting point for development of a suitable model structure may be the Type 4 generic wind turbine models. Understandably, the energy source characteristics are quite different from wind power and significantly more predictable.

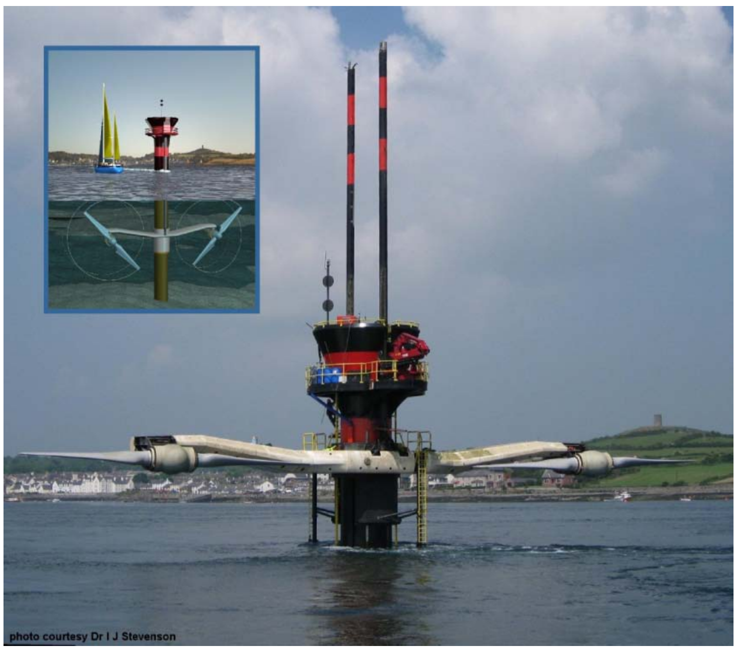

Figure 3.6: One of the many concepts for tidal generation systems (courtesy of Marine Current Turbines Limited, www.marineturbines.com).

3.5. Other Resources

There are several other emerging technologies and there are many complementary technologies (i.e., auxiliary to the variable generation resources, but designed to help with their integration into the grid) including smoothly-controlled dynamic reactive devices (static VAr systems),

[24] http://www.snopud.com/PowerSupply/tidal/tidalpress.ashx?p=1516&756_na=46

energy storage technologies etc. With respect to static VAr systems (SVCs and STATCOMs), there is an active WECC working group imminently addressing the issue of generic models for these devices.[25] The group has made substantial progress with the models defined and developed, but currently undergoing testing and validation. With regards to the other emerging technologies, most tend to be power converter based (i.e., connected to the grid through a back-to-back frequency converter) and so their electrical behavior (neglecting the characteristics of the energy source) will be similar to Type 4 wind turbines. Until these technologies mature, the basic structure of other more mature converter based generation technologies can be a good starting point.

3.6. Summary

This section has briefly presented the various types of variable generation and the present status of models and model development for power system studies. Wind generation technologies, being the most prevalent world-wide, have the most mature models. Through efforts started by WECC and being continued by IEEE and IEC, generic standard models for the four main types of WTG technologies are being developed. The first generation of these models has been released in two power system simulation software platforms most commonly used in North America. Other emerging technologies (e.g., PV, tidal power, etc.) can build on this effort to start developing generic models. For example, the WECC effort will be extending its scope in 2010 to look at PV model.

From a NERC perspective the key items are:

1. To emphasize and support efforts by WECC, IEEE and IEC to develop and standardize generic models for these technologies for power system planning studies.

2. To encourage manufacturers to familiarize themselves with the generic models being developed and be willing an able to supply parameters for these generic models to reasonably represent their equipment for power system stability studies. As highlighted in Chapter 2, more detailed manufacturer specific models may be needed in special cases and for specialized studies.

3. To encourage efforts aimed at model validation.

4. To consider any augmentation or additions to reliability standards related to Modeling, Data and Analysis (MOD) with respect to modeling and model validation of variable generation. This is discussed in greater detail in section 5 of this report.

[25] http://www.wecc.biz/committees/StandingCommittees/PCC/TSS/MVWG/SVCTF/default.aspx

4. Present Status of Model Validation

This chapter gives an overview of the model validation work that has been done hitherto as it relates to models for variable generation. Necessarily, the primary focus of this section is on wind turbine generator models, since models for this resource are presently the most mature.

4.1. What is Model Validation?

Any and all models of a dynamic system always have limitations associated with them. A model is a representation of reality; it is an emulation – that is why it is called a model. In developing a model first the question is asked as to the specified use of the model and the conditions it must reasonably emulate – this forms the basis of a model specification from which a model is developed. The developed model establishes a certain structure with parameters, which are adjustable in order to emulate different types of equipment or design of the modeled device. Thus, valid parameterization of the model to represent a particular manufacturer's equipment is essential to support the particular scenarios to be analyzed.

Model validation is often achieved through some form of testing, either in a laboratory/factory or in field. There is a range of reasons for conducting tests for wind generation. Each test has a unique set of objectives guiding the design of adequate testing practices.

- <u>Performance Compliance:</u> Compliance to contractual requirements and grid codes are one reason to perform tests. Interconnection requirements (usually included in plant Power Purchase Agreements and Interconnection Contracts) and grid codes typically outline specific technical criteria that must be met to allow a power plant to connect and operate on the grid. Since these criteria point out specific levels to be met, (for example, voltage, power factor, and response time) tests may be designed with binary "pass/fail" objectives.

- <u>Model Validation:</u> In much of the world, power plants above a pre-defined size must be accurately represented with a dynamic simulation model used in stability analysis for operations and planning purposes. As variable generation sources such as WPP are growing in size, it is becoming increasingly important to have accurate variable generation specific models. Tests may be performed to tune and verify simulation models to closely match the performance of actual equipment. In the western U.S. and Canada, WECC has mandated that any plant with 20 MVA aggregate generation must be tested for model validation, including large wind power plants. For North America, the imminent NERC MOD-026 standard presently under development will enforce model validation requirements throughout the North American region.

To achieve the goals of model validation, there are three categories of tests that may be performed:

- Type Tests: These are tests performed by the manufacturer or independent third-parties of representative equipment. The intent is to demonstrate that a particular design of equipment exhibits specific performance, and all other equipment of that same design is assumed to have the same performance. Type tests can be:
  - *Component:* Performed on specific functions or features in a power plant or generation equipment. This could be, for example, testing the fault ride-through capability or reactive capability of a WTG, where testing is performed at the component level.
  - *Factory:* A systemic test of a major assembly (i.e., a drive train) or entire turbine-generator is performed under a controlled environment like a manufacturing facility to verify performance and validate assembly design.
  - *Unit:* A systemic test of multiple components operating together (i.e., as entire operating WTG or WPP) with the specific intent of benchmarking a model or design as a type test. For example, tests performed in Europe under the WindTest program.
- Field Tests[26]: Tests performed by the power plant asset owner, developer, host utility, manufacturer and/or independent third-parties of specific operating equipment. These tests are to demonstrate that a particular implementation, design and installation of equipment exhibit specific performance.
  - *Commissioning:* Tests performed on new equipment entering its period of commercial operation service.
  - *Periodic Maintenance or Calibration:* Tests performed periodically after the plant is in commercial operation to verify that equipment continues to perform as well as it did during commissioning.

[26] See for example: WSCC Control Work Group and Modeling & Validation Work Group, "Test Guidelines for Synchronous Unit Dynamic Testing and Model Validation", February 1997. (www.wecc.biz), and IEEE Task Force on Generator Model Validation Testing, "Guidelines for Generator Stability Model Validation Testing", Proceedings of the IEEE PES General Meeting, Tampa, FL, June 2007 (http://ieeexplore.ieee.org)

- *Periodic Model Validation:* Tests performed periodically after the plant is in commercial operation to verify that simulation models adequately represent actual plant performance (for example, the periodic model validation testing required by WECC).

- *Periodic Codes & Standards Validation:* Tests performed periodically after the plant is in commercial operation to benchmark and validate plant performance per contractual requirements. These tests are typically performed to obtain a permanent operating license for the power plant.

- On-Line Monitoring[27]: Other information of interest is from continuous data gathering based on ongoing performance of an operating power plant. Data collected from external and unscheduled events, including grid disturbances or in the case of WTG large changes in wind is particularly useful. Monitoring also benchmarks performance under normal operation.

With these general concepts in mind, the following subsections present some example cases studies of model validation and validation approaches for variable generation sources. The examples emphasize WPP and WTG, since wind generation is the present dominant variable generator sources in the North America continent.

4.2. Examples of Model Validation Efforts

4.2.1 Hydro- Québec Example

The province of Québec has vast wind energy potential. Though wind energy generation in 2009 accounts for nearly 1.3% of the total installed capacity in the Québec control area, the penetration rate of wind energy generation will reach 10% by 2015. A total capacity of 528 MW is currently in operation and approximately 3,000 MW are under development. Five wind turbine manufacturers will supply the WTGs for the different projects under study.

