FINAL PROJECT REPORT

WECC WIND GENERATOR DEVELOPMENT

Prepared for CIEE By:

National Renewable Energy Laboratory

Project Manager: Eduard Muljadi
Authors: Edward Muljadi, Abraham Ellis
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University of California

A CIEE Report

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- Renewable Energy Technologies
- Transportation

The draft final report for the Western Electricity Coordinating Council (WECC) Wind Generator Development project (contract number 500-02-004, work authorization number MR-065), is the summary of activities reported in separate interim reports:

WIND POWER PLANT EQUIVALENCING

WIND POWER PLANT DATA COLLECTION

MODEL VALIDATION OF WIND TURBINE GENERATOR

This project is sponsored by the WECC-WGMG, California Energy Commission (Energy Commission), and the National Renewable Energy Laboratory (NREL). The information from this project contributes to PIER's Energy Systems Integration Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

Table of Contents

List of Figures

Abstract and Keywords

Wind energy continues to be one of the fastest-growing power generation sectors. This trend is expected to continue globally as we attempt to meet a growing electrical energy demand in an environmentally responsible manner. As the number of wind power plants (WPPs) continues to grow and the level of penetration becomes high in some areas, there is an increased interest on the part of power system planners in methodologies and techniques that can be used to adequately represent WPPs in interconnected power system studies. This project is part of an overall industry effort to develop, validate and implement generic positive-sequence stability models for wind power plants (WPP). Although the models are designed specifically to meet Western Electricity Coordinating Council (WECC) modeling requirements, the results also benefit the industry as a whole. These goals represent challenges, some of which are described below:

- There are currently four major different types of wind generators, and all of them are fundamentally different from conventional generators. It is necessary to have different types of wind turbine generator (WTG) dynamic models to closely represent each of the four types.
- Wind turbine generators are a relatively new kind of technology where significant technical innovation is still occurring. Thus, planning models were not readily available until recently. From an engineering point of view, representing WPPs as negative loads or conventional generators is unacceptable. With the recent development and implementation of WECC generic models of WTGs, wind power plants can now be represented more properly.
- WPPs are topologically complex. Typical plants have hundreds of turbines spread over a very large area, interconnected by miles of radial feeder circuits, and finally connected to the utility grid at the point of interconnection (POI). In grid planning studies, it is impractical to represent this complex system explicitly. Although each WPP has unique characteristics (e.g. terminal voltage, wind condition, line impedance, etc), it is necessary to find a reasonable equivalent representation that reproduces the important plant behavior as seen from the POI.
- Validation of dynamic models is needed to verify that the models closely match the dynamic behavior of actual equipment. Field measurement can be used to validate WPP models. Since suitable field data is difficult to obtain, model verification by comparison to manufacturer-specific, higher-order (more detailed), and validated dynamic models can be used.
- Models have limited value unless they are well documented and made available to grid planners in the simulation platforms of their choice. For this reason, this project aimed at implementing the models in simulation platforms that are typically used for grid planning (GE PSLF and Siemens-PTI PSSE). In addition, dissemination of the project

results is accomplished via publications at the appropriate conferences, websites, workshops, seminars, and, short courses.

In this report, we summarize the project which covers dynamic model development of four types of wind turbine generators, data collection needed for model validation, power flow wind power plant equivalencing, model validation, and modeling guidelines developed for WECC.

The interim reports are included as appendices of this final report. The generic dynamic model of four types of wind turbine generator has been implemented on two major power system simulation platforms: Siemens-PTI PSSE and General Electric PSLF. The term "generic" is used to refer to the dynamic model that does not contain proprietary information protected by wind turbine manufacturers. These dynamic models of WTG are now part of the standard model library in PSSE and PSLF. The modeling guides are publicly available at the WECC website[1].

Keywords: Dynamic model, equivalencing, model validation, wind power plant, wind turbine, wind integration, and system integration.

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

Executive Summary

It is expected that large amounts of wind capacity will continue to 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 (WPPs) has also increased significantly. In the past, a typical WPP consisted of several turbines. Today, typical WPP nameplate capacity is 100MW to 200MW. Total capacity in a region or cluster can reach 1 GW 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 level of penetration of renewable energy generation in the WECC region, and California in particular, poses significant challenges concerning the ability of the power system to maintain reliable operation.

For many years, lack of open access to adequate models has resulted in much of the wind capacity being modeled as conventional induction machines or negative loads in regional planning studies. The increased use of this energy source necessitates a more accurate representation of installed wind capacity. Misrepresentation of a WPP in a dynamic model reduces confidence in the transmission planning process and can lead to erroneous conclusions. Manufacturer-specific, proprietary models are made available for interconnection studies; however, their use is also challenging in practice. The overall goal of the generic modeling effort is to address these challenges.

The Wind Generator Modeling Group (WGMG) has completed the first phase development and implementation of generic wind turbine models. Four generic models produced by this effort represent the types of turbines that currently hold the largest market share in the North American region. WECC is interested in ensuring that accurate and validated models of standard wind turbines are readily available for regional studies. This means that the models should be suitable for inclusion in the WECC standard dynamic model database. The availability of data sets for testing the models is critical to meet WECC's model validation requirements. WECC is also interested in guidelines discussing the methods of representing a WPP in power system studies. These goals are reflected in the functional guidelines of the WECC WGMG. 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 (i.e., generic, non-proprietary) dynamic models would enable planners, operators, and engineers to plan and operate the system taking into account the characteristics capabilities of modern wind turbines (e.g., dynamic, variable, reactive power compensation, dynamic generation shedding capability, and soft-synchronization with the grid). With the appropriate dynamic models available for wind turbines, planners could more accurately study transmission congestion or other major grid operating constraints, either from a real-time grid operations 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.

This has become increasingly important as the penetration amounts of wind energy systems have increased. The WECC-WGMG efforts also provides opportunities for researchers at universities and national laboratories to more easily access to wind turbine models and conduct research.

