FINAL PROJECT REPORT

WECC WIND GENERATOR DEVELOPMENT

Appendix V
MODEL VALIDATION OF
WIND TURBINE GENERATOR

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Abstract and Keywords

For the most part, wind turbine generator (WTG) manufacturers have sponsored the development of WTG dynamic models. Models developed under this paradigm tend to be proprietary and manufacturer-specific. The models are often disclosed under confidential terms for interconnection studies and design of individual projects. However, the use of proprietary models to represent installed wind power plants is incompatible with critical grid planning activities that are conducted by regional reliability organizations as a collaborative effort among many stakeholders. In this context, the use of generic or simplified models is desirable.

To address this industry need, the Western Electricity Coordinating Council (WECC) has embarked on the development of generic positive sequence WTG models for large-scale power system transient stability analysis. As an integral part of this WECC activity, the National Renewable Energy Laboratory (NREL) is engaged in this model validation effort.

The dynamic models developed are sometimes referred to as "generic" WECC models because of the non-proprietary nature of these models. The objective of this report was to provide a methodology for validating dynamic models of wind turbine generators for power system studies. This report discusses the process of model validation against field measurements. The procedure is illustrated with a specific example.

Keywords: Dynamic model, power system, renewable energy, variable-speed generation, weak grid, wind energy, wind farm, wind power plant, wind turbine, wind integration, systems integration, WECC, wind turbine model, validation.

Executive Summary

Within the next 3 – 5 years, it is expected that a large amount of wind capacity will be added to the power system. The size of individual turbines has increased dramatically from a mere 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. Today, wind power plant ratings can be as high as 300 MW or more. By some projections, as much as 20 GW of additional wind generation capacity may be added in the Western Electricity Coordinating Council (WECC) footprint within the next 10 – 15 years. The increase in the level of penetration of renewable energy generation in the WECC region, and California in particular (20% by 2010), poses significant questions concerning the ability of the power system to maintain reliable operation.

While the use of induction generators or negative loads to represent wind power plants has been acceptable in the past (during the era of low wind penetration), the increased use of this energy source necessitates a more accurate representation of a modern wind turbine. Misrepresentation of a wind power plant in a dynamic model may lead the transmission planners to erroneous conclusions.

The Wind Generation Modeling Group (WGMG) has initiated and will complete the research and development of standard wind turbine models of four different types of wind turbines. These four types of turbines currently hold the largest market share in the North American region. WECC is interested in providing accurate and validated models of standard wind turbines that will be made available in their database, including the data sets to be used for testing the models, and the methods of representing a wind power plant in power system studies. These goals will be accomplished through the development and validation of standard models, development of an equivalent method for an array of wind generators, and recommended practices for modeling a wind power plant. The WECC models will be generic in nature, that is, they do not require nor reveal proprietary data from the turbine manufacturers.

These improved standard (generic, non-proprietary) dynamic models enable planners, operators and engineers to design real time controls or Remedial Action Schemes (RAS) that take into account the capability of modern wind turbines (for example, dynamic, variable, reactive power compensation, dynamic generation shedding capability, and soft-synchronization with the grid) to avoid threats to reliability associated with the operation of a significant amount of wind energy systems. In addition, researchers at universities and national laboratories will have access to wind turbine models, and will be able to conduct research without the need to provide for non-disclosure agreements from turbine manufacturers.

With the tasks proposed, planners could more accurately study transmission congestion or other major grid operating constraints, either from a real time grid operation or transmission planning perspective. These models could be used by transmission planners in expanding the capacity of existing transmission facilities to accommodate wind energy development in a manner that benefits electricity consumers.

Failure to address this modeling problem either increases the risk to California's electricity supply, grid instabilities and outages or reduced amounts of power that can be imported into and transported within California and the region within the WECC footprint.

Wind Turbine Model Validation is one of the final reports for the Wind Generator Development Project, contract number #500-02-004, work authorization number MR-065, a project sponsored by Western Electric Coordinating Council – Wind Generator Modeling Group, California Energy Commission, and National Renewable Energy Laboratory.

1.0 Introduction and Scope

Modern wind turbine generators (WTGs) utilize power electronics and state-of-the-art real and reactive power controls that allow wind power plants to have much better steady-state and dynamic performance compared to wind power plants of the past. For reliability and cost reasons, it is very important to properly represent steady and dynamic characteristics in large-scale positive-sequence simulations. For the most part, the development of WTG positive-sequence dynamic models has been sponsored by WTG manufacturers. Simulation models developed under this paradigm tend to be proprietary and manufacturer-specific.

The models are often disclosed under confidential terms for interconnection studies and design of individual projects. However, the use of proprietary and manufacturer-specific models to represent installed wind power plants is incompatible with critical grid planning activities that are conducted by regional reliability organizations as a collaborative effort among many stakeholders. In this context, the use of generic or simplified models is desirable.

To address this industry need, the Wind Generation Modeling Group (WGMG) of the Western Electricity Coordinating Council (WECC) has embarked on the development of generic positive-sequence WTG models for large-scale power system transient stability analysis. This effort is based on the premise that it is technically feasible to develop a generic model for each of the four basic WTG configurations that are currently in use: 1) squirrel-cage induction generator, 2) wound-rotor induction generator with adjustable rotor resistance, 3) doubly fed asynchronous generator (DFAG), also known as doubly fed induction generator (DFIG), and 4) a full-power conversion wind turbine generator. Although additional work is required to achieve the stated goals, substantial progress has been made. As an integral part of this WCC WGMG activity, the National Renewable Energy Laboratory (NREL) is engaged in an extensive model validation project aimed at testing the models against field measurements and refining the WECC generic models as needed.

The dynamic model developed by WECC is referred to as a generic WECC model with the understanding that the model does not contain proprietary information specific to any turbine manufacturers. To simulate a particular turbine from a turbine manufacturer, this generic model requires non-proprietary input data that is available from the WECC database or from the turbine manufacturer.

The validation of the dynamic model is intended to examine if the model produces the same characteristics of the actual wind turbine. The best scenario is to compare field measurements taken during transient events to the response of the dynamic model to the same events performed by simulation. However, field data is not easy to access. The next best scenario is to use the detailed model (including all the proprietary information) developed by the wind turbine manufacturers as the baseline turbine. The detailed model is usually validated with field data (in some cases, considered to be proprietary by the turbine manufacturers).

The scope of this document is focused on the methodology of wind turbine model validation. The method of validation can be applied to different types of generators, however, in this report

the type 3 wind turbine generator model validation is presented based on data measurements taken at the New Mexico Wind Energy Center.   This report is organized as follows:

- Section 1 – Introduction and Scope

  o Section 1 is devoted to the introduction and project scope.

- Section 2 – Background

  o This section provides historical background and the requirement for a generic dynamic model of a wind turbine generator.

- Section 3 – Wind Turbine Dynamic Model

  o In this section, the general discussion of wind turbine dynamic model is presented. The four types of generic models are also discussed. The detail of the model is not presented, but there are many other publications available in the public domain to describe each individual wind turbines.

- Section 4 – Wind Power Plant Representation

  o This section describes the wind power plant in the context of modern wind turbine technology, with a particular emphasis on electrical characteristics. The difference between a conventional power plant and wind power plant are described.   Single-machine equivalent representation, representation of the dynamic model, wind turbine equivalent rating, voltage controller, and pitch control are presented in this section.

- Section 5 – Wind Power Plant Model Validation

  o The method to represent the network and the disturbance are presented. The comparison between the simulation and measurement will be discussed in detail. The measured raw data is processed before it is used in the simulation. Equivalent circuit, dynamic data, and event representation are described in this section.

- Section 6 – Simulation Results

  o In this section, the comparison between the simulation results and the field measurements is presented.   Both a single turbine representation and the complete (136 turbines) representation are discussed.

- Section 7 – Summary

  o This section summarizes the model validation methodology for the wind turbine generator.

2.0 Background

Initially, the size of wind power plants was small compared to conventional power plants. The process of integrating wind power plants into the power system grid was accomplished by representing the wind power plant as an induction generator or as a negative load. This representation works fine as long as the size of the wind power plant is relatively small compared to the short circuit capability at the point of interconnection (POI). However, wind power development in the mid nineties started to see a phenomenal increase in quantity. Numerous wind power plants were built one after another within a short time. The size of the wind power plant started to grow from small sizes (under 50 MW to 600 MW). The impact of wind power plants can no longer be ignored. New wind turbine types were developed, and power electronics were added to improve the control of the wind turbines.

As a consequence of the large influx of wind energy into the power grid, and the new type of generators that were introduced to the generation mix, a lot of efforts were geared toward improving planning tools to help wind energy to integrate into the power system network. Turbine manufacturers, utilities, system operators (e.g., ERCOT) developed dynamic models of wind turbine generators. Many of the manufacturers developed models using their own software for their turbines. Most of the turbine models available at that time contained proprietary data and information, and many users had to sign a non-disclosure agreement (NDA) to use the dynamic models.

In June 2005, WECC convened the Wind Generator Modeling Group (WGMG) under the auspices of the WECC Modeling and Validation Work Group (MVWG) to develop a set of generic, non-proprietary wind generator models suitable for positive-sequence dynamic simulations. It was envisioned that four standard models are required to represent the basic types wind turbine generator technologies available in the market: conventional induction machines, wound rotor induction machines with variable rotor resistance, doubly-fed induction machines, and full converter machines. Although the standard models are being developed for use in the WECC, it is anticipated that the models will be embraced as the industry standard.

The WECC Wind Turbine Dynamic Model of four different wind turbine types represents the wind turbine types with the major market share in the United States. These wind turbine models were written to work with two major software platforms used by the majority of utilities in the United States. The model is simplified to make it possible that the manufacturers do not have to reveal their proprietary information, yet this model is accurate enough to simulate real wind turbines. The objective was to provide a model to the general public without the need for non-disclosure agreements between the user and the turbine manufacturers.