The configuration of the Hydro-Québec transmission system is essentially radial. Approximately 85% of the total installed generation feeding the system is located at distances up to 1,300 km

[27] See for example: P. Pourbeik, "Automated Parameter Derivation for Power Plant Models From System Disturbance Data", Proceedings of the IEEE PES General Meeting, Calgary, Canada, July 2009 (http://ieeexplore.ieee.org). This reference shows actual application of on-line disturbance monitoring to power plant model validation for conventional fossil fuel generation. It may be feasible to apply similar algorithms and approaches for continuous re-validation of WTG and other variable generation technologies once generic standard models have been developed. This is a current topic for research.

from the closest major load centers. With this configuration, the system transfer capability is mainly limited by stability constraints (transient stability and voltage stability) rather than congestion or thermal capacity of equipment; hence the need for reliable models for wind power plants and all other generation.

Stability studies are critical to determine the compensation equipment required to maintain the reliability of the power system when integrating new generation. They are also essential for operation planning studies including control system design and tuning and determination of transfer capabilities.

So far, Hydro-Québec has faced two major difficulties regarding user-written models provided by the wind turbine manufacturers. First, models often lack robustness and do not represent accurately some important features (convergence problems in low short-circuit network, do not take into account frequency excursions, do not represent secondary voltage regulation, etc.). Second, model validation by the manufacturers is often incomplete, not available, or difficult to translate to real projects (different settings or software versions, design of the collector system, etc.). In some cases, these difficulties have lead Hydro-Québec to build its own models (see Hypersim section below).

General validation test program

Since 2006, Hydro-Québec has performed validation tests on WPP connected to its transmission system and a general validation test program was established in 2009.[28] The power producer has the obligation to perform validation tests in order to demonstrate that its facilities meet the Transmission Provider requirements. The purposes of this program are:

1. To demonstrate that WPP meet the Transmission Provider technical requirements related to wind generation;
2. To validate numerical models and parameters associated with the WPP, specifically those given to the Transmission Provider by the power producer, by comparing the model response to recordings taken during field tests;
3. To confirm the electrical data of power producer facilities.

The validation program is divided into seven functions to be validated:

1. Primary voltage regulation

[28] http://www.hydroquebec.com/transenergie/fr/commerce/pop_raccordement_transport.html

2. Undervoltage response (LVRT)
3. Inertial response
4. Secondary voltage regulation
5. Power factor
6. Maximum ramp rates
7. Power quality

The tests for the primary voltage regulation are performed on a single WTG and consist in producing instantaneous voltage variations of low amplitude on the terminal of the WTG and small voltage steps of limited duration injected directly into the WTG voltage control system. Three-phase voltages and currents are recorded at the wind generator to measure the local dynamic response of a wind generator to a rapid voltage change and to verify that the response meets voltage regulation requirements. The results are also used to set the model parameters (time constant and gain) used in dynamic simulations. The tests regarding the secondary voltage regulation are similar but are conducted for the entire power plant.

The validation test program includes LVRT tests on one generating unit to verify that requirements during undervoltage conditions are met. The power producer has the responsibility to conduct the tests or to provide a complete report describing tests performed on an identical generating unit (same software version) to demonstrate that the requirements are met. So far, no LVRT tests were performed on site on WPP integrated on the Hydro-Québec network. However, monitoring equipment has been installed at three locations in wind plants: at their point of interconnection, on a 34.5 kV feeder of the collector system and on one generating unit. The monitoring system records signals either continuously or upon detecting variations occurring at the point of interconnection: active power variations, voltage sags and swells and system frequency excursions. These signals are primarily voltages and currents but may also be mechanical variables or other signals.

The field recordings recorded on the network can thereafter be used to validate the dynamic response of the models. This is a time consuming effort that requires the collaboration of the manufacturers to modify the models if necessary. Event recordings to-date have made possible suitable validation of two Hydro-Québec Siemens PTI PSS®E models and one ElectroMagnetic Transients Program (EMTP) model.

Inertial response requirements were not in defined for the projects started before 2005. Consequently, existing wind plants do not have to fulfill them. However, the requirements have to be met for WPP to be commissioned in 2011 and after. The corresponding validation tests consist in emulated frequency steps and ramps of limited duration. Besides verifying the requirements, the test results will be used to validate the parameters of the models and their dynamic response.

The power factor and the maximum ramp rates modules are tested with all WTGs in service to verify that the requirements are met. Power factor tests consist in supplying and absorbing a maximum amount of reactive power at different levels of active power. Maximum ramp rate tests consist in performing a power plant shutdown sequence followed by a startup sequence. These tests are not really used to validate the models but are rather helpful to fix model parameters.

The last module regarding the power quality is not covered by scheduled testing but by means of a monitoring system that verifies harmonics and emission limits. The recordings are compared to the report provided by the developers to verify if the requirements are met. However, they are not useful to validate the EMTP model since the WPP is represented by a single-wound generator and does not simulate the detailed collector bus system and individual wind turbine generators.

Field tests department

Hydro-Québec field-testing department (UMES) conducts a wide range of special tests and measurements for Hydro-Québec and has done so for 30 years.

To test WPP, UMES installs a monitoring systems to record three-phase voltages and currents generally at three locations within the plant: at the point of interconnection, at the starting point of a 34.5 kV feeder of the collector system and at the terminals of a WTG connected to the same monitored feeder. For extended model validation, other signals within the wind turbine are monitored including the rotor side converter voltages and currents, the network side converter currents, and the DC bus voltage.

High speed recorders with anti-aliasing filters are used. Normally, the sampling rate is 5 kHz with at least a 200 second window per event. The monitoring system is reachable via an Ethernet connection for remote trigger and data retrieval. UMES has also the responsibility to perform the data processing and analysis of the recordings in order to verify the compliance with the interconnection requirements and to extract relevant data for model validation.

Hypersim

The Hydro-Québec Research Institute (IREQ)[29] also has an important expertise in control system and wind generation modeling for extensive studies of electrical networks. The simulation environment used is Hypersim, a real-time simulator and powerful simulation tool that uses a highly detailed representation of the Hydro-Québec network. A full-transient detailed model of a Type 3 WTG was developed at IREQ using the MATLAB® SimPower Systems Toolbox. The model was also implemented in EMTP and in the Hypersim real-time simulator.[30] This model is in the process of being validated with data processed by the UMES team. The range of events recorded does not make it possible to validate the model completely and the design and parameters will continue to be adjusted to improve the representation of the wind turbines. The validation of the MATLAB® model developed by IREQ was very useful to validate and improve Hydro-Québec's Siemens PTI PSS®E user model.[31]

4.2.2 GE Example – based on GE's work with client facilities

In the case of the first example presented here, a 10 MVar capacitor bank, located at the 25kV WPP collector bus, is switched off-line as an external physical stimulus. Figure 4.1 shows detailed response to capacitor switching from the WindCONTROL®. The WindCONTROL® system allows coordination of all on-line turbine-generators for plant-level fast and smooth voltage regulation at the point of interconnection (POI), located contractually at the 25kV substation bus. The red curve (Q_ACTUAL [KVar]) shows that total plant reactive power initially drops after the switching action, but the fast autonomous controls on each turbine generator quickly and stably respond to increase reactive power generated by individual turbines, shown by the orange curve (Q_TURBINES [KVar]). The WindCONTROL® command (Q_CMD) distributed to the turbines is shown in blue. The response of Q_CMD is dominated by the gains of the voltage regulator portion of the WindCONTROL®, specifically the proportional gain, K_{pv}, and integral gain, K_{iv}. The difference between the response of the individual turbines (Q_TURBINES [KVar]) and the WindCONTROL® command (Q_CMD) is due to the dynamics of the individual wind turbines. The coordinated response of the wind plant and the individual

[29] http://www.hydroquebec.com/technology/index.html

[30] R. Gagnon, G. Sybille, S.Bernard, D. Paré, S. Casoria and C. Larose, "Modeling and Real-Time Simulation of a Doubly-Fed Induction Generator Driven by a Wind Turbine," IPST Conf., Paper No. IPST05-162, Montréal, Canada, 2005.
C. Larose, R. Gagnon, G. Turmel, P. Giroux, J. Brochu, D. McNabb and D. Lefebvre, "Large Wind Farm Modeling Techniques for Power System Simulation Studies," in Proc. 8th International Workshop on Large-Scale Integration of Wind Power into Power Systems, Bremen, Germany, Oct. 14-15, 2009.