This report is the final report for the WECC Wind Generator Development Project, contract number #500-02-004, work authorization number MR-065, a project sponsored by the WECC-WGMG, California Energy Commission (Energy Commission), and National Renewable Energy Laboratory (NREL). This report summarizes the activities performed in this project as reported in the interim reports:

- Wind Power Plant Equivalencing
- Wind Power Plant Data Collection
- Model Validation of Wind Turbine Generator

Two WECC guides were published by WECC-WGMG:

- WECC Wind Power Plant Power Flow Modeling Guide
- WECC Wind Power Plant Dynamic Modeling Guide (currently posted for comment through the WECC Modeling and Validation Work Group)

The generic models of wind turbine generators (Type 1 – Type 4) have been developed and are now included in the standard model library of the PSSE and PSLF software platforms. The generic models are also being implemented in two other software platforms: Operation Technology ETAP, and Powertech Labs DSA Tools. Results from this project have been widely disseminated through presentations at workshops and short courses conducted at meetings and conferences sponsored by WECC, IEEE, Utility Wind Integration Group (UWIG), and universities. During the progress of this project, technical reports, and conference papers were also published at different conferences.

1.0 Introduction and Scope

This report summarizes the results accomplished at the time of project conclusion. Before WECC-WGMG embarked on working on dynamic models of wind turbine generators, availability of appropriate models for representation of WPPs were limited. For the most part, only manufacturer-specific user-written models were available on a limited basis (through non-disclosure agreements) for the purposes of conducting interconnection studies. These types of dynamic models are developed in full detail, including information deemed to be proprietary by the turbine manufacturers. Manufacturer-specific models sometimes are not fully integrated into the standard model library of simulation software, which leads to model maintenance and compatibility issues. Also, difficulties sometimes occur when we want to study an area with several WPPs from multiple manufacturers. Compatibility issues, limited access to models and long technical support iterations often results in long delays to complete the studies. After projects are completed, the proprietary nature of the models prevents their inclusion in the WECC standard dynamic database for the purposes of conducting regional studies.

With funding from WECC, CEC and DOE, and support from several organizations including DOE and Sandia, the WECC-WGMG completed the first phase of the effort to develop and implement wind turbine generator (WTG) dynamic models. The WECC dynamic models are intended to be generic in nature and non-proprietary, and thus are readily available for use. Generic models allow for unique characteristics of WTGs from different manufacturers to be represented by adjusting model parameters. These WECC dynamic models are currently available in the library of the PSLF (developed by GE) and PSSSE (developed by Siemens PTI). Default input data for each models is also provided. The generic models are also being implemented in two other software platforms: Operation Technology ETAP, and Powertech Labs DSA Tools.

This report is organized as follows:

- Section 1 – Introduction and Project Scope
- Section 2 – Background
    - This section provides background of different tasks considered in this project
- Section 3 – Description of Four different types of Wind Turbine Generator Technologies
- Section 4 – Wind Power Plant Equivalencing
    - This section describes the equivalencing method used to represent hundreds of turbine within the WPP as a reduced model for bulk system planning.
- Section 5 – Wind Power Plant Data
    - This section describes the data needed to simulate and validate WPP.
- Section 6 –Model Validation of Generic Models for Wind Turbine Generators
    - This section describes the method used to validate WPP
- Section 7 –Summary and Dissemination

    - This section describes the summary and dissemination to the public
- Section 8 –Future Plans
    - This section describes the plan to expand the modeling effort

2.0 Description of Wind Turbine Generator Technologies

Despite the seemingly large variety of utility-scale WTGs in the market, each can be classified in one of four basic types, based on the generator topology and grid interface. The distinctive topological characteristics of each type are shown in Figure 1 and are listed below:

- Type 1 – Fixed-speed, induction generator
- Type 2 – Variable slip, induction generators with variable rotor resistance
- Type 3 – Variable speed, doubly-fed asynchronous generators with rotor-side converter
- Type 4 – Variable speed generators with full converter interface

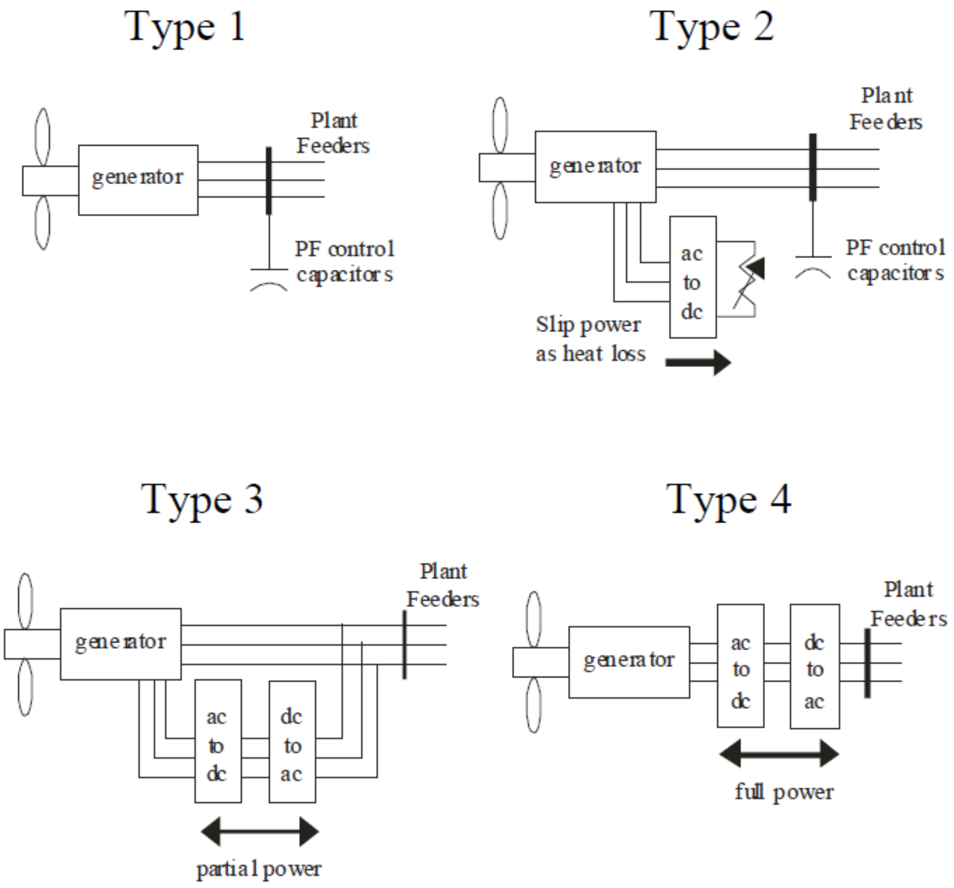


Figure 1 - Four different types of wind turbine generator

Type 1 – Fixed-speed, induction generator

The Type 1 WTG is an induction generator with minimal control. The torque speed characteristic is very steep (about 1% slip at rated torque). There is no power semiconductor switches used in this WTG in a normal running condition. The WTG absorbs reactive power both in generating or motoring mode. The reactive power required by the WTG is compensated by mechanically switched capacitor bank (MSC). With a slow varying wind speed, the MSC is able to follow the reactive power variation and the terminal voltage is very closely regulated. Under fast transients, the terminal voltage may be lagging in response and a wider voltage and output variation can be expected. Similarly, with sudden changes in frequency, the output power may respond instantaneously without any output current restrictions, thus, a frequency response similar to a synchronous generator can be expected.