WGMG has defined the technical requirements of standard models. There is strong consensus within WGMG and externally that the following functional specifications are reasonable. Additional specifications were developed by WGMG consensus, as required.

- The models should be suitable for implementation in positive-sequence power system simulation programs such as PSLF and PSS/E, and should be consistent with existing models for other rotating machine generators in terms of accuracy, complexity, and numerical stability.

- The models should be suitable for assessing, on a preliminary basis, voltage ride-through and reactive compensation requirements. As with any other power system component, additional studies using a more detailed system representation and higher-order models may be required to refine the results of planning studies.

- The generic models should reproduce wind-turbine generator performance reasonably well in the range of 0 (DC) to 6 Hz, and in response to electrical disturbances such as close-in and remote electrical system faults, assuming constant wind speed during the transient stability simulation.

- The models should correctly reflect performance differences with respect to a range of initial wind speed assumptions (cut-in to rated output). However, since traditional transient stability simulations are concerned with performance over short periods of time, wind speed can be considered constant during the simulation.

3.0 Wind Turbine Dynamic Model

Dynamic models are very important in modern power system studies. A few percent of design error could cost millions of dollars and/or compromise reliability. Overly pessimistic models will slow down the development of wind energy and cause unnecessary additional supporting infrastructure at potentially significant cost. On the other hand, overly optimistic models may produce wrong conclusions, resulting in inadequate infrastructures to support wind generation. Any reliability issues can cause service disruptions or blackouts, which cost millions of dollars to the customers who were affected, the utilities for not producing power, and to workers' loss of time for not being productive. Different aspects of dynamic simulation studies can be found in the references [3-5].

The use of wind turbine dynamic models in power system studies includes the following:

- Transmission planners, operators, wind plant developers, turbine manufacturers, utility engineers, researchers, and consultants use dynamic models to study the dynamic behavior of power system.
- To study the impact of the wind turbine generator (WTG) on the power system and vice versa (i.e., to keep voltage and frequency as stable as possible for customers connected to the grid).
- To study the impact of expansion, reduction, and outages in areas such as the transmission line, transformer, switch gear, generator, new wind power plant, repowering or resizing wind plants, and additional reactive compensation.
- To study the reliability of a power system during transient events such as loss of line, loss of load, short circuits, loss of generation, loss of wind, and voltage ride through of generators, etc.

There are four types of wind turbines that are currently used for wind power plants. In the future, new wind turbine types may become available. The four types of wind turbine models are shown in Figure 1.

3.1. Type 1 – Induction Generator

Wind turbine type 1 is one of the oldest technologies used in wind turbine generators. It consists of an induction generator connected to the rotor blades via a gearbox. This type of turbine is very rugged and very simple in its construction. The induction generator used in most of the turbines is usually type A or type B, operating in a low slip range between 0 - 1%. Many turbines use dual-speed induction generators where two sets of windings are used within the same stator frame. The first set is designed to operate in a low rotational speed (corresponds to low wind speed operation), and the second set is designed to operate in a high

rotational speed (corresponds to high wind speed operation). Since the start-up current is high, many wind turbines employed a phase controlled soft-start to limit start-up currents. This soft start consists of back-to-back thyristors in series with each phase of the induction generator.

Type 1

Type 2

Type 3

Type 4
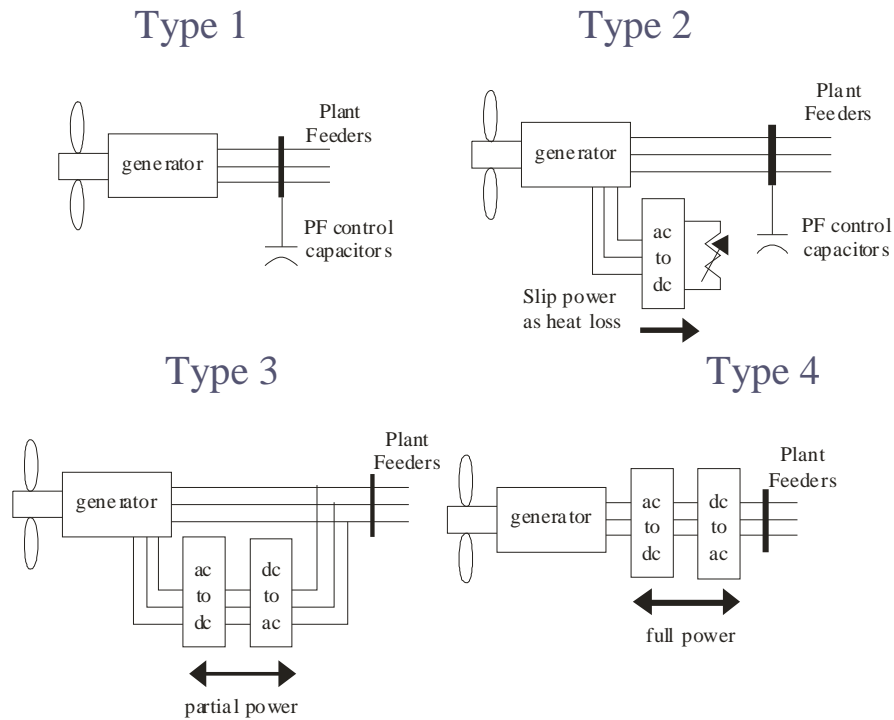
Figure 1. Four types of wind turbine generator models

The natural characteristic of an induction generator is that it draws reactive power from the utility supply. Thus, this type of turbine requires reactive power compensation implemented in the form of switched capacitors in parallel with each phase of the winding. Operation without switched capacitors can lead to excessive reactive power drawn from the utility, thus creating a significant voltage drop across the transmission line, and results in low voltage at the terminals of the induction generators.

The size of the capacitors switched in and out is automatically adjusted according to the operating point of the induction generator. At higher wind speed, the generated power increases and the operating slip of the induction generator is higher and as a result, the reactive power required is also larger. It is customary to keep the operation of the induction generator at close to the unity power factor.

3.2. Type 2 – Wound Rotor Induction Generator with Adjustable External Rotor Resistance.

Wind turbine type 2 is a wound rotor induction generator with adjustable external resistors. The adjustable external resistor is implemented by a combination of external (three phase) resistors connected in parallel with power electronics circuit (diode-bridge and DC chopper). Both the resistors and the power electronics circuit are connected to the rotor winding. To adjust the effective values of the external rotor resistance, the duty ratio of the DC chopper.

The wind turbine starts to generate when the rotor speed is above synchronous speed. As the wind speed increases, the input aerodynamic power increases, the rotor slip increases, and the electrical output power increases. In this region (P < P rated), the external rotor resistors are short circuited (duty ratio =1). Once the output power reaches its rated output, the external rotor resistance is adjusted to keep the output of the turbine constant. This is done by keeping the effective total rotor resistance constant at the value of $R_2/slip_{rated}$.

$$R_{2total} = R_2 + R_{2ext}$$

$$R_{2total}/slip = R_2/slip_{rated}$$

To keep the rotor speed from run-away conditions and to reduce the mechanical loads on the blades and the turbine structures, the aerodynamic power is also controlled by controlling the pitch angle of the blades in the high wind speed regions. The blade pitch is controlled to keep the rotor speed below its maximum speed (up to 10% slip above synchronous speed).

3.3. Type 3 – Variable Speed Wind Turbine Generator with Doubly Fed Induction Generator

Wind turbine type 3 is a variable speed wind turbine generator employing a wound rotor induction generator. It is usually design to operate at + 30% slip. A variable frequency power converter is connected to the rotor winding. The power converter is ac-dc-ac system. The power converter connected to the rotor winding is a variable frequency three-phase power converter, and the power converter connected to the line is a 60-Hz power converter. The power converter is usually the current-regulated pulse-width modulation (CRPWM) type. The size of the power converter is smaller than the rating of the induction generator because it is designed only to carry the slip-power. Thus, for operation of 30% slips, the size of the power converter is about 30% of the rating of the induction generator. A larger operating slip range is possible, however, larger slip operation requires a larger power converter (added cost, reduced efficiency, etc). Below synchronous speed, the rotor power flows from the line to the rotor winding, and above synchronous speed, the rotor power flows from the rotor winding to the lines.

The wind turbine is usually controlled to generate optimum aerodynamic power for low wind speed up to rated wind speed. Above rated wind speed, the pitch controller adjusts the pitch angle to limit the aerodynamic power, thus, the rotor speed is limited.

3.4. Type 4 – Variable Speed Wind Turbine Generator with Full Conversion Power Converter

Wind turbine type 4 is a variable-speed wind turbine generator. The output of the generator is passed through the power converter to the grid. Thus, the rating of the power converter is the same as the rating of the electric machine used. The electric machine used can be an induction machine, wound field synchronous generator, or permanent magnet synchronous generator. The power converter completely separates the generator from the grid. The generator generates power at different rotor speeds. It is directly converted by the power converter to a three phase 60-Hz alternating currents. The same type of power converter is used for the type 4 wind turbine generator. It is able to control the real and reactive power independently. It is controlled to optimize the operation of the turbine by controlling the real power, and to provide a constant power factor or constant reactive power, or voltage control at the line side.

4.0 Wind Power Plant Representation

A conventional power plant consists of a single generator or multiple large (e.g., 100 MW) synchronous generators. The prime mover driving conventional generators is steam, often requiring combustion of non-renewable fuel affected by cost, politics, and pollution restrictions. The conventional generator is controllable and its output is adjustable up to the maximum limit and down to the minimum limit of the generator. The output power is generally scheduled generation based on load forecasting, influenced by human operation based on optimum operation (scheduled operation). It is located relatively close to the load center. The synchronous generator operates in a fixed speed – no slip, and the magnetic flux is controlled via exciter winding. Flux and rotor rotate synchronously.