[31] C. Langlois, D. Lefebvre, L. Dube and R. Gagnon, "Developing a Type-III Wind Turbine Model for Stability Studies of the Hydro-Québec Network," in Proc. 8th International Workshop on Large-Scale Integration of Wind Power into Power Systems, Bremen, Germany, Oct. 14-15, 2009.

turbines is multi-modal: a fast initial response to address severe perturbations as well as a slower, grid friendly refinement. For purposes of this test, the automatic control of the capacitor bank by WindCONTROL® was disabled and manual switching was used as a stimulus to record individual WTG response.

The detailed plot in Figure 4.2 shows a zoomed view of the response to step change in voltage at the WTG. 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 200 milliseconds. The slow, refined control then takes over to allow for coordination with other equipment and maintain post-disturbance stability. This aggregate response also allows for a very abrupt action when needed, and a grid-friendly refinement that maintains stability in less severe cases.

The green curve in Figure 4.3 shows that when the capacitor is switched off-line, the measured voltage at the point of interconnection (or POI) decreases due to reduced reactive power flowing into the grid. 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 control set point determined by the operator. The lower traces in Figure 4.3 show a gap during the period when the capacitor bank is online between total plant Q (Q_ACTUAL) and summation of Q out of each WTG (Q_TURBINES). This gap represents the capacitive reactance added by the shunt bank. When the capacitor is switched offline, the gap between Q_ACTUAL and Q_TURBINES closes and all reactive power is supplied solely from the WTGs. The initial loss in plant reactive power is mitigated within approximately 15 seconds as each WTG settles to a new, increased level operating point of reactive power. This new, increased reactive level for each WTG, is the total Q increase from all units on-line in the plant, divided by the total number of units online at the time of the test.

Figure 4.4 shows a comparison between these measured values and the simulation results of the PSLF model. Model outputs Q_g, Q_{plant}, Q_{cmd} and V_{reg} correspond to measured Q_TURBINES, Q_ACTUAL, Q_CMD and U_LINELINE respectively. This plot shows the model performance adequately represents what is happening in the field. The response matches closely, with a difference immediately following the switching operation being due to lower sampling rate in the measurement than in the GE PSLF® simulation.

Response to grid events demands relatively rapid control action. Manual grid or plant operator changes in operating set-points do not normally demand fast response, and indeed, system behavior ought not to be rapidly disturbed by moving set-points. Figure 4.5 shows the response of GE plant to 2% step in voltage reference. The blue trace in the figure shows a well mannered response to the reference step. The red trace is from the simulation model, which matches very well. In the blue trace, after, the perturbation occurring about 8 seconds after the reference change the plant supervisory control switched on a shunt capacitor to retain dynamic range on the wind turbines. The switching perturbation is rapidly balanced by the turbines, allowing the response to continue smoothly.

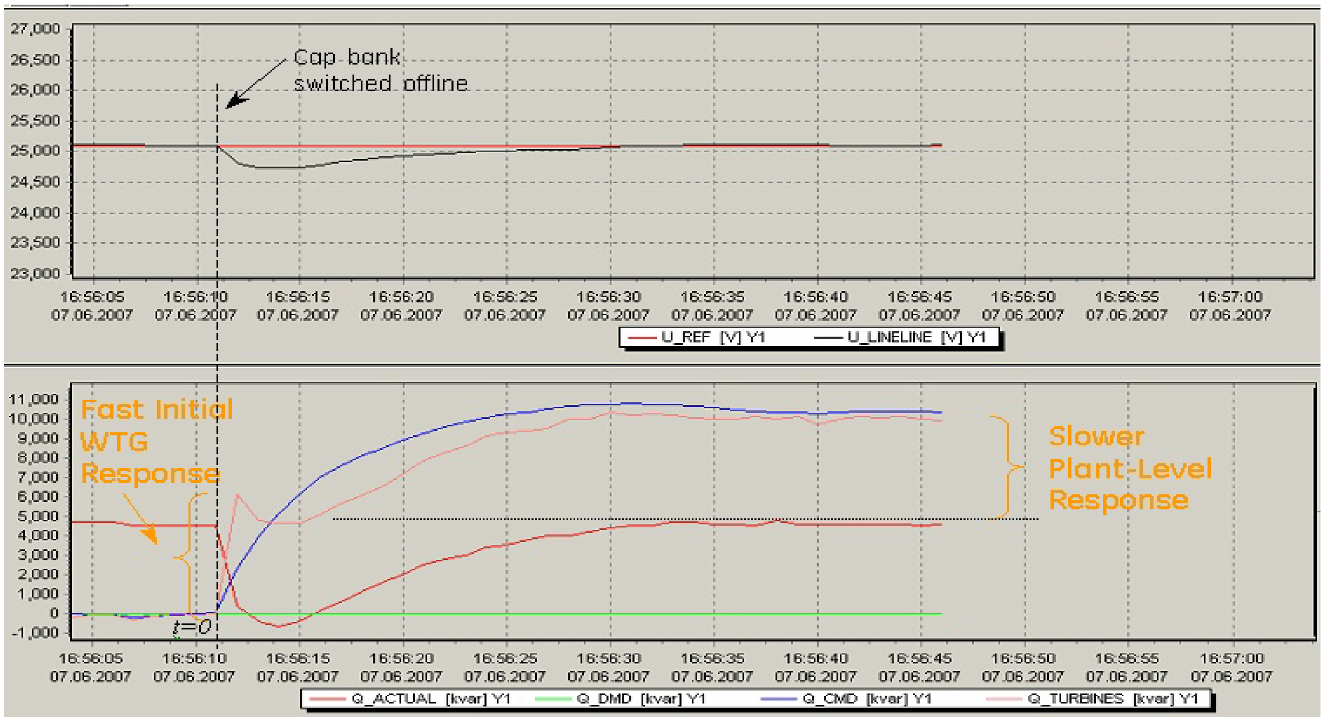

Figure 4.1: 10 MVar Capacitor removal response measured from WindCONTROL®.