Type 2 – Variable slip, induction generator with variable rotor resistance

The Type 2 WTG is a wound rotor induction generator with the capability to adjust the effective external rotor resistance. The effective value of the external rotor resistance is adjustable via a simple three-phase diode rectifier, DC chopper, and a parallel resistance. Thus effectively, the WTG can be controlled to deliver a constant rated power for wind speeds higher than rated by adjusting the total rotor resistance. Below rated wind speeds (low to medium wind speeds), the operation of Type 2 WTGs is very similar to the operation of Type 1 WTGs. In the high wind speed region, the WTG generates constant output power, output currents, and output power factor. Although the external rotor resistance is capable of maintaining constant output power at higher slips, the heat loss within the rotor resistance can be very high at higher slips. The pitch controller of the WTG is usually adjusted to keep the slip to be as close as possible to the rated slip when the WTG operates in high wind speed. The WTG of this type tends to react faster to sudden (transient) changes than WTG Type 1 because of its ability to maintain the output real and reactive power with the adjustable external rotor resistance and pitch controller. Thus, a sudden wind gust does not produce large power and reactive power surges, nor voltage drops like with Type 1 WTGs.

Type 3 – Variable speed, doubly-fed asynchronous generators with rotor-side converter

The Type 3 WTG is also known as doubly-fed induction generator (DFIG). Type 3 and Type 4 WTGs include a power converter to control the WTG. In a Type 3 WTG the rotor winding is connected to the power converter and the stator winding is connected to the grid. Under normal conditions or small transients, the power converter controls the output power of the generator, reactive power or bus voltage. It can control the real and reactive power independently and instantaneously. The power converter controls the stator output via electromagnetic coupling between stator and rotor separated by the air gap. Under severe disturbance (i.e., fault transients), the stator winding is exposed to abnormal and unbalanced voltage due to the faults that occur in the transmission lines. As a result, the power converter may lose its ability to control the output of real and reactive power, and it may have to apply the crowbar mechanism to protect the DC bus from an over voltage condition. The crowbar in effect is shorting the rotor winding, thus, making the rotor winding appear like a squirrel-cage induction generator. The temporary imbalance between the aerodynamic power and the electrical output power may accelerate the rotor speed. To limit the rotor speed, the pitch controller adjusts the pitch angle of the blades to avoid an over speed condition.

Type 4 – Variable speed generators with full converter interface

For the Type 4 WTG, the power converter acts as a buffer between the grid and the electric generator, thus, any transients occurring in the grid are not translated to the electric generator. Under normal or fault transients, the power converter can be fully controlled. However, one should realize that the power converter has a current limit to protect the output current of the power semiconductors (e.g. IGBT and diodes), and when the grid voltage is low during a fault transient disturbance, the maximum output power that can be delivered to the grid is also limited. Thus, the pitch controller will limit the rotor speed from over-speeding avoiding a run-away situation.

3.0 Wind Power Plant and Power Flow Equivalencing

A typical modern WPP, as shown in Figure 2, consists of hundreds of turbines of the same types. A WTG is usually rated at low three phase voltage output (480 – 600 V). A pad mounted transformer at each turbine generator steps up the voltage to the medium voltage collector system (12 kV – 34.5 kV). Several turbines that are physically close together are connected to laterally to form a group. Several of these groups are connected to a larger main feeder. Several of these feeders are connected to the substation where the substation transformer steps up the voltage to a desired transmission level (e.g., 230 kV). A very large WPP can have several substation transformers. An example of a WPP layout can be seen in Figure 1.

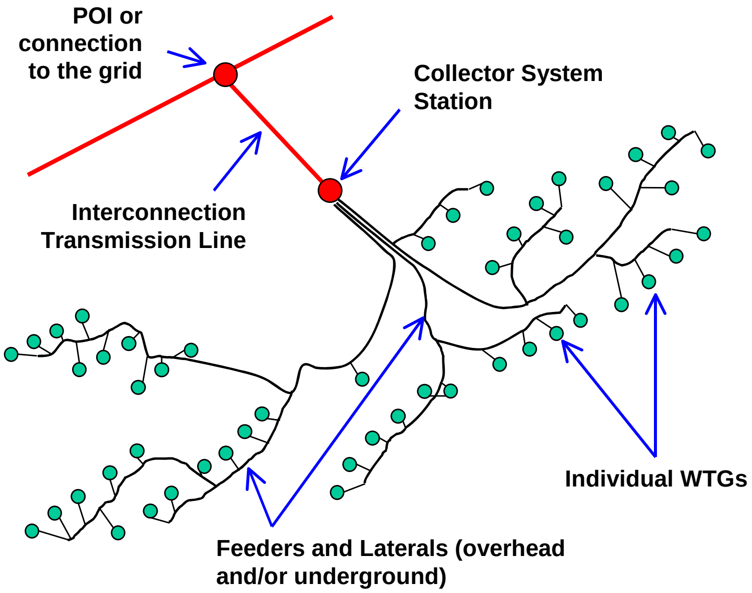


Figure 2 - Physical diagram of a typical WPP

Within a WPP, different turbines may operate under appreciably different conditions. Line impedance connecting each wind turbine to the POI differs from each other. At a particular instant in time, the wind speed experienced by one turbine can be significantly different from another turbine located at another part of the WPP. The diversity of a WPP is a good attribute in many ways. For example, the output variability of the entire WPP is attenuated with respect to the variability observed on a single wind turbine. The interaction between a WPP and the grid is determined by the collective behavior of the WPP. In contrast, a conventional power plant interacts with the grid as a single large generator.