In comparison, a wind power plant consists of many (hundreds) of wind turbines of small sizes (1 MW – 5 MW each). The prime mover (wind turbine) is driven by wind – renewable (free, natural, pollution free). The wind power plant has limited controllability. In general it is desirable to generate as much energy as can be harvested, however, it is possible for curtailment of the output power. Generation output is often not predictable, although modern wind forecasting has gained a better degree of accuracy over the years. Wind power plant output depends on wind variability based on wind forecasting, influenced more by nature (wind) than humans, and the generation philosophy is based on maximizing energy production (unscheduled operation). The wind power plant is often located at rich wind resource sites and may be far from the load center. There are different types of generators used for wind turbines. Currently, there are four different types of generators commonly used (i.e., fixed speed, variable slip, variable speed, full converter). Thus, these are non synchronous generators. Some types of wind turbine generators (i.e., type 3 & 4) are variable speed and are based on flux oriented controllers (FOC), and are controlled by a power converter. Thus, the rotational speed of the rotor does not have to rotate synchronously with the magnetic flux.

In this section, the wind power plant representation will be discussed. For dynamic simulation, the major components of a wind power plant must be properly represented. If the wind power plant collector system data is available, an equivalent of all wind turbines and its corresponding collector system should be derived. A method of wind power plant equivalencing can be found in documents [1-2].

A typical modern wind power plant consists of hundreds of turbines of the same types. A wind turbine generator is usually rated at low three phase voltage output (480 – 600 V). A pad mounted transformer at the turbine steps up the voltage to medium voltage (12 kV – 34.5 kV). Several turbines are connected in a daisy chain to form a group. Several of these groups are connected to a larger feeder. Several of these feeders are connected to the substation where the substation transformer steps up the voltage to the desired transmission level (e.g., 230 kV). A very large wind power plant consists of several substations with the sizes of 50 MVA or higher for substation transformers. These substations are connected to an interconnection transmission

line to a larger substation where the voltage is stepped up to a higher voltage level (e.g., 500 kV). An example of a wind power plant layout is shown in Figure 2.

Within a wind power plant, there are a lot of diversities in the line feeder and the wind speed at each turbine. The line impedance in the line feeder connecting each wind turbine to the point of interconnection differs from each other. The wind speed experienced by one turbine can be significantly different from another turbine located at another part of the wind power plant. The diversity of wind power plants is a good attribute in many ways. For example, the interaction between the wind power plant and the grid is determined by the collective behavior of the wind power plant. In contrast, a conventional power plant interacts with the grid as a single large generator. During disturbances, a conventional power plant may be disconnected from the grid and it may lead to a cascading effect. On the other hand, a wind power plant may loose a small percentage of total generation, depending on the location of each wind turbine with respect to the fault origin.
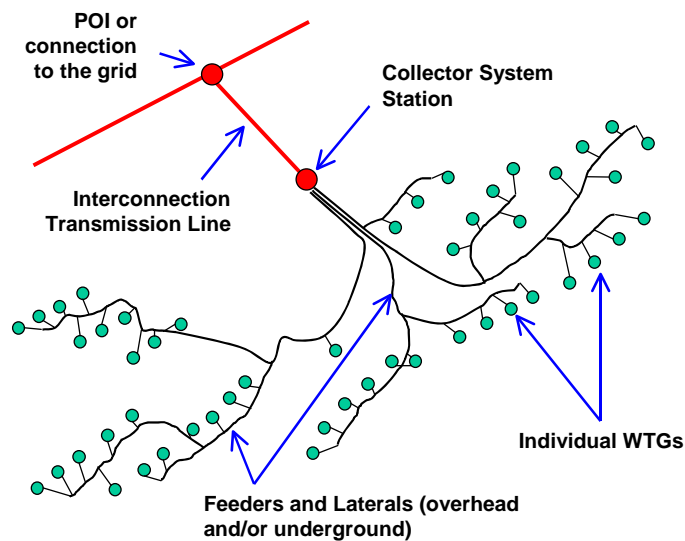

Figure 2. Physical diagram of a typical wind power plant.

4.1. Single-Machine Equivalent Representation

The Wind Generator Modeling Group recommends the use of the single-machine equivalent model shown in Figure 3 to represent wind power plants (WPPs) in WECC base cases [7]. This representation is recommended for transient stability simulations.

All the components shown in Figure 3 are represented in power flow calculations. The dynamic simulation may be represented by the following components of the wind power plant:

- The equivalent generator (type 1, type 2, type 3 or type 4)

- The plant level reactive compensation (switched shunt capacitors, SVC, STATCOM)
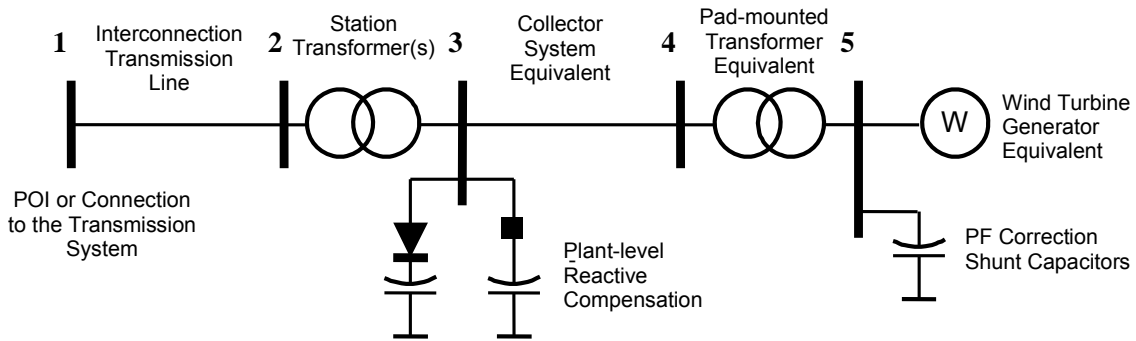

Figure 3. Single-machine equivalent power flow representation for a WPP.

4.2. Representation of Wind Turbine Dynamic Model

The wind turbine dynamic must be represented by the correct wind turbine model available from the WECC database. A detailed description of the type 3 wind turbine generic model can be found in reference [6]. WECC, with collaboration with wind turbine manufacturers, attempt to provide input parameter data to many turbines representing turbines installed or future turbines to be installed within the WECC footprint. There are several ways to get the input parameters for different turbines in place within the WECC database:

- The input parameter of the WECC Generic Model is tuned to match the manufacturer's field test data. If the field test data is considered proprietary, this process is best conducted by the wind turbine manufacturer.

- The input parameter of the WECC Generic Model is tuned to match the manufacturer's the output of the complete/detail, manufacturer's specific dynamic model. If access to the field data is not available, the generic model can be tuned to match the complete/detail model.

- The input parameter of the WECC Generic Model is tuned to match both the manufacturer's field test data and the output of the complete/detail, manufacturer's specific dynamic model.

Since tuning the input parameter to the generic model takes some effort, WECC has to rely on the cooperation and the contribution of the wind turbine manufacturers to provide the tuned parameters and/or the access to the complete detailed models. The input parameter data from the turbine manufacturers is given for a generic 100-MVA WPP and a typical controller adopted by most of the WPPs. However, each WPP has its own control requirements and certain parameters or flags of the original typical data from the manufacturer may have to be adjusted or changed to reflect the WPP represented.

4.3. Representation Wind Turbine Equivalent Rating

WPP size must be incorporated into the dynamic model for type 3 and type 4. The size of the WPP is used to calculate the per unit values for the WPP under investigation.

For type 1 and type 2:
The WPP size is derived from the information provided by the power flow (i.e. P_{max}).

For type 3:
The wind power plant size is used in the following sub-modules:

- WT3G: Generator/Converter Model for the WT3 Generic Wind Model

  wt3g [<n>] {<name> <kv>} <id>} : #<rl> {mva=<value>}

    o Example:

       wt3g   5   "BUS5"   0.575   "1 "   : #9   mva=33.3 /

    o Where:

       mva = Rated MVA

- WT3E: Converter Control Model

  wt3e [<n>] {<name> <kv>} <id> ! ! ! ! ! [<mon_i>] {<namei> <kvi>}

  [<mon_j>] {<namej> <kvj>} <ck> <sec> : [mwcap=<value>]

    o Example:

       wt3e 5 "BUS5" 0.575 "1 " 3 "BUS3" 34.5 "1 " 1 : #9   mwcap=33.3 /

    o Where:

       mwcap = Rated MW capability

4.4. Representation of Wind Turbine and Wind Plant Voltage Controller

For type 1 and type 2:
The wind turbine reactive power is compensated by a capacitor. It is represented by the power flow data as a shunt capacitor (see WECC Power Flow Guide for detail).