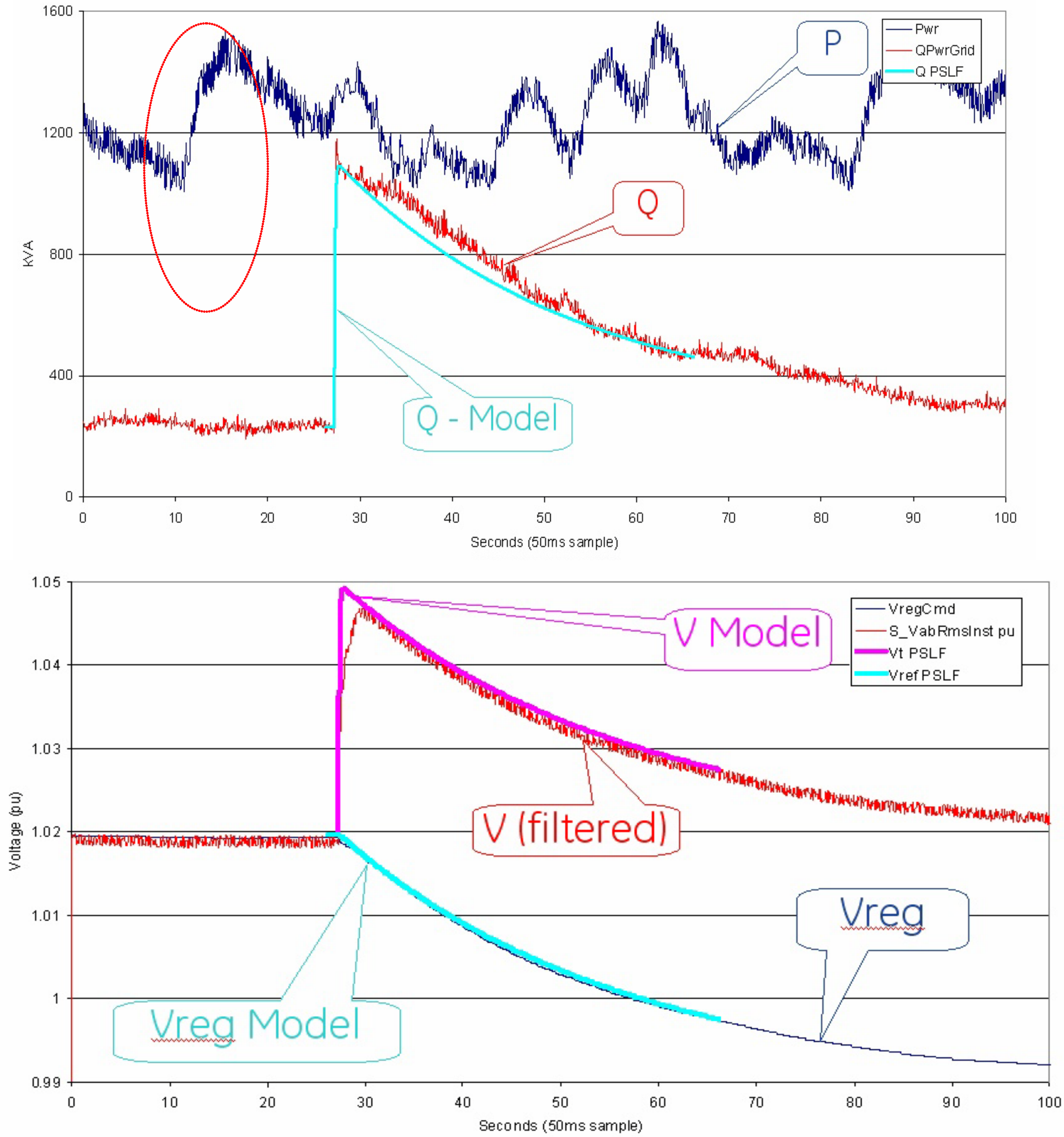

Figure 4.2: Wind turbine-generator level voltage step test response

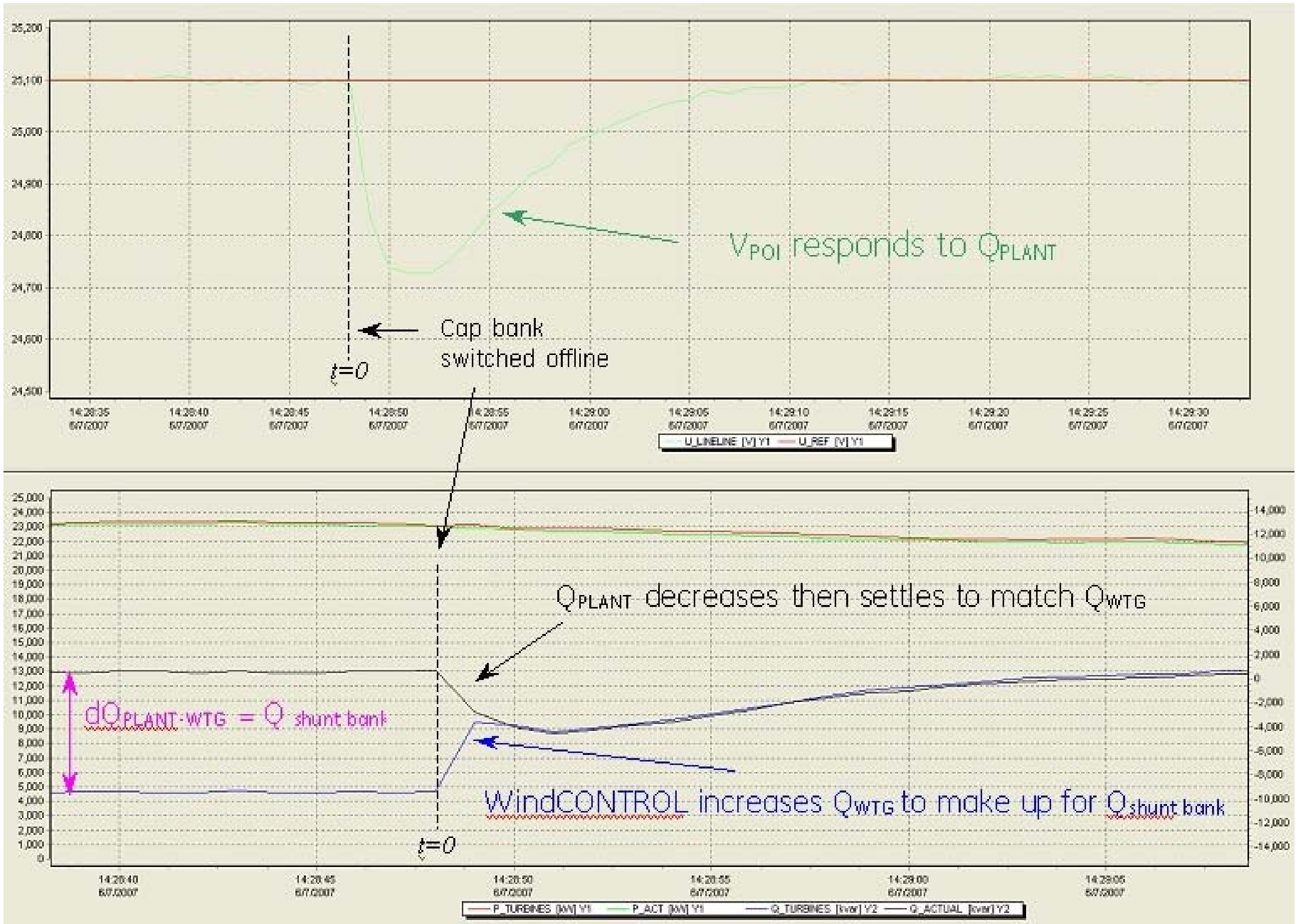

Figure 4.3: 10 MVar Capacitor removal response – POI variables.