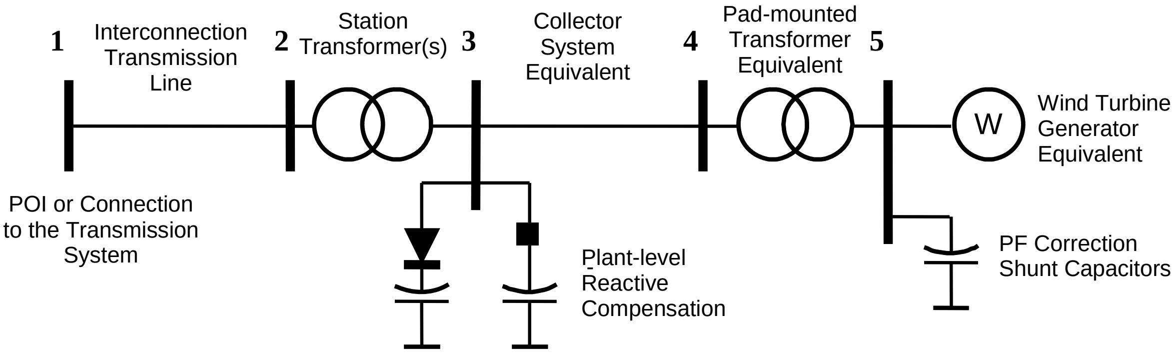


Figure 3 - Single turbine representation for a WPP

WPP equivalencing describes methods of equivalencing collector system in a large WPP. We simplified a WPP with many wind turbines into a simplified turbine representation, as shown in Figure 3.

The full system representation (FSR) is a representation of WPP where every turbine is represented along with the interconnecting collector system connecting each turbine with another, and connecting group of turbines to the POI.

A single turbine representation (STR) is a representation of WPP where a single turbine is used to represent the entire WPP. This representation is more practical for bulk system simulations. A later section of the report will provide technical justification for the use of the STR in power flow and dynamic stability simulations. For various reasons, some WPPs may contain different types of wind turbines. Sometimes, a single WPP could have clusters that are very different from the electrical connection point of view. For example, a portion of the plant may be connected through a long overhead feeder, while another portion of the plant may be connected through short underground feeders. This diversity of WPPs, if deemed significant, can also be represented with a model similar to the STR by defining distinct WTG groups, each of which can be modeled as an STR. Several methods of grouping considerations are also possible, resulting in a multiple turbine representation (MTR) that can more accurately represent the unique characteristics of a significantly diverse WPP. The interim report presented in Appendix III describes methods used to represent WPPs by equivalence in a more lengthy and detailed description.

4.0 Wind Power Plant Data

The data required can be divided into two parts; the steady state data needed to solve the power flow portion of dynamic simulation, and the dynamic data needed to solve the electro-mechanical interaction between the grid and the WTGs. A more detailed discussion about wind plant data required to simulate WPP and to validate a WTG dynamic model can be found in Appendix IV.

The steady-state data is mostly power system network data from the WPP and its reactive power capability. This includes power factor correction capacitors at the WTG terminals or reactive power support equipment (e.g., capacitors, STARCOM or similar) located elsewhere in the WPP. Since a WPP consists of hundreds of turbines, the collector system is simplified by equivalencing the WPP into a simple representation (e.g., single turbine representation).

The dynamic data consists of the generic model parameters for the specific WTG being represented and plant level reactive controls.

- The wind turbine model requires the use of several modules corresponding to the turbine type used in the simulation. Some of the model parameters may need to be adjusted to match the characteristics of each turbine manufacturer.
- Special flags and several parameter values of the WTG modules need to be set to reflect how the WTGs participate in the voltage/reactive power control strategy for the plant. Some of the generic models require wind speed condition as an input to initialize the pitch angle.
- Other dynamic elements including reactive power support equipment are modeled explicitly, using conventional models.

The power system network normally operates within a narrow voltage and frequency envelope. In a normal situation, the voltage and frequency at the buses are at or very close to rated values (voltage = 1.0 per unit, and frequency = 1.0 per unit). Equipment (i.e., loads) connected to the grid is designed to operate near rated frequency and voltage levels, with some tolerance to allow for temporary excursions. The allowable voltage and frequency deviation is limited in magnitude (range) and duration. Generally and under normal conditions, steady-state voltage is allowed to vary in a very limited range (max. 5% under normal conditions and 10% under transient conditions). Steady-state frequency variation follows even more strict limits. During transient events caused by faults or equipment switching, voltage and frequency can deviate more significantly. The characteristics of the system, including the network, generators and load, determine whether the system is stable during steady-state and transient conditions. Steady-state and dynamic analysis are performed to measure the margin of stability and power system performance under transient events.

The WECC-WGMG recommends the use of the single-machine equivalent model shown in Figure 3 to represent WPPs in WECC base cases. This representation is recommended for transient stability simulations and power flow studies. In Figure 4, the dashed line circumscribes the power system elements that may require dynamic models. The solid line circumscribes the power system network of a WPP representation.

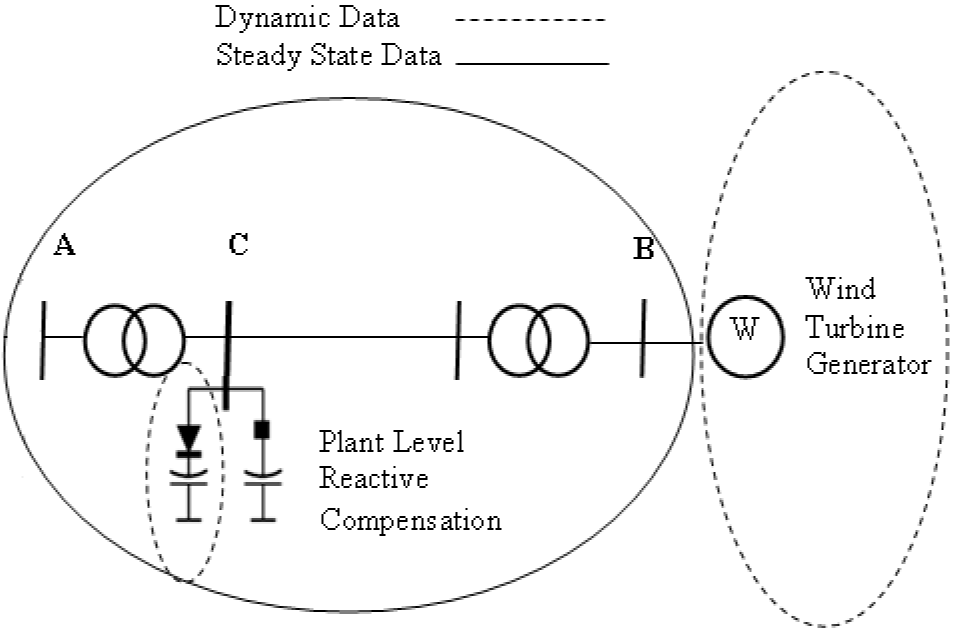


Figure 4 – Steady state and dynamic data groupings.