Note, that for type 1 and type 2 WTG, the Q_{gen} is set constant by setting $Q_{max}=Q_{min}$, thus, the voltage is not controllable by the generator.
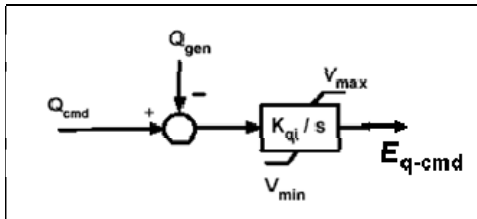
For type 3 and type 4:

The wind turbine voltage controller is used in the following sub-modules. The block diagrams are shown in Figure 4.
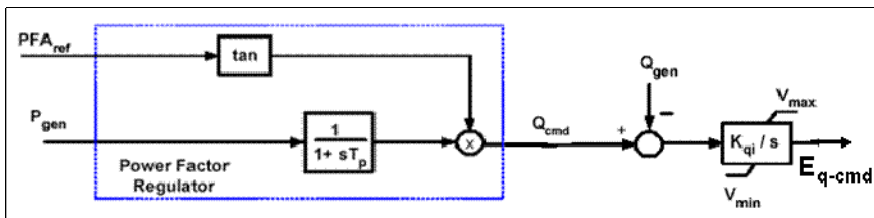
- WT3E: Converter Control Model

  The following flags have influence in reactive power controllability.
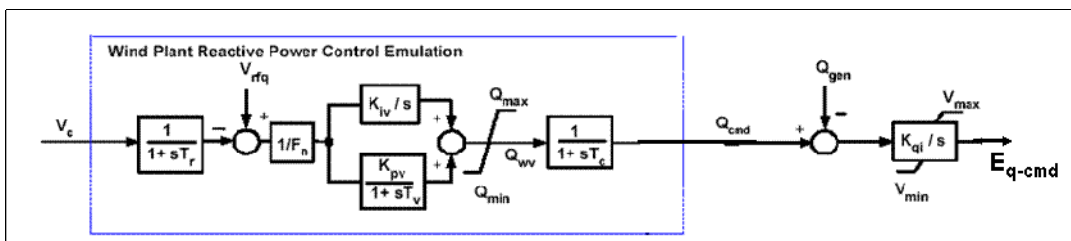
  varflg and vltflg

Reactive power control:
- $Q_{cmd} = Q_{ref} = Q_{gen\_load\_flow}$
- varflg = 0; vltflg = 0
- voltage is not controlled

[a] Reactive Power Control

Power factor control:
- varflg = -1; vltflg = 0
- voltage is not controlled
- PFA_{ref} is defined at initial load flow solution based on P_{gen}, Q_{gen}

[b] Power Factor Control

Voltage control emulation for plant level reactive compensation:
- varflg = 1; vltflg = 0
- voltage V_c (remote bus) is controlled = V_{rfq} defined initially from load flow solution
- terminal voltage V_{term} is not regulated

[c] Plant Level Reactive Compensation

- 15 -
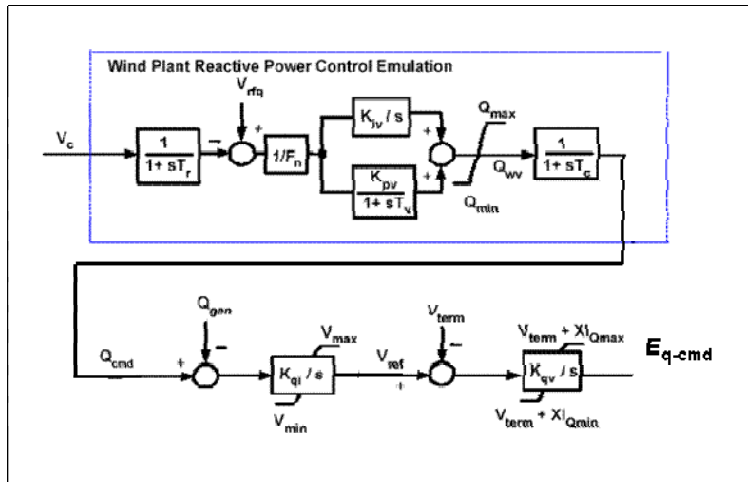
Voltage control emulation for Plant Level Reactive compensation:
- varflg = 1; vltflg = 1
- voltage is controlled at the V_{rfq} defined separately
- the terminal voltage V_{term} is controlled with the faster control loop (good response during fault event).

[d] Plant Level Reactive Compensation Including Terminal Voltage Control

Figure 4. Block diagram of converter control model with different settings

Example:

    wt3e 5 "BUS5" .575 "1 " 3 "BUS3" 34.5 "1 " 1 : #9   mwcap=33.3 /

    "varflg" 1.0   "vltflg" 1.0

Where:

varflg   0 – constant Q control; Qref is derived from the initial reactive power Qgen set in the power flow data.

1 – use Wind plant reactive power control emulator; the regulated bus will be controlled.

In the example above, the regulated bus voltage is bus 3:

$$V_{bus3} = V_{reg\text{-}bus3}$$

- If Xc (compensating reactance for voltage control) = 0 to get

$$Vc = Vrfq$$

- If X_c (compensating reactance for voltage control) > 0 to get

$$V_c = |V_{rfq} - jX_c\ I_{reg}|$$

where (V_c = voltage at the regulated bus voltage and $V_{rfq} = V_{reg}$ specified in the power flow data, Xc is an impedance to be used to create a virtual measurement of voltage within a branch from "regbus" to "tobus", circuit ID "ckt", specified, and Ireg is the current flowing in this branch from "regbus" to "tobus" specified).

Example:

wt3e 5 "BUS5" .575 "1 " 3 "BUS3" 34.5 "1 " 2 "BUS2" 230 "1 "   1 : #9   mwcap=33.3 /

In the example above, the regulated bus voltage is bus 3:

$$V_{busX} = |V_{reg-bus3} - j \, X_c \, I_{reg\_3-2}|$$

Where V_{busX} is a voltage at a bus away from the regulated bus 3 in the direction to bus 2. Thus, it is possible to control the voltage at a virtual bus X in the middle of the transformer. The distance from the regulated bus 3, depends on the size of impedance X_c.

-1 – constant power factor control; in this case Q_{gen} will be controlled to keep PF=PFAref

vltflg

1 – use closed loop terminal voltage control.

0 – no terminal voltage control

The closed-loop voltage control (vltflg) is a fast controller to restore the terminal voltage during transient. The vltflg should be set to 1 only if the terminal voltage of the generator needs to be controlled to a set value of Vref. Otherwise, if a remote bus voltage is to be regulated, vltflg can be set to 0.

F_n

Fraction of WTG in wind plant that are on-line.
1.0 = 100% of the total WTG is in operation

0.8 = 80% of the total WTG is in operation and 20% is off-line (maintenance, decommission, etc)

4.5. Remote voltage definition:

Figure 5 shows a simplified diagram of a wind power plant with remove voltage control capability.

X_C = compensating reactance for voltage control (in p.u.)

V_C = voltage at a remote point

$V_C = V_f - jX_C \, I_{ft}$ V_f = voltage at bus_{from} I_{ft} = current flowing from bus_{from} to bus_{to}

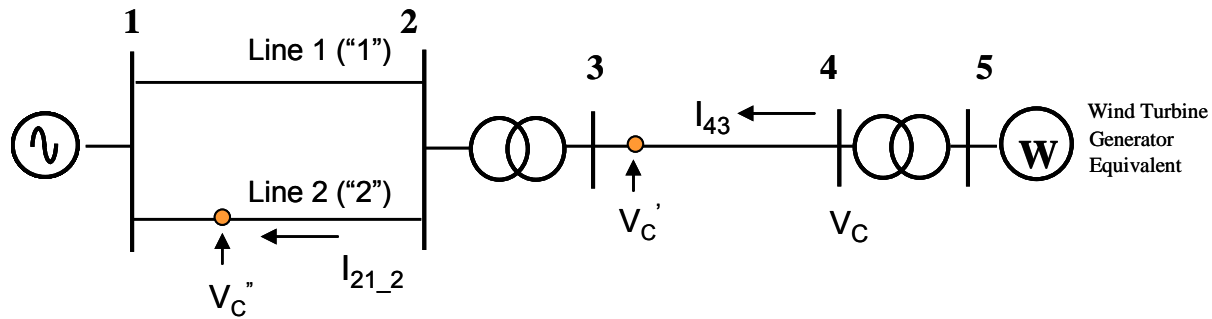$V_{rfq} = V_C$ computed from the load flow solution at initial condition.

Figure 5. Simplified single line diagram describing voltage control at a remote node

Examples:

> wt3e 5 "BUS5" 0.575 "1 " 1 : #9   mwcap=33.3 / monitored bus is not defined; Thus terminal voltage (bus 5) is controlled.

> wt3e 5 "BUS5" 0.575 "1 "   4 "BUS4" 34.5 "1 " 1 : #9   mwcap=33.3 /
>
> Thus bus 4 (V_C) will be controlled

> wt3e 5 "BUS5" 0.575 "1 "   4 "BUS4" 34.5   3 "BUS3" 34.5 "1 " 1 : #9 mwcap=33.3 /
>
> Thus remote node ($V_C^{'}$) on branch 4-3 is controlled. $V_C^{'} = V_4 - jX_C\,I_{43}$ $X_C \le X_{43}$

> wt3e 5 "BUS5" 0.575 "1 "   2 "BUS2" 138   1 "BUS1" 138 "2 " 1 : #9 mwcap=33.3 /
>
> Thus remote node ($V_C^{''}$) on branch 2-1 is controlled. $V_C^{''} = V_2 - jX_C\,I_{21}$ $X_C \le X_{21}$

- **Turbine model (WT3T – module) and pitch model (WT3P – module)**

The block diagrams to describe the pitch control function are shown in Figures 6, 7, and 8.