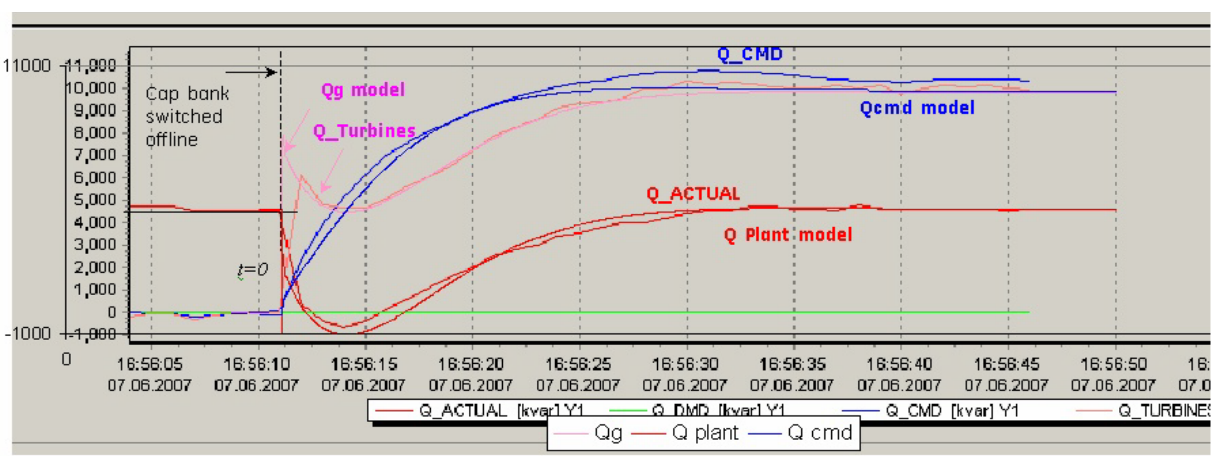

Figure 4.4: 10 MVar **capacitor removal field test vs. simulation results**

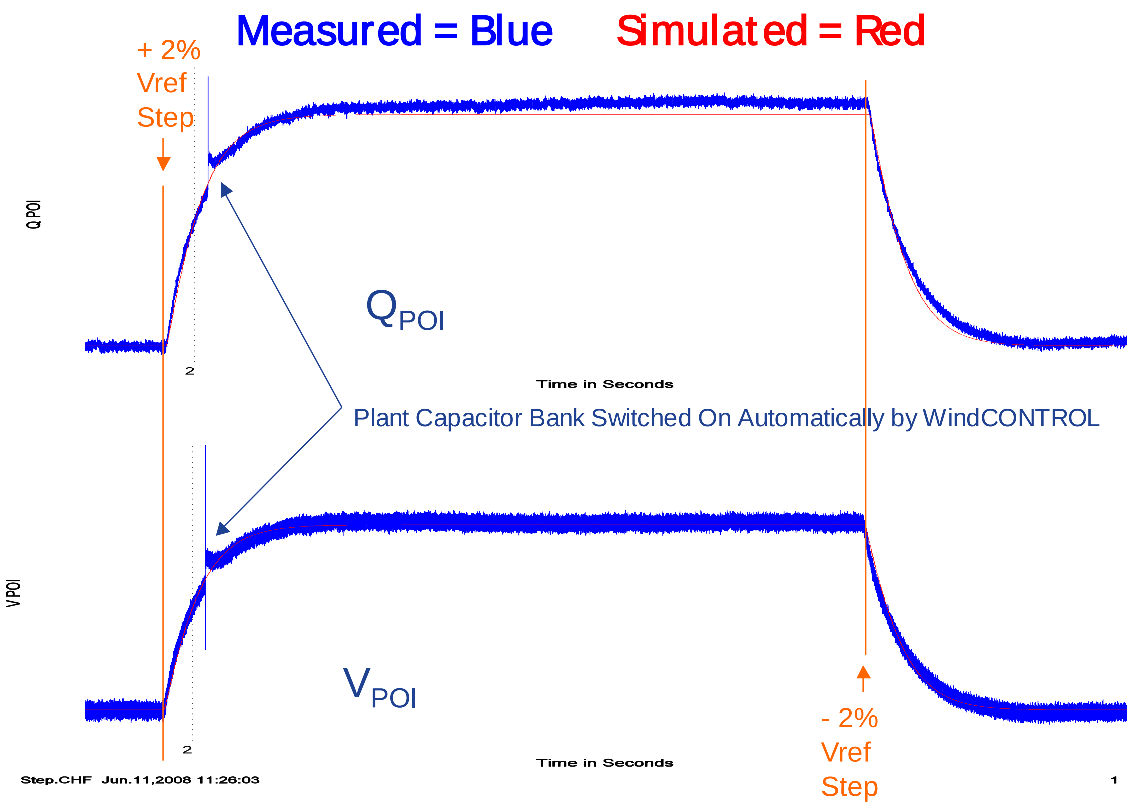

Figure 4.5: A different step test. +/- 2% step of voltage reference

The performance for grid fault events is of considerable interest in system planning. Staging faults, particularly severe ones on operating wind plants, is difficult and expensive. Figure 4.6 shows a comparison between a staged fault test and the (present) Siemens PTI PSS®E model of the GE 2.5 (full converter) WTG. The fault event is quite severe: a 3-phase 700ms of voltage depression to less than 20% of nominal at the high voltage terminal of the WTG unit transformer. The measurement traces (on the left) include some of the signal noise characteristic of measurement and extraction of fundamental frequency positive sequence information from real, high resolution measurements. The simulation traces on the right, are, of course, cleaner. The match between test and simulation is of very high fidelity for phenomena relevant and legitimately examined with positive sequence simulation tools (i.e., greater than one cycle).

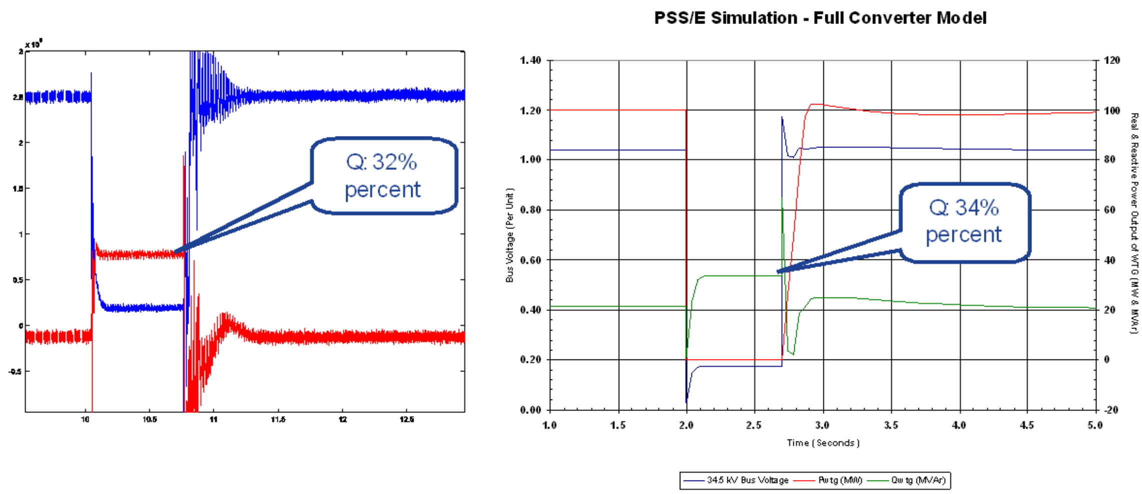

Figure 4.6: GE 2.5 WTG Fault Test vs. PSS/e Model Performance

The discussion provide above is solely geared to hardware testing and validation, however, another highly valuable and legitimate means of providing validation of simulation models (for planning and otherwise) is to use more complex simulation software to validate simpler planning models. Manufacturers normally have highly complex, and highly proprietary, models of their equipment. These models are used, among other things, to design equipment and are normally physically based and must have sufficient fidelity for original equipment manufacturers (OEMs) to make sound engineering judgments for equipment design and application. The OEMs are highly motivated to have these detailed high fidelity equipment level models. These detailed models therefore can often be used to design, test and validate simpler planning models to be used by the industry.

There is a long, accepted history in the power industry of this practice. For example, a typical (GE) gas turbine has on the order of 4,000 state variables in the design model; planning models typically have on the order of four state variables: simplification is necessary and expected. These design codes have been used to develop planning models of gas turbines. Figure 4.7 below shows a comparison between a fault simulation using a GE design code (GE WindTrap®) and the planning model in GE PSLF® for a GE 1.5 (double fed machine) WTG.

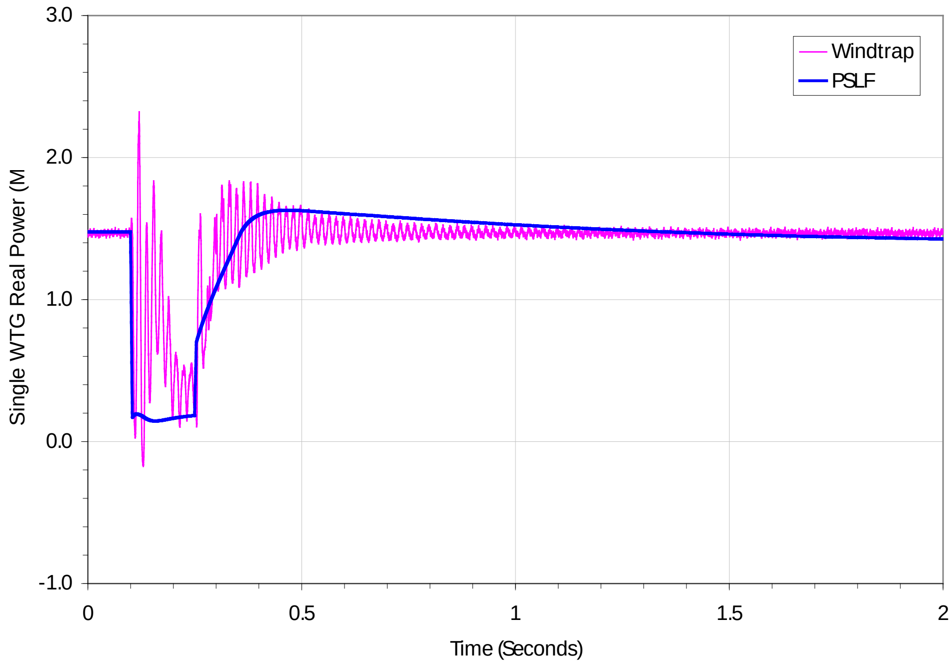

Figure 4.7: Detailed Design Simulation (GE WindTRAP®) vs. GE PSLF® Model Performance (active power during a severe fault for a GE 1.5 WTG)

5. Summary & Recommended Actions – Standards Implications

This document has presented a general overview of modeling and model validation as it pertains to variable generation resources. Clearly, to date, the bulk of the experience and work has been on wind turbine generators. Never-the-less, similar approaches for modeling and model validation are being pursued for other variable generator technologies such as PV.

Non-proprietary and publicly available models for the simulation of steady-state (power flow), short-circuit (fault calculations) and dynamic (time-domain simulations) behavior of such generation resources must be made readily available for use by power system planners. Furthermore, these models should be routinely validated to ensure proper representation of variable generation power plants in bulk power system studies. A model is valid if its dynamic behavior is close enough to reality so that its influence on the network of interest (i.e. used for power system studies) is consistent with the fidelity of model structures and available data for the power system and other generation, as it pertains to the phenomena of interest (i.e. in stability studies). That is, perfect curve fitting is not necessary, but to the extent possible erroneous model dynamics must not result in a notable over-design or under-design of the network.

Each of the NERC standards discussed below in Section 5.2 address to aspects of meeting a standard: (i) the technical requirement, i.e. the need to define, measure validate a model, its parameters etc., and (ii) the procedural requirements, i.e. the functional model of how this technical requirement should be met, reported and monitored. The bulk of this working group's recommendations stated below address the technical requirements. Variable generation is a new and quickly evolving technology and consideration should be given to the timing with which standards be implemented.

Section 5.1 below first gives a summary of the planning process based on NERC standards to put the discussions in this report into context with the NERC standards. Then in Section 5.2 we provided our recommendations and comments on the NERC existing and developing standards.

5.1. Applying the NERC Standards

The NERC standard FAC-001 (see Figure 5.1) should be expanded to clearly cover modeling requirements during the coordinated joint study phase of the Facility connection process. Simple generic models of variable generation may be adequate for the IES phase and more detailed models may be needed for the IFS phase. Validation of the simple and detailed model parameters may be needed during commissioning.