4.1 Data for steady-state representation

The term steady state analysis in this section refers to the power flow or load flow analysis commonly performed in power system studies. The data represents the equivalent circuit of the network to be analyzed, different types of buses i.e., a generator bus or P-V bus, load bus or P-Q bus, and infinite bus or swing bus.

Power Flow Network Data

Before proceeding with model validation, it is necessary to model the WPP network, and adjust reactive power control strategy to reflect what is implemented in the field and match data recordings. As an example, the WPP equivalent circuit for the New Mexico Energy Center (NMEC) WPP is shown in Figure 5. This equivalent is a single turbine representation. The WPP consists of 136 turbines with a total capacity of 204 MW. Each wind turbine is rated at 1.5 MW. The wind turbine used is a variable-speed wind turbine (doubly-fed induction generator). Most of the collector systems are underground cables. The method of equivalencing described previously was used to find the equivalent impedances of the collector systems, the pad-mounted transformer, and the station transformer. The system base used is 100 MVA.

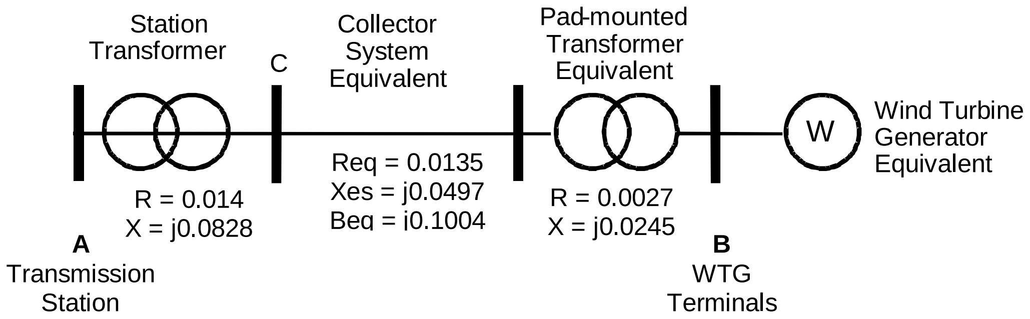


Figure 5 - Single-machine equivalent impedance of NMEC-WPP

Since the WPP is controlled to keep the voltage at the POI and the voltage at the generator terminal constant, the dynamic model was set to VARFLG = VLTFLG = 1. The regulated voltage (bus C) setting was not recorded. We can use the reactive power output at the POI bus A to determine the setting of the regulated bus voltage. After trial and error, we adjust the regulated voltage at bus C so that the output reactive power at bus A is 23 MVAR.

4.2 Data for dynamic analysis

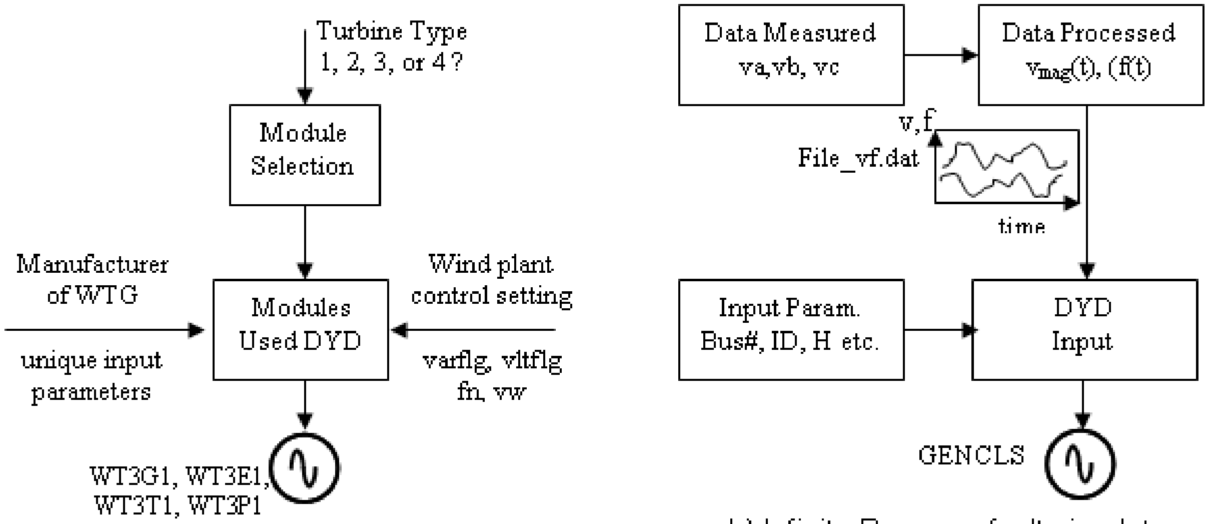
Power system stability is defined as the ability of the system to reach equilibrium after a disturbance with most system variables bounded so that practically the entire system remains intact. Power system stability has been an area of interest since the initial development of interconnected power systems, particularly following the advent of long-distance transmission. The importance of the subject cannot be overstated. Loss of stability can result in severe economic, technical, and social upsets.

To study power system stability, dynamic analysis is usually performed for the system under investigation. In general, the dynamic data required is the input data for the WTG. The dynamic data is usually contained in an input file with extension .dyd. The input file will have the description of the wind turbine dynamic modules with the appropriate input data for the corresponding wind turbine to be simulated.

The process of creating a dynamic file for a WTG

The process of creating a dynamic file (.dyd or .dyr) for a WPP is illustrated in the flow chart shown in Figure 6. It consists of several steps:

1) Choose the type of wind turbine that matches the plant whose model is being validated
2) Select the corresponding generic model and input parameters related to the turbines chosen.
3) Select an appropriate model for plant-level control reactive power equipment in the plant.
4) In many cases, reactive power controllability is provided by the WTGs through a plant-level controller (for WTG Type 3 and Type 4). The generic models for Type 3 and Type



a) Wind Turbine Generator

b) Infinite Bus as a fault simulator represented by GENCLS

Figure 6 - Dynamic model input preparation

a) WTG

b) ideal generator/ infinite bus (fault simulator)

4 WTGs have emulators for plant-level controls options that allows for several control options.

a) Select voltage control or power factor control or reactive power control, according to what is implemented in the project.

b) If there is voltage control capability (terminal voltage and remote bus), specify the remote bus that is controlled.