General input setting:

- Initialize the blade pitch when the wind speed V_w > 1.0 p.u.
- Unless we specify that the wind speed V_w > 1.0 p.u. The initial (pre-fault) pitch angle = 0.
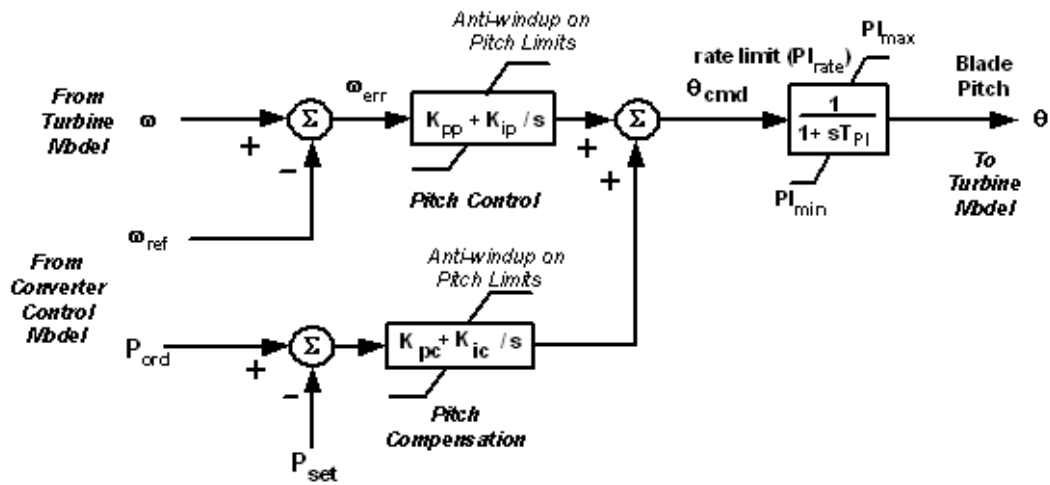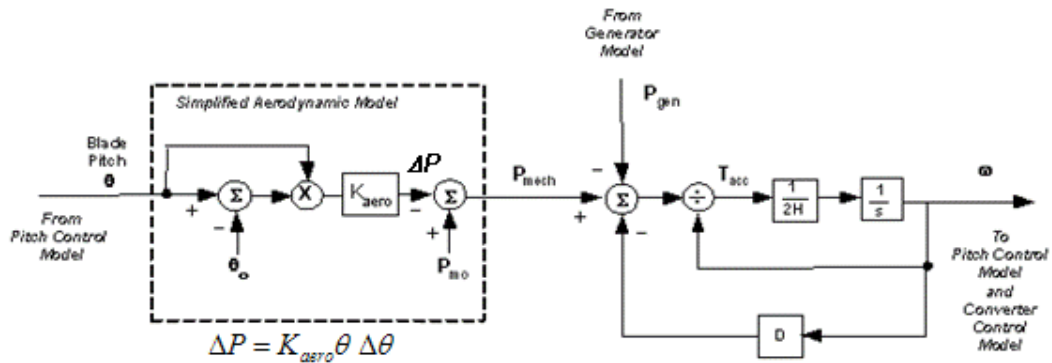
Figure 6. Type 3 WTG pitch control

$$\Delta P = K_{aero}\theta\,\Delta\theta$$

Figure 7. Type 3 WTG turbine model with one-mass model
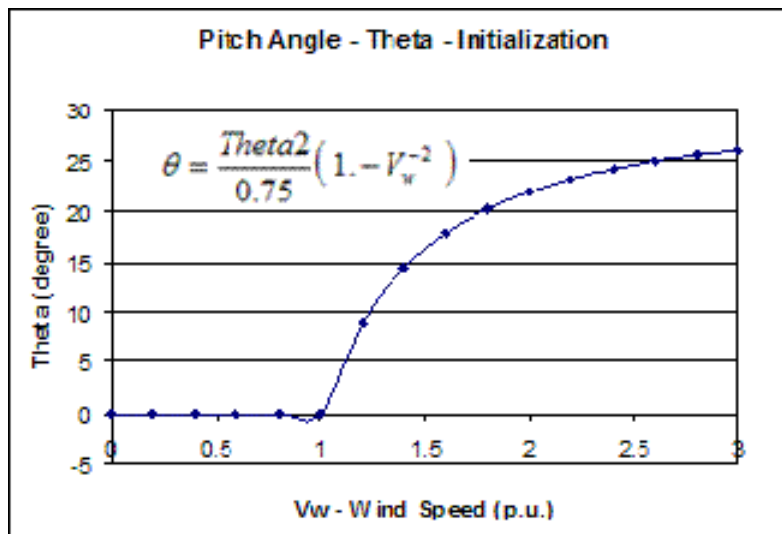

Figure 8. Pitch angle versus wind speed initialization

Example:

Example:

wt3t   5   "BUS5"   .575   "1 "   : #9 /"vw"   0.44 /

Where:

vw   Initial wind speed (vw) is used only if WTG is at rated power output and
            if vw is greater than rated wind speed (to compute the initial pitch angle).
            Otherwise, this value is ignored, the pitch angle is set to its optimum
            value (0 degree in most cases), and wind speed is initialized to give initial
            generator power output (specified in power flow data as Pgen).

Real power input setting:

The wind plant operation may have different output levels

- In the dynamic:

- If P_{gen} = 60 MW in load flow solution and MWCAP = 100 MW in the dynamic, it means
  that the wind speed is less than rated wind speed, the turbine speed set point will be
  initialized accordingly (~ 1.12 p.u.) and Vw should be set to Vw < 1.0p.u. , and the blade
  pitch is adjusted to its optimum (θ = 0 degree)

- If P_{gen} = 100 MW in load flow solution and MWCAP = 100 MW in the dynamic, it means
  that the wind speed is at or higher than rated wind speed the turbine speed set point
  will be initialized accordingly (1.2 p.u).   The pitch angle setting will be as follows (wt3t -
  module):

- If V_w = 1.5 p.u. the wind speed is higher than rated wind speed and the blade pitch must
  be adjusted at the initial condition.

- If V_w = 0.7 p.u. this information is ignored and the blade pitch is adjusted to its optimum
  (θ = 0 degree).

Pitch model (WT3P – module)

Example of WT3P: Pitch Control Model

wt3p   5   "BUS5"   .575   "1 " : #9   "pset"   1.0   /

Where:

- pset   Pset should normally be 1.0 unless it is controlled by a separate active power
  control model, e.g. to provide governing response. It must always be greater than or
  equal to the initial power output of the WTG.

- Potentially, this setting can be used to curtail the maximum output of the wind turbine, so that under normal situations the blade pitch is set to produce $P < P_{rated}$. Thus, for example, when pset =0.8, the output of the wind turbine is scaled back to generate 0.8 p.u. at rated wind speed by adjusting pitch angle.

- During a fault event, the pitch mechanism has some headroom to adjust its pitch angle to resume to the pre-fault condition.

5.0 Wind Power Plant Model Validation

The goal of this validation effort is to match the output of the dynamic model against actual measurements captured at the transmission station, where disturbance recordings can be obtained relatively easily. The disturbance used as an example in this report consists of a line-to-ground fault in the vicinity of the transmission station, which resulted in a voltage transient large enough to excite a significant dynamic response from the wind power plant, within the design response capability of the generic model (up to about 5 Hz). Data before the fault occurred is required to establish the pre-disturbance power flow conditions that are used to initialize the model.   The disturbance record should extend several seconds after the contingency, consistent with the time frame of interest of positive-sequence transient stability analysis.

5.1. Network and disturbance representation

It can be difficult to represent a power system network to properly simulate a remote fault. In addition, the nature of the fault in most cases is difficult to characterize. Fortunately, there is a simpler method that uses data captured at the point of interconnection to drive a dynamic simulation. During the dynamic simulation, the measured positive-sequence voltage and frequency boundary conditions can be imposed at the transmission station (specifically at the POI).   This technique is achieved with the aid of a modified classical generator model (GENCLS) capable of holding terminal voltage and frequency as specified in an input file. This "system generator" is connected at node A in Figure 9, and must be defined as the slack bus in the simulation. A direct comparison between the simulated and measured real and reactive power at the POI can provide some evidence of model performance. It should be kept in mind that some aspects of the model may not be exercised by the disturbance. Therefore, validation requires multiple tests across different system conditions and different wind power plants of the same type of generators.
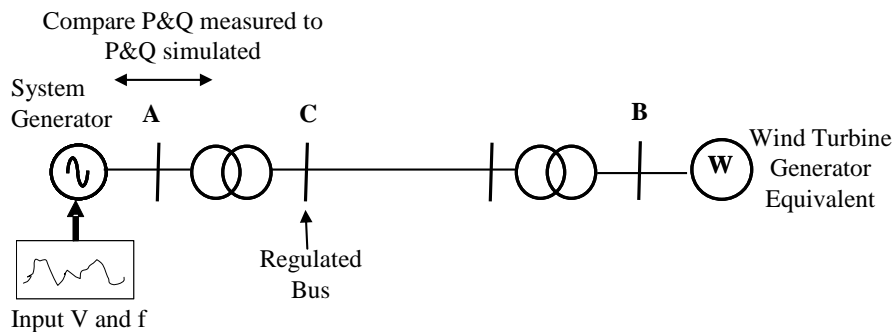

Figure 9. Simplified single-line diagram of the WPP network

5.2. Data for the Simulation

To perform the validation, it is important that we simulate the system to be as accurate as possible. The simulation should represent the actual WPP and the actual events we tried to simulate. There are several types of data required.

- Measured data (voltage, currents, and real/reactive power if any)
- Equivalent circuit of the network
- Dynamic data
- Sequence of events

5.3. Measured data

The data was measured at the high side of the substation transformer (node A in Figure 9). All the three-phase voltages and currents are measured at high sampling rates (about 5 kHz). The record is triggered by the transient events during faults at the transmission lines or in power system network surrounding the wind power plant. In general, the fault is removed from the power system network within 4 – 9 cycles, depending on the relay protection set-up. The data is recorded before the fault occurs, during the fault, and after the fault. It is important to note that the model should capture the entire sequence of events. A five-second record or longer is desirable to get a good representation of what actually happens.