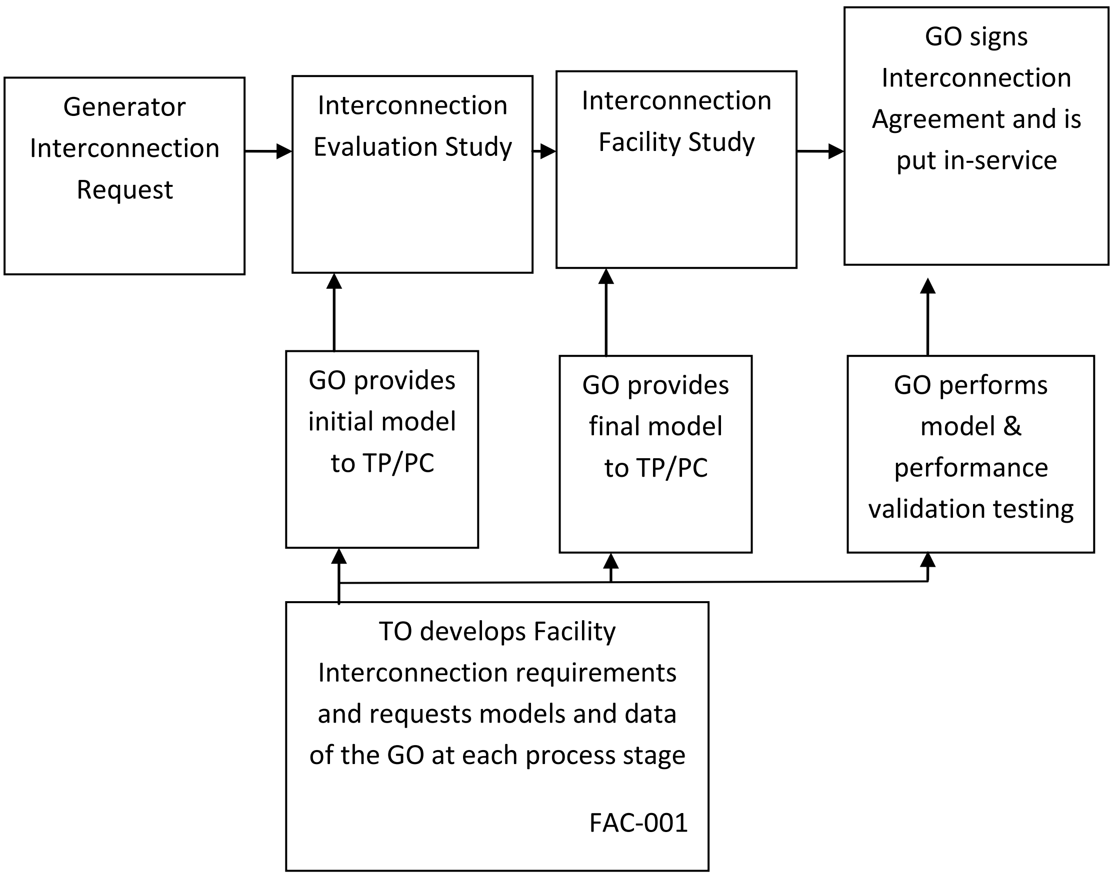

Figure 5.1: Facility connection process.

The generic model with associated parameters feed into the NERC model building process shown in Figure 5.2. As an example, for WTG, presently there is insufficient evidence of the accuracy of presently available generic models for WTG[32] for all the various WTG manufacturers. Some confirmation tests during commissioning or type tests or comparison simulation tests with a detailed model are necessary to get buy in from the Transmission Owner/Planner. As the technology matures, and generic models are enhanced, and associated data parameter sets are developed for specific machine types, the new generic models will become more accepted as is the case with models of hydro or thermal plants.

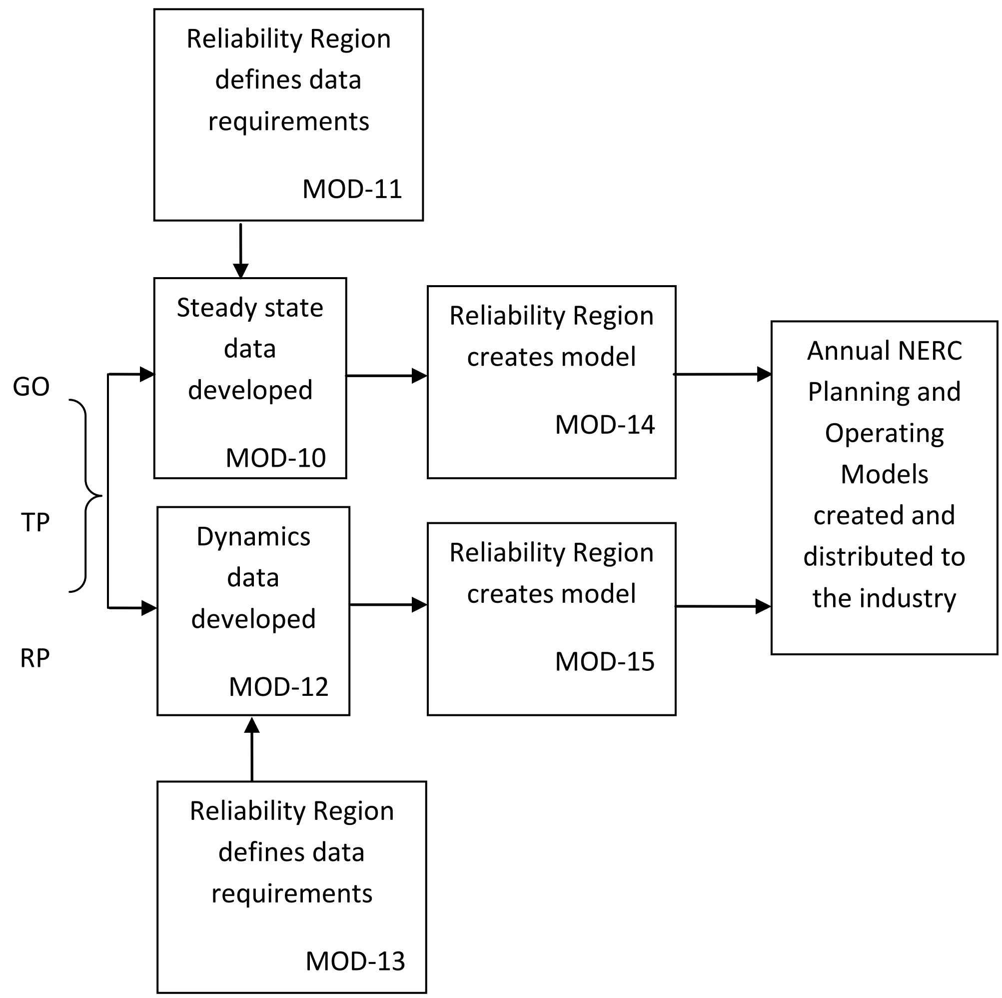

Figure 5.2: Annual NERC Model Development Process

[32] PSS®E-32.0 Program Application Guide: Volume II, Chapter 21.
PSS®E-32.0 Model Library, Chapters 17 through 21
GE PSLF User's Manual. v.17.0_04. October, 2009.

The regional model building manuals developed as part of MOD-11 and MOD-13 must provide sufficient clarity to model variable generation. These manuals may ask for best available models or generic models. These models cover the operational time frame and the 10-year planning horizon. The manuals do not currently cover the frequency for revalidating model data.

While not included in the standards, more emphasis is currently being placed on meeting the Eastern Interconnection Reliability Assessment Group (ERAG) model building manual requirements in addition to regional requirements.

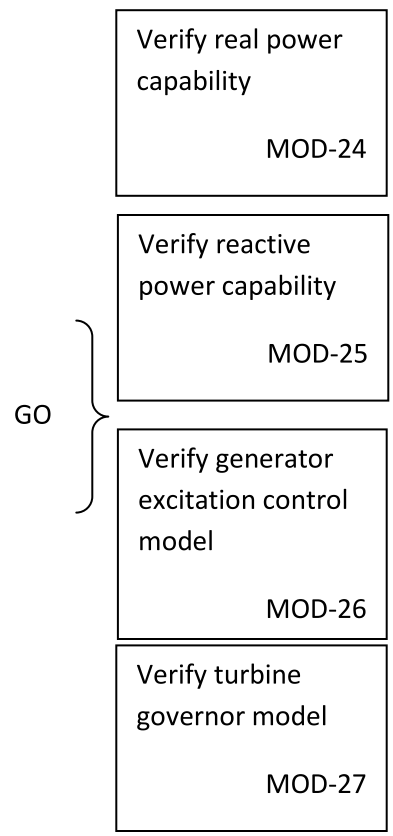

Figure 5.3: NERC Model Validation Process

The Regional Entities develop the test procedures and dictate testing frequency for the Generator Owners to follow. The model data then feeds in to the annual NERC model building process.