4.3 Data for WTG Model Validation

Infinite bus representation

For the purpose of validation, the network is represented as an ideal generator connected to the POI through an equivalent impedance. We are using a facility in PSLF whereby a classic generator model (GENCLS specifically) can be used to inject a measured voltage and frequency traces as a way to simulate a transient event and compare the model response (specifically, real and reactive power) to field measurements. This technique has limitations, including unbalanced situations, lack of complete knowledge of network conditions, and the fact that we are using a STR instead of MTR or FSR. Referring to Figure 6b, the ideal generator is represented by a generator classic GENCLS. This module allows the voltage and frequency profiles to be specified. The input data to this module is an input file containing three columns. The first one is the time indicator. The second column is the time series of voltage, and the third column is the time series of the frequency.

Field Measurement for Dynamic Data for Model Validation

Field-data measurement can be used to verify or validate a dynamic model. The field data is a set of data measured at the POI. The data can be recorded at high sampling rates and the recording is triggered by a transient event and used to record the event from pre-fault to post-fault. Ideally, 10 to 20 seconds post-disturbance data at sufficient resolution (20 samples per second or higher if the data is RMS; 7200 samples per second or higher if the data is point-on-wave) is needed for model validation exercise. Typical fault recorders only capture 2 – 4 seconds of per-phase voltage and current data, which is marginally useful for model validation. The model validation example below uses an actual 4-seecond fault recording for the New Mexico WPP described above. The location of data monitoring equipment is usually at the substation POI. The data measured is used to drive the simulation, and the response of the wind plant model simulated is compared to the actual measured data.

The per phase voltage waveforms

It can be seen in Figure 7 that the three-phase voltage currents v_{an}, v_{bn} , and v_{cn} recorded are symmetrically balanced voltages in the pre-fault condition. The fault occurs in the transmission lines in the vicinity of the WPP. It can be seen that the three-phase voltage becomes an unbalanced voltage with phase B dropping significantly for a period of four cycles, before the fault is cleared. The post-fault condition shows that the three-phase voltages recover to normal again and a small oscillation is shown on the three-phase waveforms.

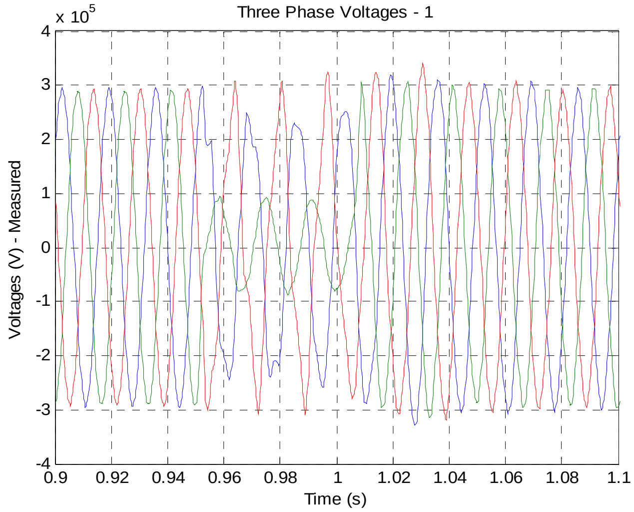


Figure 7 - The per-phase-voltages v_{an}, v_{bn} , and v_{cn} as recorded

Processing Data for PSLF Simulation – Model Validation Exercise

The generic dynamic model to be validated is available in PSSE and PSLF programs. To use PSLF program, we need to get the input data to drive the simulator. The input data will be the captured voltage waveform at the POI representing the fault and the outside power system network. As described earlier, the model validation strategy is to use the gencls PSLF model, which can take positive-sequence voltage magnitude and frequency as a function of time to impose as boundary conditions in the simulation. Thus, conversion from the sinusoidal voltage waveform into the positive-sequence voltage magnitude and frequency needs to take place.

The process of converting monitored voltage data into input data is illustrated in Figure 8. More detail information can be found in Appendix II.

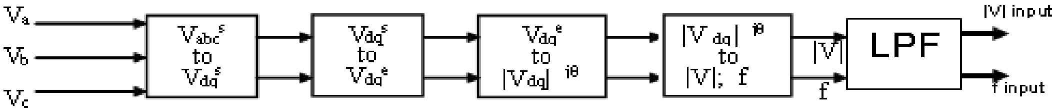


Figure 8 - Block diagrams indicating the flow process to convert the monitored voltage into the input data for GENCLS module

Then the dq axis quantities in stationary reference frame are converted into a synchronous reference frame. To use the dq voltage for the input to the program, we convert the voltage in the synchronous reference-frame phasor quantities using the following equation:

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

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

Since the module simulating the voltage source GENCLS uses the voltage magnitude and its frequency, we need to convert the phase angle information to the corresponding frequency changes. The frequency changes can be computed from the phase angle changes divided by the time step.

$\Delta f\ (t) = \Delta\theta_{qde} / \ (2\pi\ \Delta t)$

Positive-sequence simulation models are not designed to accurately reproduce response to high frequency components of the transient event (typical integration time step is approximately 4 milliseconds). For this reason, it is prudent to filter out these high-frequency components in voltage, frequency and power should be filtered appropriately. Finally, the input data (voltage and frequency) are ready to be used in module GENCLS as shown in Figure 9. An example of an input file containing voltage and frequency for the GENCLS is given in Appendix 2.