In this section, an example of data preparation is presented. As pointed out earlier, disturbance data was measured at the POI. A window of observation is set up by using a data fault recorder that will capture the entire fault event (a few seconds before, during, and after the fault event). The data recorded are the three-phase voltage and currents at a sampling rate of 3486 Hz.
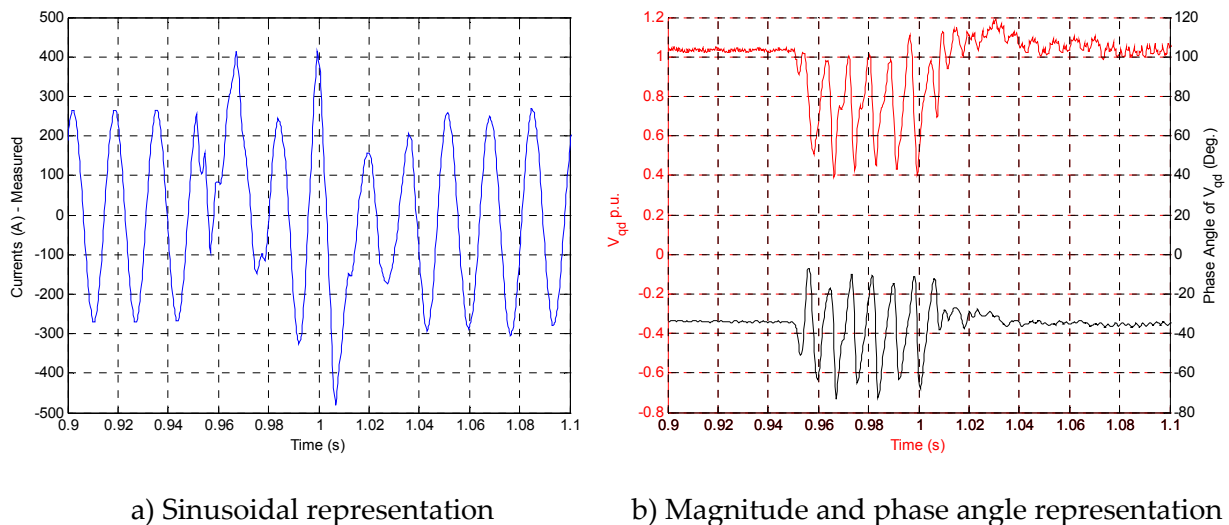

a) Sinusoidal representation   b) Magnitude and phase angle representation

Figure 10. Phase-voltage wave form during fault event

An example of the per-phase voltage waveform is shown in Figure 10a. The time series of the voltage presented in Figure 10a is shown in a "stationary reference frame." To integrate this information in a positive-sequence simulation, we need to have the positive-sequence magnitude of the voltage, frequency, as well as the real and reactive power magnitude as a function of time. Most station instrumentation software tools have the capability to make the conversion easily. However, the procedure is not difficult. First, we convert the voltages and currents from a, b, c representation into a d-q axis representation in a stationary reference frame. The equation used to perform this transformation is presented in equation [1].

[1]
$$\begin{bmatrix} f_{qs} \\ f_{ds} \\ f_{os} \end{bmatrix} = \begin{bmatrix} \dfrac{2}{3} & -\dfrac{1}{3} & -\dfrac{1}{3} \\ 0 & -\dfrac{1}{\sqrt{3}} & \dfrac{1}{\sqrt{3}} \\ \dfrac{1}{3} & \dfrac{1}{3} & \dfrac{1}{3} \end{bmatrix} \begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \end{bmatrix}$$

From a stationary reference frame, we convert these variables into its representation in synchronous reference frame by using equation [2].

[2]
$$\begin{bmatrix} f_{qe} \\ f_{de} \\ f_{oe} \end{bmatrix} = \begin{bmatrix} \cos(\omega_e t + \theta_o) & -\sin(\omega_e t + \theta_o) & 1 \\ \sin(\omega_e t + \theta_o) & \cos(\omega_e t + \theta_o) & 1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f_{qs} \\ f_{ds} \\ f_{os} \end{bmatrix}$$

$$V_{qde} = \sqrt{V_{qe}^{\,2} + V_{de}^{\,2}} \angle \theta_{qde}$$

[3]

$$\theta_{qde} = \operatorname{atan}^{-1}\left(\dfrac{V_{de}}{V_{qe}}\right)$$

The traces shown in Figure 10b are the voltage phasor quantities (magnitude and phase angle) obtained from the measured per-phase voltage and current waveform data recorded at node A in Figure 9.

In this case, the variable f can be substituted with v for voltage or i for current. The subscript s represents the stationary reference frame and the subscript e represents the synchronous reference frame. Under normal conditions, the quantities in the synchronous reference frame will show constant values in the d and q axis. Finally, we can convert the voltage or current into its phasor form as shown in equation (3). Thus, we convert the voltages and currents from a three-phase a, b, and c representation into its magnitude and phase angle (in phasor form) to follow the progression of the fault and to show how the voltage phasor changes during the fault. The methods described in this section can be found in more detail in reference [8].

The frequency change at each step can be derived from the phase angle changes in each time step by using equation 4:
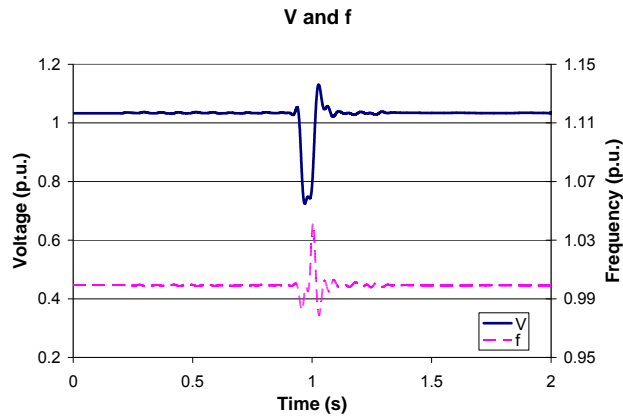
[4]
$$\Delta f(t) = \Delta \theta_{qde} / (2\pi\, \Delta t)$$

Instantaneous real and reactive power can be computed from the measured voltages and currents with the following equations:
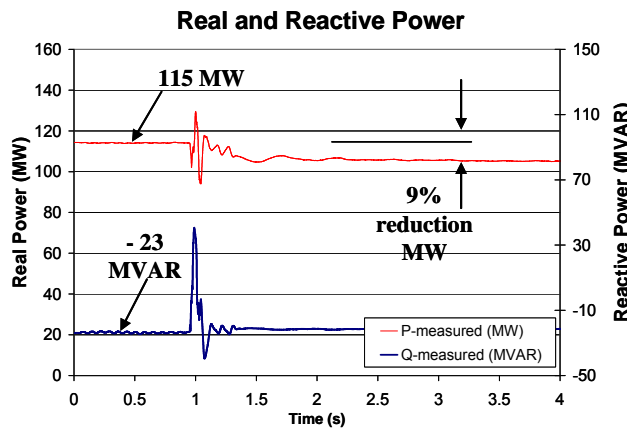
[5]
$$p = \frac{3}{2}\left(v_{qe}i_{qe} + v_{de}i_{de}\right)$$
$$q = \frac{3}{2}\left(v_{qe}i_{de} - v_{de}i_{qe}\right)$$

The lower case indicates that these quantities are instantaneous values.

a) Per unit voltage and frequency at the POI

b) Real and reactive power measured at the POI

Figure 11. Input (voltage and frequency) and output (real and reactive power) of the dynamic simulation

The traces presented in Figure 11a show the voltage phasor magnitude and frequency as time varies. Both the voltage magnitude and the frequency are passed through a low pass filter to remove the higher frequency component, and the resulting voltage and frequency are used as the input to the GENCLS model. Note, that during the fault, the voltage dips to 0.73 p.u.

Figure 11b shows the measured real and reactive power. It can be seen that, prior to the disturbance, the wind power plant was operating at an output level of 115 MW, about 56% of rated output (ignoring losses). It can also be seen that the WPP output goes down by approximately 9% after the disturbance. Since wind speed can be assumed to be constant over the time frame of this event (a few seconds), this reduction is an indication that some turbines tripped as a result of the fault. With respect to reactive power, it is noted that there is a significant response during the fault.

5.4. Equivalent circuit of the network

The power system network data can be obtained from the actual equipment installed (i.e., the substation transformer, the pad mounted transformer, and the underground and overhead wire). Usually, the collector system is a complex circuit interconnecting hundreds of turbines to the POI. Generally, the collector system schedule is provided using an Excel file consisting the resistance, capacitance, and inductance of the feeders within the WPP. A method of equivalencing should be used to find the equivalent of the WPP. This method can be found in reference [1] and will not be repeated here.

Although the method described here is generic in nature, a specific WPP will be used as an illustration. The reference WPP has a nameplate rating of 204 MW and consists of 136 1.5-MW DFIG WTGs. It is connected the transmission system operated by Public Service Company of New Mexico (PNM), at 345 kV. There are a total of eight 34.5-kV feeders, two of them are overhead and the rest are underground. The collector system station is adjacent to the transmission station. The WPP is equipped with a voltage regulator that controls voltage at the transmission station, relying on the reactive capability of the WTGs only. There is no additional reactive compensation within the WPP.

The single-machine equivalent representation of the reference WPP is shown in Figure 12. All impedances are in a 100-MVA base. The derivation of equivalent impedances is explained in more detail in [1]. The station transformer was modeled explicitly. Node A represents the transmission station or POI. Node B is the generator terminal. Note C represents the 34.5-kV collector system station.