5.2. NERC Standards Technical Issues

One general comment is that the NERC Glossary of Terms would benefit from the term "Variable Generation" being include in it and appropriately defined. A suitable definition can be found in the Phase I report of the IVGTF.

MOD-011: Regional Steady-State Data Requirements and Reporting Procedures

The technical requirement in this MOD reads:

> "R.1.2 Generating Units (including synchronous condensers, pumped storage, etc.): location, minimum and maximum Ratings (net Real and Reactive Power), regulated bus and voltage set point, and equipment status."

This statement could be read to equally apply to variable generation as a source of generation. However, it may be prudent to explicitly include variable generation in this statement. For example, to change the sentence to:

> "R.1.2 Generating Units (including synchronous condensers, pumped storage, ***variable generation resources*** etc.): location, minimum and maximum Ratings (net Real and Reactive Power), regulated bus and voltage set point, and equipment status. ***For variable generation a suitable aggregate steady-state model of the collector system and equivalent unit representing the full plant.***"

MOD-012: Dynamics Data for Transmission System Modeling and Simulation

This MOD equally applies to variable generation and needs no augmentation. The requirements in the MOD are quite generic. The requirements of this standard are dependent on and point to MOD 13, discussed below.

MOD-013-1: RRO Dynamics Data Requirements and Reporting Procedures

This MOD explicitly discusses synchronous type generation. It would be beneficial to include an explicit statement to cover variable generation. For example,

> "Plant-specific dynamics data shall be reported for variable generating units (e.g. wind turbine generators, PV etc.) such as the type of generating unit, its interface with the grid and the appropriate model and model parameters to adequately represent unit dynamic response for bulk power system studies. The typical size of a single variable generating unit (e.g. wind turbine generators, PV array, etc.) is several hundreds of kilo-watts to several mega-watts. Thus, it may be acceptable for the total plant to be represented by an adequate aggregated model of the collector system and a single equivalent generating unit scaled up to represent the total name-plate capacity for each type of generating technology employed in the plant. Furthermore, models may need to be provided for other equipment installed in the collector system or at the point of interconnection such as reactive compensation devices."

MOD-024-2 — Verification and Data Reporting of Generator Real Power Capability

This latest posting of this MOD, posted for commenting on January 18th, 2010, exempts variable generation from this requirement. It states:

> "Variable energy units such as wind generators, solar, and run of river hydro are exempt from the requirements of this Standard."

For a variable generation plant the definition of Real Power Capability can be slightly challenging. One way to view it is to see the total gross capability as the sum of the nameplate rating of all individual units within the plant, e.g. for a wind power plant the total sum of the nameplate rating of all wind turbine generators in the plant. However, there must be two realizations (i) the amount of actual power injected into the grid at the point of interconnection requires a suitable representation of losses on the collector system and auxiliary loads, and (ii) by its very nature variable generation is a highly variable energy source and thus it is quite rare to find point in time when all units in the plant are coincidentally at their peak nameplate capacity. Finally, the seasonal variable generation output variations need some discussion since they are quite different than conventional generation technologies.

MOD-025-1 — Verification of Generator Gross and Net Reactive Power Capability

The technical requirement in this MOD reads:

> "R1.5. Information to be reported:
>
> R1.5.1. Verified maximum gross and net Reactive Power capability (both lagging and leading) at Seasonal Real Power generating capabilities as reported in accordance with Reliability Standard MOD-024 Requirement 1.5.1.
>
> R1.5.2. Verified Reactive Power limitations, such as generator terminal voltage limitations, shorted rotor turns, etc.
>
> R1.5.3. Verified Reactive Power of auxiliary loads.
>
> R1.5.4. Method of verification, including date and conditions."

Note: the above requirements are from the existing version of the standard. MOD-025 is currently being enhanced.

Although all of the above could equally apply to variable generation, some clarification may be needed. Namely, variable generation reactive capability of the "power plant" is not entirely inherent in the individual generating units. A variable generation power plant, such as a wind power plant, may contain many reactive power sources such as the individual generating units themselves (e.g. Type 3 or 4 WTG, see Appendix I), discretely switched shunt reactive devices (e.g. shunt capacitors or reactors), smoothly controlled shunt reactive devices (e.g. SVC or STATCOM), or a combination of these devices. Thus, care should be taken as to how the total reactive capability of the power plant is defined and at what point (e.g. point of interconnection, and whether this is defined as the high or low side of the substation transformer). Also, it may not be practical under normal operating conditions to exercise the full reactive capability of the power plant (this is a known issue, even with conventional synchronous generator plants) to test it, thus it should suffice to demonstrate the plants reactive capability to the extent possible in the field and to then augment this with engineering calculations to derive the plants full reactive capability. This is particularly, true of variable generation because there is no control over the energy resource. So for example, a typical wind power plant may only achieve its name-plate rating for a hour or two during an entire year. Thus, it would not be possible to demonstrate the full reactive capability of the plant in the field. Rather, it should suffice to demonstrate the reactive capability of a single WTG and then to derive through engineering calculations (considering all other reactive devices in the plant, such as SVC, STATCOM etc.) the total reactive capability of the plant. These comments should be somehow used to appropriately modify MOD 25.

MOD-026-1 — Verification of Models and Data for Generator Excitation System Functions – SECOND POSTING (and MOD 27)

MOD 26 (and MOD 27 *Verification of Models and Data for Turbine/Governor and Load Control*) are presently under development[33]. These two standards deal specifically with the routine validation of generating unit dynamic models for power system stability studies.

Presently, these standards are tailored explicitly to deal with synchronous type generators, since much of the language revolves around technology associated with synchronous generation (e.g. excitation system, AVR, power system stabilizers etc.). Thus, the following key items need to be clarified in these standards, as they pertain to variable generation. In addition, the comments that follow apply to all components in a variable generation plant that may include devices such as the actual power generating units, shunt compensation devices, centralized control systems spanning the entire facility, etc.:

1. Unit/Plant Size for Validation: These MOD's specify the size of generating unit above which model validation is required. It should be recognized that the typical size of a

[33] MOD 26 and MOD 27 standards under development are found at http://www.nerc.com/filez/standards/Generator-Verification-Project-2007-09.html.

variable generation unit is in the hundreds of kilo-watts to several megawatts range. Thus, the language should be changed (or introduced) to indicate “net power plant” size.

2. Validation of various technologies in a single plant: Variable generation power plants can consist of multiple generation technologies. For example, a wind power plant may consist of WTGs of two different types. Thus, we need to consider the following points as they pertain to variable generation:

    a. For a uniform variable generation plant (i.e. all generating units are of the same technology type) a single aggregate generator model representation should be sufficient.

    b. For a significantly diverse variable generation plant, the plant should be represented by multiple aggregated unit models representing each technology type.

    c. Unique representation of a group of variable generation units as a single aggregated generator model representation should be based on:

        i. The size of the group is a significant proportion of the total plant size (e.g. > 20% of plant rating).

        ii. Each group should represent a unique characteristic (e.g. Type 1 WTG as compared to a Type 3 WTG).

3. Validation of different control layers: Variable generation plants, such as wind power plant, may have several functional layers of control. For example, in a wind power plant with Type 3 WTGs we may have one level of closed loop voltage regulation at the terminals of the WTG, a second slower control loop that regulates voltage at the point of interconnection (POI), and a third layer of control that coordinates the switching of shunt capacitors at the POI based on the reactive output of the individual WTGs. In addition, devices such as STATCOMs may be present at the POI. Modeling and model validation should incorporate such devices/control layers to the extent that the dynamics of these functional layers are important for stability studies (see Figure 3.1).

4. Modeling and Model Validation: Models are an emulation of actual equipment. Not all model parameters necessarily translate to actual physical components or measureable features. Judgment needs to be exercised in the modeling and validation process.

    a. Models should be validated typically against the performance of an actual plant for a given event/disturbance, within the given operating range it is designed for.

b. Models should state clearly the type and the range of events they have been designed to simulated and the limitation of the models beyond which the model deviates from the actual variable generation plant performance (e.g. a model developed to represent electrical transient behavior of a WTG may not be adequate for studying wind fluctuations over a many minute time frame).

c. In general, the best approach to model validation is to use field (or test bench) measurements of various disturbances that must exercise the different control functions to a wide range of operation points. For example, a model is not necessarily valid if the only a comparison between simulation results and field measurements for a single voltage step response is performed at one operating condition. Ideally, illustration of validation against recorded response to various system disturbances (faults, frequency deviations, etc.) gives the greatest confidence in validation.

d. A model is valid if its dynamic behavior is close enough to reality so that its influence on the network of interest (i.e. used for power system studies) results in relatively negligible errors for the phenomena of interest (i.e. in stability studies). That is, perfect curve fitting is not necessary, but to the extent possible erroneous model dynamics must not result in a notable over-design or under-design of the network.