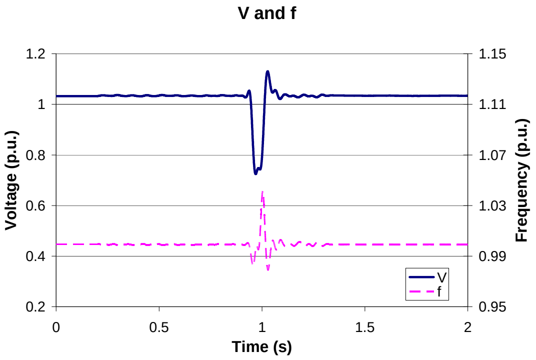
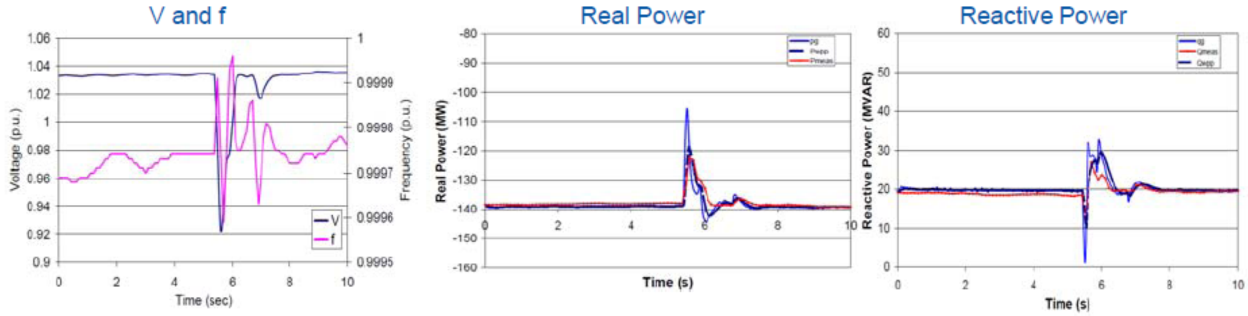


Figure 9 - Input data to GENCLS to perform the dynamic simulation

5.0 Model Validation of Wind Turbine Generator

WTG needs to be validated to ensure that the behavior of the dynamic model reflects the behavior of the actual WTG. The wind turbine manufacturer usually develops a detailed model of their turbine. This model contains detailed information considered proprietary by the turbine manufacturer. The detailed model or manufacturer's specific dynamic model is not released to the public, thus, the WECC generic models developed in this project are the closest models to the detailed model without revealing the proprietary information embedded in the detailed model. The detail model is usually validated rigorously by the turbine manufacturer against laboratory measurement within a controlled environment, and it is considered the best representation of the wind turbine. Ideally, the WECC generic dynamic models should be validated by turbine manufacturers against field measurements. In addition, it is not always easy to get field data measurement from the WPP operator or owner. Thus, as an alternative to using field measurement, you can compare the simulation of generic dynamic models to the detailed models. A more detailed discussion on WTG Model Validation is presented in the Appendix V of this report.

Example of Type 2 WTG Validation



Example of Type 3 WTG Validation

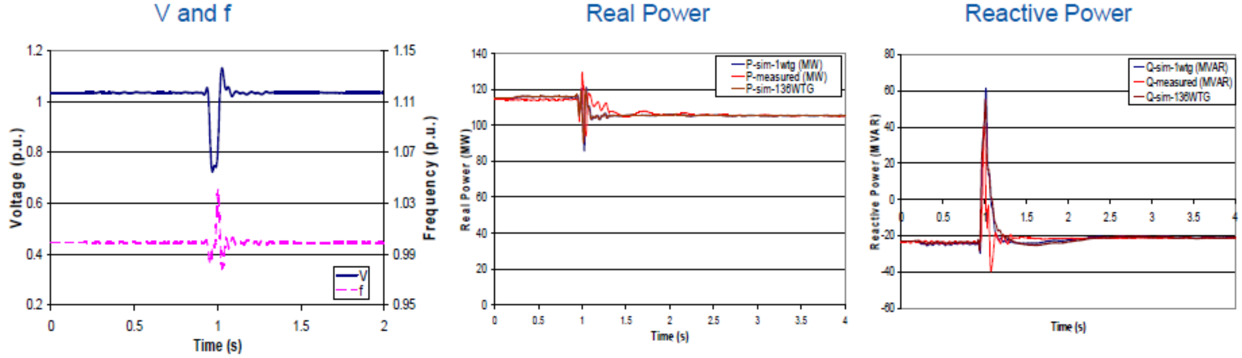


Figure 10 - Comparison between the generic model and the measured data for a Type 2 and Type 3 WTG.

5.1 Validation against the field measurements

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 WPP, 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.

An example of validation using measured data is presented in Figure 10. The validation requires measured data to be preprocessed. The measured three phase voltage recorded at high speed is preprocessed to get the voltage magnitude and the frequency variation during the fault. The voltage and frequency waveform are used to drive the simulation. The real and reactive power outputs from the simulations are compared to the measured real and reactive power.

5.2 Validation against the detailed (manufacturer specific) models

In this subsection, the validation of generic dynamic models against the detailed models will be presented. The generic dynamic models and the detailed models are simulated on the same power system network, the same size of WPP, and using a prescribed fault event. The simulation results from the two different dynamic models are then compared, and the difference is used to tune the parameters of the generic models until the two dynamic models generates the same output characteristics.

The dynamic models developed in this project are validated against the detailed dynamic models by the model developers (Siemens Power Technologies International, and General Electric). The model developers have signed a non-disclosure agreement with the turbine manufacturers to develop the detailed dynamic models. In Figure 11, a Type 1 WTG (induction generator) from a specific turbine manufacturer is simulated. The output of the generic model is compared to the output simulation of the Type 1 WTG detailed model.

The dashed line is the output simulation of the detailed model, and the solid line is the output simulation of the generic model. It is shown that the terminal voltage VTERM, the real power output PELEC, the reactive power QELEC and the rotor speed SPEED are all in agreement between the generic model and the detailed model.

In Figure 12, the generic model of a Type 4 WTG is simulated and the simulation output is compared against the detailed model of a Type 4 WTG when it is subjected to the same fault event using the same power system network. The solid line represents the generic model and the dashed line represents the detailed model. The real power PELEC and reactive power QELEC traces are shown and the signals are almost identical. Note, that the Type 4 WTG is modeled based on full power conversion that excludes the modeling of the mechanical dynamic of the wind turbine.