It is important to understand that the impedance between the terminals of each WTG and the transmission station is different; therefore, the terminal behavior of each WTG during a major system disturbance would differ. During a major disturbance, it is possible for a portion of the WTGs to experience voltages beyond control or protection limits. It is not possible to capture

these differences with the single-machine equivalent representation. The equivalent WTG is meant to represent the aggregate terminal behavior of the "average" WTG in the WPP.
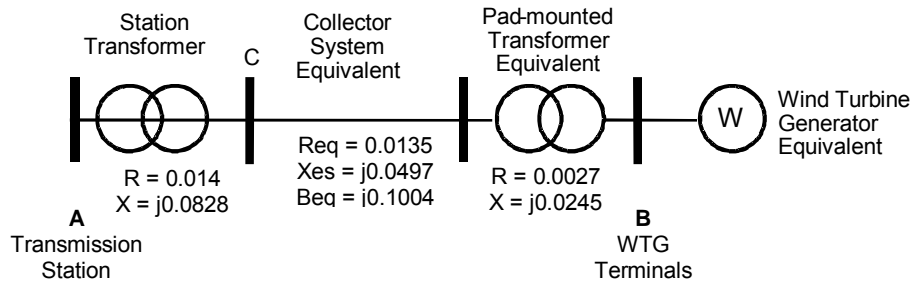

Figure 12. Single-machine equivalent representation for reference WPP

5.5. Dynamic data

In this case, we are interested in checking the performance of the WECC generic DFIG model [6]. This model has been implemented as standard library models in two positive-sequence simulation programs commonly used in the United States. A high-level block diagram of the model is shown in Figure 13. Since the goal is to illustrate the model validation process, the specific model structure and parameters are not of primary interest to report. Since the turbine used in this particular WPP is the GE 1.5 variable-speed wind turbine generator, the default model parameters corresponding to GE 1.5 wind turbine dynamic model were used. Additional information about the model can be found in [6] and [7].
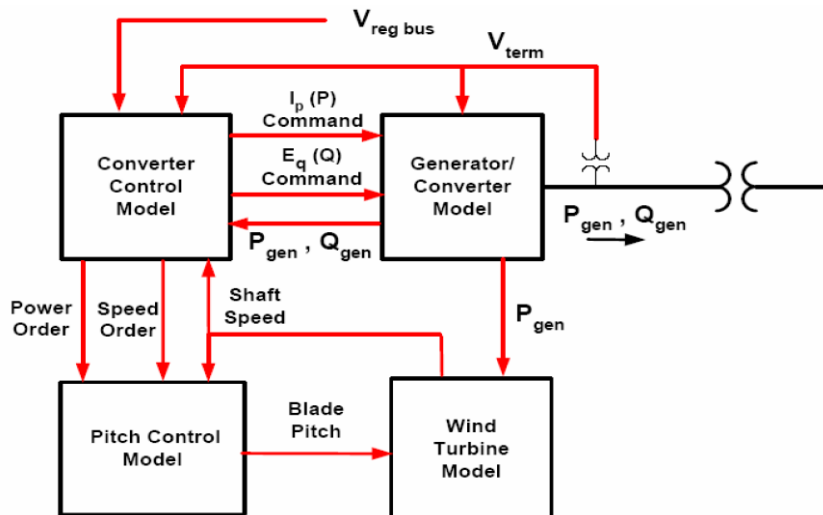

Figure 13. Block diagram of WECC generic DFIG model

5.6. Event representation

As was discussed in the previous section, the WPP may survive better than a conventional WPP during transient events. This is due to the fact that there are many turbines in a large WPP. The diversity within a WPP causes the terminal characteristics at each turbine to be significantly different from each other.   Previous investigation indicates that in most of the fault events, only a small percentage of the turbines were disconnected from the grid.

Consider the figure 11 showing the real and reactive power generated by a wind power plant. In the pre-fault condition, the WPP generates 115 MW of real power and it absorbs 23 MVAR of reactive power. While the reactive power does not change significantly during the fault, there is a noticeable reduction of the real power by approximately 9% due to the relay protections at the turbine that disconnect some of the turbines during the fault. This sequence of events must also be represented in validating the turbine model. The simplified equivalent circuit of the event representation is shown in Figure 14.
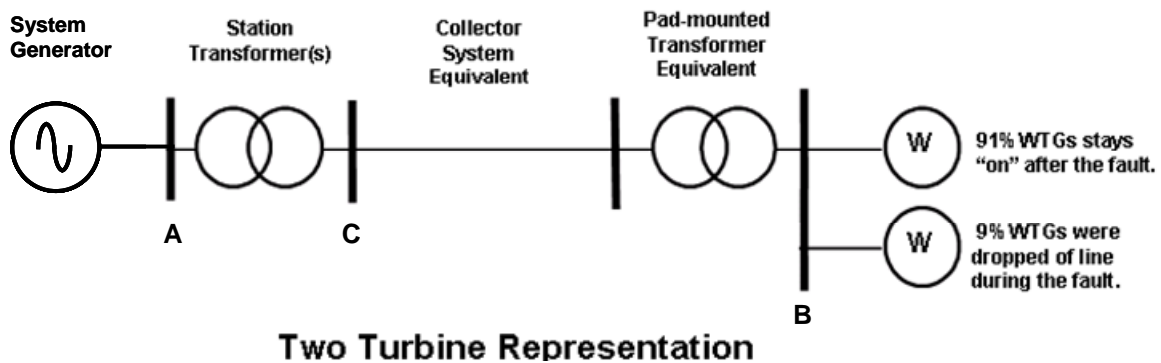

Figure 14. The WPP is represented by a two turbine representation

6.0   Simulation Results

To account for the portion of the WPP that may have tripped as a result of the disturbance, two generators at node B were used to represent the equivalent generator, as shown in Figure 14. This event representation allows for tripping of part of the WPP during the simulation.

In power flow, node A is the slack bus, and the scheduled voltage is set to the measured pre-fault voltage (i.e., 1.0325 p.u.). The output power of the equivalent generators was adjusted to match the total output power measured at the POI (i.e., 115 MW) as shown in the pre-fault event. The equivalent generators are set up to control voltage at node C. The scheduled voltage at node C is adjusted until the reactive flow matches the measured flow (i.e., -23 MVAR). Once the power flow is set up and initialized, the dynamic transient can be simulated.

6.1.   Dynamic Simulation

The reactive power control module of the WECC generic DFAG dynamic model (Figure 15) has the capability that allows for simulation of reactive control modes. As stated before, the WPP we are using as an example operates in voltage control mode; therefore, VARFLG is set to 1. Other control modes available are the power factor control mode and reactive power control mode. The vswitch VLTFLG is set to 1, indicating that the fast control loop to control the WTG terminal voltage is activated. The control block diagram can be shown in Figure 15.
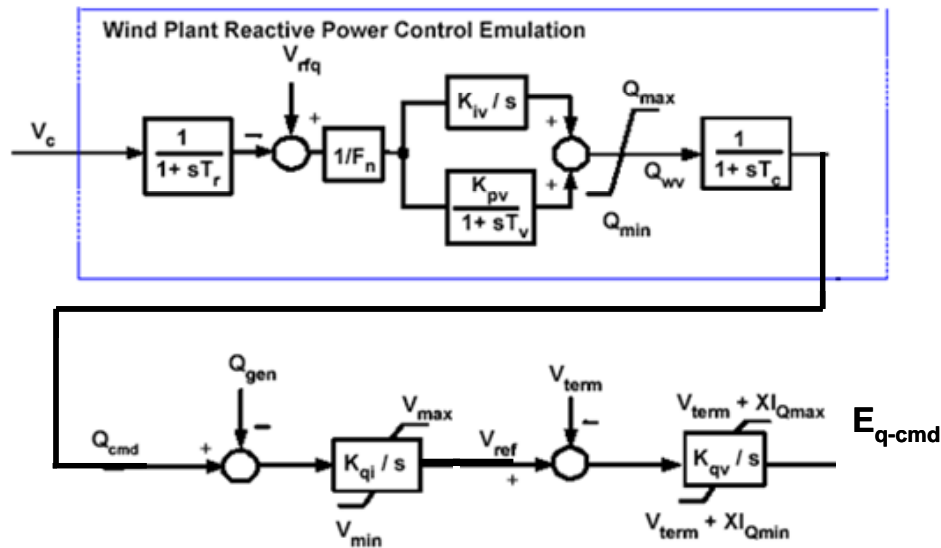

Figure 15. The control block diagram for the system being validated

Note that a WECC generic model is required for each of the equivalent wind power plant generators represented at node B. As explained before, a GENCLS model was used for the system generator, with instructions to hold the voltage and frequency in accordance with the disturbance measurements.

A 4-second dynamic simulation was conducted with the system setup explained above. The smaller equivalent generator was taken off line during the fault to simulate the observed tripping. The timing at which these turbines trip off line is not recorded, thus, the tripping timing was estimated to be at t = 0.99 seconds.

6.2. Comparison of simulation response and measurements

Figures 16 and 17 compare the simulated real and reactive power response to the measured real and reactive power response at the node A.

Overall, the simulation results follow the measured data closely, especially the reactive power. The simulated response does not reproduce the observed higher frequency perturbations during the fault; however, these details are of lesser importance in this type of simulation. The generic dynamic models are not designed to be accurate at that level of detail.