5. Future functionality: Due to the rapidly evolving nature of variable generation technologies, variable generation models should be of a modular nature, such that future functionality can be incorporated, as much as possible, into old model structures by adding a functional modular block. For example, presently Type 3 and 4 WTGs do not exhibit inertial response. However, at least one manufacturer now supplies a functional control addition that can emulate inertial response on these units. Such functionality is likely to be made available soon by most vendors. Thus, a functional model block can be developed that can be added to the existing models for Type 3 and 4 WTGs to emulate the behavior of this additional control.

6. Modeling of protection: Variable generation, much like conventional generation, will have associated under/over voltage and under-over frequency protection. These should be modeled. Attention should also be given to protective relay coordination with plant controls, particularly in light of the nature of the grounding system within the variable generation plant (e.g. a wind power plant spans an entire collector system, which can be grounded in several different ways and thus have various implications on protective relay coordination). Such coordination issues relate to the PRC and FAC-001 standards.

7. Issues related to the fuel source for variable generation: For variable generation one needs to be cognizant of the variable nature of the energy source and thus the possible impracticality of performing model validation at a desired plant output, but rather having to accept model validation at whatever plant output can be achieved at the time of testing or disturbance monitoring.

8. Revalidation: How often should models be revalidated?

    a. Many variable generation technologies are rapidly changing, for example in wind power plants new control software or new setting may be uploaded every year, if not sooner.

    b. If the changes are insignificant, the existing dynamic models should be revalidated if possible as a matter of prudency – say within six months or so of a control system update/upgrade. The changes (in parameters or dynamic model) should be reported to the local Reliability Entities.

    c. If the changes are significant, the existing dynamic models should be revalidated – say within three months or so after the update/upgrade. The changes (which may include a new module, new software etc.) should be reported to the local Regional Entities.

5.3. Final Recommendation

An earlier draft of this report and recommendations were presented to NERC's Planning Committee at their March, 2010 meeting. The Committee members urged the IVGTF to pursue NERC reliability standard development. Thus, several NERC Standards Drafting Teams undertaking MOD Standard development will be contacted to present the recommendations from this report for their consideration and incorporation in subsequent updates. The standard drafting teams for MOD-026 and MOD-027 are aiming to incorporate variable generation considerations in the next release of these draft standards.

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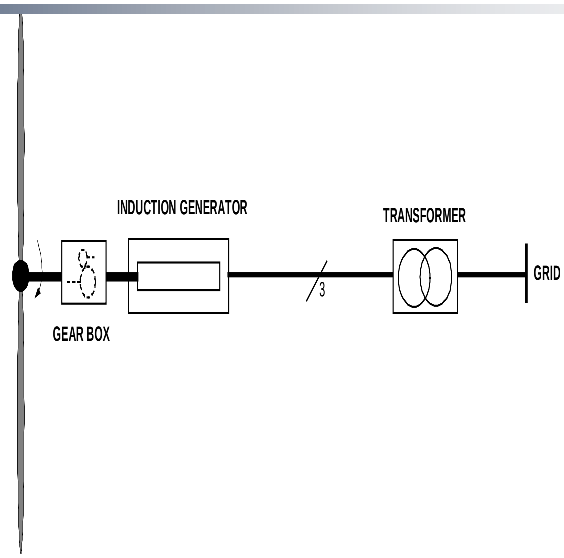
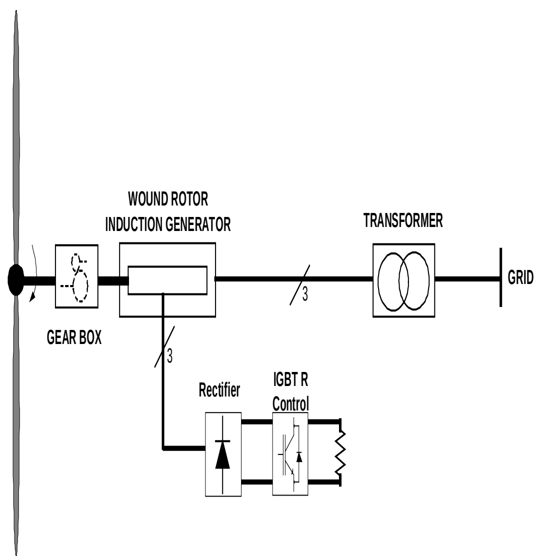
Appendix I: Wind-Turbine Generation (WTG) Technologies

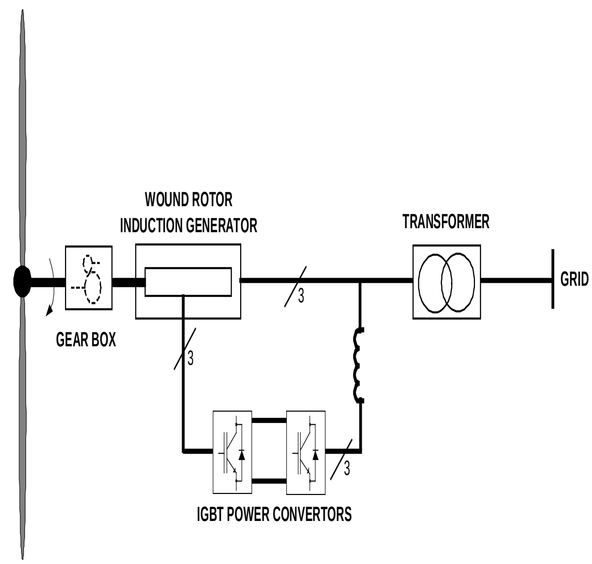


(a) Type 1 Wind Turbine-Generator: Fixed Speed Induction Generator

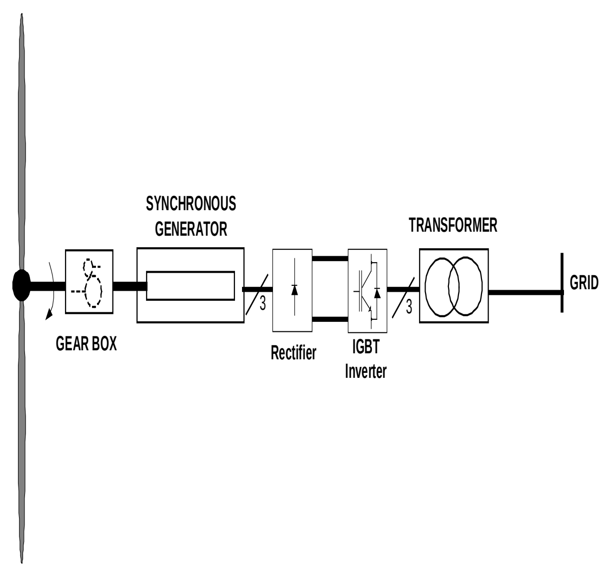


(b) Type 2 Wind Turbine-Generator: Variable Slip Induction Generator [34]

[34] IGBT R control = Resistor controlled by Insulated Gate Bi-Polar Transistor



(c) Type 3 Wind Turbine-Generator: Double-Fed Asynchronous Generator



(d) Type 4 Wind Turbine-Generator: Full Power Conversion

Acronyms

CSP – Concentrating Solar Power

CIGRE - International Council on Large Electric Systems

DFAG – Doubly Fed Asynchronous Generator (also often referred to as DFIG – Doubly Fed Induction Generator)

FERC – Federal Energy Regulatory Commission

HVDC – High-Voltage Direct-Current transmission

IEC – International Electrotechnical Commission

IEEE – Institute of Electrical and Electronic Engineers

IGBT – Insulated-Gate Bipolar Transistor

IGCT – Insulated-Gate Commutated Thyristor

IVGTF – Integration of Variable Generation Task Force

ISO – Independent System Operator

LCC – Line-Commutated Converter

LVRT – Low-Voltage Ride-Through

MOD – Modeling, Data and Analysis Standards

NERC – North American Electric Reliability Corporation

OEM – Original Equipment Manufacturer

PHEV – Plug-in Hybrid Electric Vehicle

PV – Photovoltaic

POI – Point of Interconnection

RPS – Renewable Portfolio Standard

RTO – Regional Transmission Operator

SAR – Standards Authorization Request (NERC process)

SCADA - Supervisory Control and Data Acquisition

SSTI – Subsynchronous Torsional Interaction

STATCOM – Static Compensator (voltage source converter based technology)

SVC – Static Var Compensator (thyristor based technology)

TSO – Transmission System Operator

VAr – volt-ampere reactive (standard units for reactive power)

VRT – Voltage Ride-Through

VSC – Voltage Source Converter

WPP – Wind Power Plant

WTG – Wind Turbine Generator

WECC – Western Electricity Coordinating Council

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