We also simulated the WPP in detail, with all 136 turbines and collector system branches. The diagram shown in Figure 18 shows the simplified diagram full system representation. The boundary conditions at the POI were the same as before. The purpose of this exercise was to see the diverse terminal characteristics due to collector system effects resulted in any significant differences with respect to the simplified system representation. The exercise also served to validate the collector system equivalent parameters. The results of that simulation are shown in figures 16 and 17. Note that there were no significant differences in this particular disturbance.
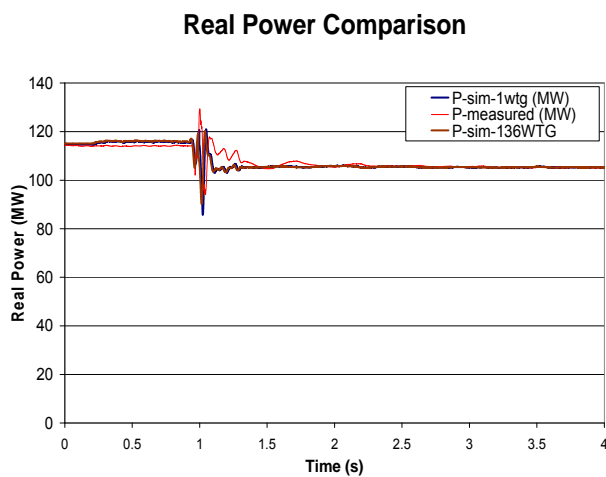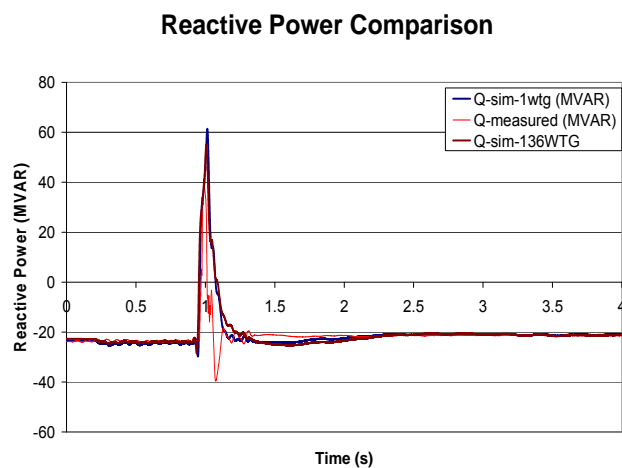
Real Power Comparison

Figure 16. Real Power Comparison

Reactive Power Comparison

Figure 17. Reactive Power Comparison
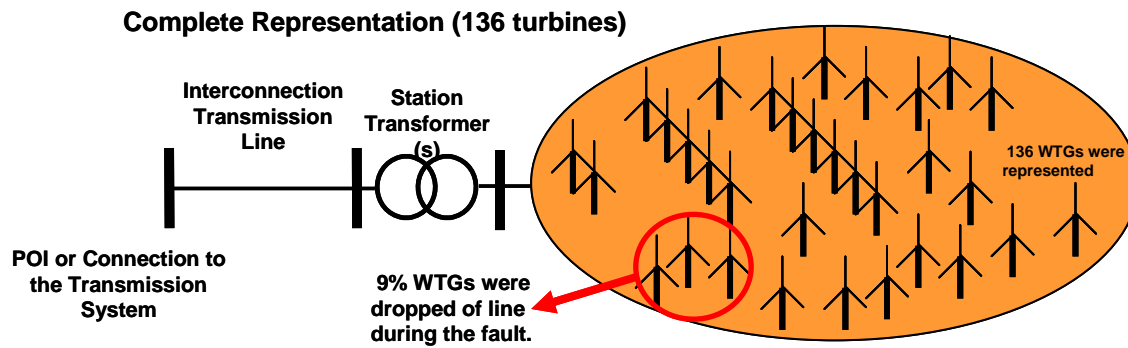
Complete Representation (136 turbines)

Figure 18. Simplified diagram of full system representation of the WPP

In a single turbine representation, individual turbine output and terminal characteristic is not apparent. Thus, the single turbine representation generated output and terminal characteristic of an "average" turbine within the WPP. For the full system representation, each individual turbine is represented and the output and terminal characteristics is accessible for plotting.

As shown in Figure 19, the terminal voltage at several turbines are plotted on the same graph with the voltage at the POI. The deepest voltage dip occurs at the terminal of turbine number 1, the closest to the POI. While turbine number 136 (farther away from the POI) has a shallow voltage dip. Thus, assuming the relay protection at each individual turbine is set to the same settings among 136 turbines in the WPP, the turbines disconnected from the grid during a fault will depend on the severity of the fault and the location of the turbine within the WPP.
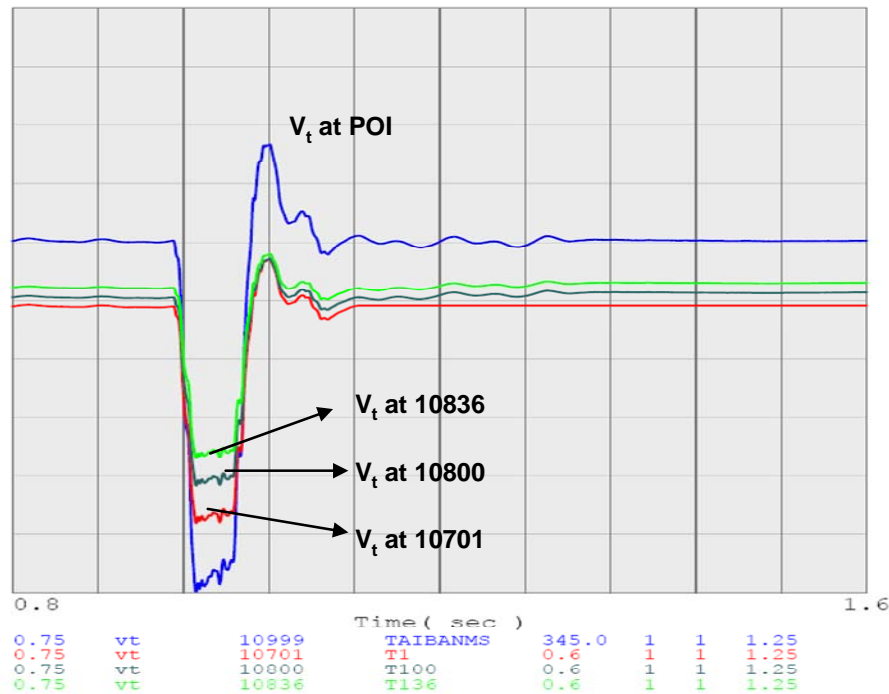

Figure 19. Terminal voltage of different WTGs and the voltage at the POI

7.0 Summary

This report presents the methods to validate positive-sequence wind dynamic models. This technique was applied to the WECC generic model as an example.

The validation method described in this report is applicable for all the four types of wind turbine generators.

The results of the simulations demonstrated that a generic model of DFIGs provides an adequate representation of the actual wind turbines under fault conditions.

In the report, the simulation is also performed with all 136 turbine connected on line. For both the full system representation and the two turbine representation, it shows that the output of real and reactive power at the point of interconnection matches the measured field data. Thus, modeling the WPP with an equivalent representation preserves the basic response of the WPP.

References

[1]   E. Muljadi, C.P. Butterfield, A. Ellis, J. Mechenbier, J. Hocheimer, R. Young, N. Miller, R. Delmerico, R. Zavadil, J.C. Smith, "Equivalencing the Collector System of a Large Wind Power Plant", presented at the IEEE Power Engineering Society, Annual Conference, Montreal, Quebec, June 12-16, 2006.

[2]   E. Muljadi, B. Parsons, "Comparing Single and Multiple Turbine Representations in a Wind Farm Simulation," presented at the European Wind Energy Conference (EWEC-2006), Athens, Greece, February 27 – March 2, 2006.

[3]   N. W. Miller, J. J. Sanchez-Gasca, W. W. Price, and R. W. Delmerico, "Dynamic modeling of GE 1.5 and 3.6 MW wind turbine-generators for stability simulations," in Proc. 2003 IEEE Power Engineering Society General Meeting, pp. 1977–1983, June 2003

[4]   J. O. G. Tande, E. Muljadi, O. Carlson, J. Pierik, A. Estanqueiro, P. Sørensen, M. O'Malley, A. Mullane, O. Anaya-Lara, and B. Lemstrom. Dynamic models of wind farms for power system studies–status by IEA Wind R&D Annex 21," European Wind Energy Conference & Exhibition (EWEC), London, U.K., Nov. 22–25, 2004.

[5]   T. Petru and T. Thiringer, "Modeling of wind turbines for power system studies," IEEE Transactions on Power Systems, Volume 17, Issue 4, Nov. 2002, pp. 1132 – 1139.

[6]   "Generic Type-3 Wind Turbine-Generator Model for Grid Studies", Version 1.1, prepared by WECC Wind Generator Modeling Group, September 14, 2006

[7]   "WECC Wind Power Plant Power Flow Modeling Guide", prepared by WECC Wind Generator Modeling Group, November 2007

[8]   P.C. Krause, Analysis of Electric Machinery, McGraw Hill Co. NY, 19862

Glossary

The following acronyms are used in this report:

CEC   California Energy Commission

CRPWM   Current Regulated Pulse Width Modulation

DFAG   Doubly Fed Asynchronous Generator

DFIG   Doubly Fed Induction Generator

DOE   Department of Energy

ERCOT   Electric Reliability Council of Texas

FERC   Federal Electric Regulatory Commission

FOC   Flux Oriented Controller

FPL   Florida Power and Light

FSR   Full System Representation

IEC   International Electrotechnical Commission

IEEE   Institute of Electrical and Electronic Engineers

LVRT   Low Voltage Ride Through

NMEC   New Mexico Energy Center

NDA   Non Disclosure Agreement

NEC   National Electrical Code

NERC   North American Electric Reliability Council

NREL   National Renewable Energy Laboratory

PFC   Power Factor Correction

PIER   Public Interest Energy Research

PNM   Public Service of New Mexico

POI   Point of Interconnection

PSLF   Positive Sequence Load Flow

PSSE   Power System Simulator for Engineers

RAS   Remedial Action Scheme

SVC Static VAr Compensator

TSR Tip Speed Radio

VAr Volt-Ampere Reactive

WECC Western Electricity Coordinating Council

WGMG Wind Generator Modeling Group

WTG Wind Turbine Generator

WF Wind Farm

WPP Wind Power Plant