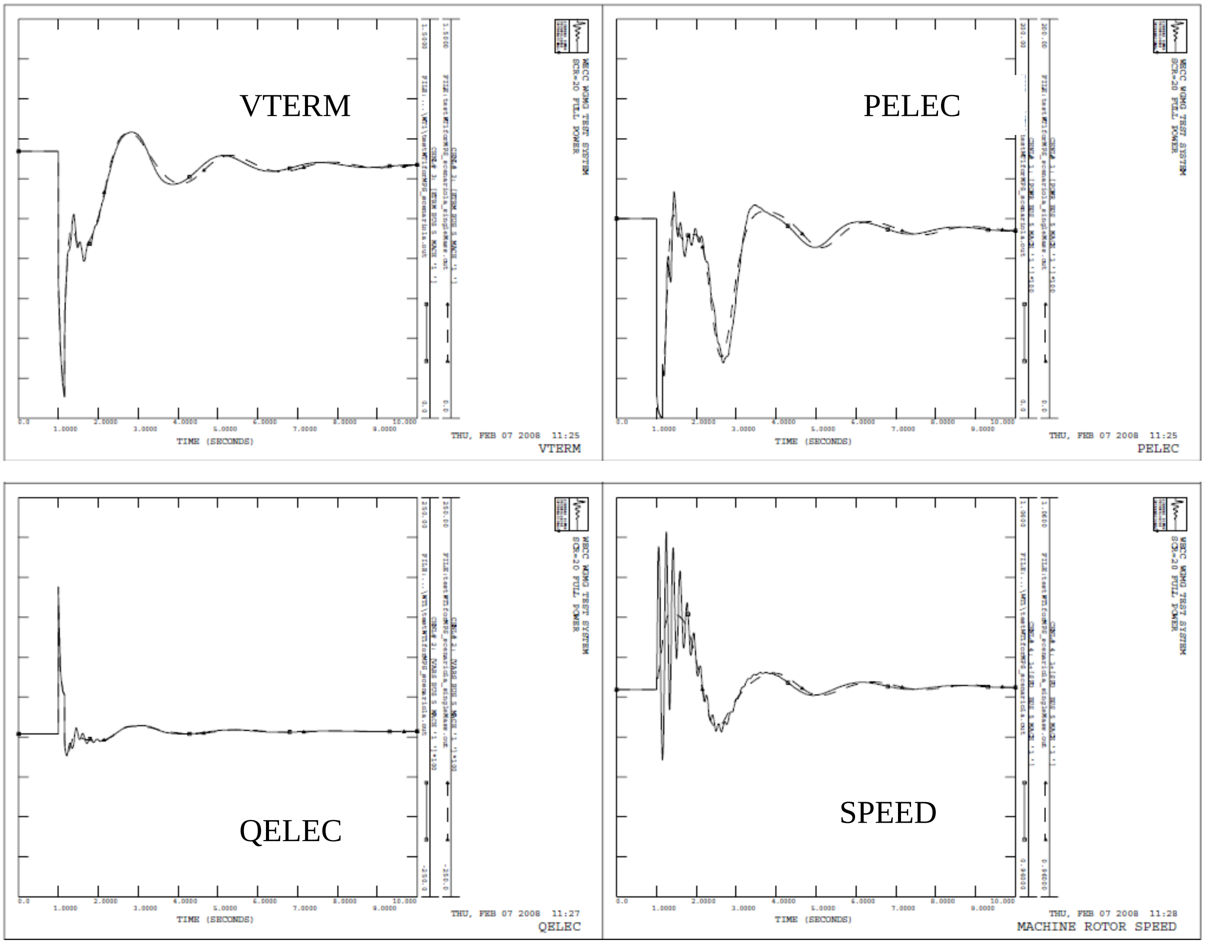


Figure 11 - Comparison between the generic model and the detailed model for a Type 1 WTG.

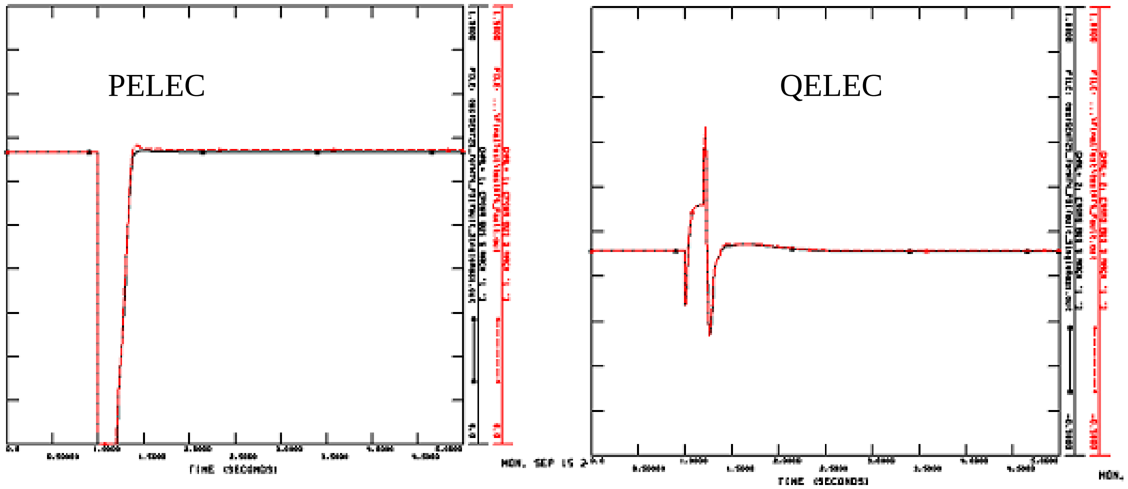


Figure 12 - Comparison between the generic model and the detailed model for a Type 4 WTG.

6.0 Summary and Dissemination

This project concluded with major accomplishments, including the completion of dynamic models of four types of wind turbine generators on two major power system software platforms (PSLF and PSSE), model validation of the four types of WTG dynamic models, and the WECC modeling guides.

The result of this project is disseminated in many different ways. Currently, the Generic WTG dynamic models (Type 1 – Type 4) developed by Siemens PTI and General Electric are presently included in the software library of the PSSE and PSLF. In the past many power system planners did not have any option to model WPP other than representing the WPP as negative loads or a simple induction generator. The availability of the dynamic models of four types of WTG gives the power system planners better options to represent the WPP correctly.

The WECC Power Flow Guide (2009) and WECC Dynamic Modeling Guide (to be completed in 2010) is accessible via the WECC website. This guide was developed by the Wind Generator Modeling Group (WGMG) of the WECC. The Power Flow Guide is currently available from the WECC website. The Dynamic Modeling Guide is currently being reviewed by the WGMG – WECC and it will be made available from the WECC website.

Workshops/short-courses/seminars on WTG dynamic modeling were presented at various events sponsored by the IEEE, WECC, UWIG, IEC, and various universities.

Technical papers given at the IEEE, Wind Power, and other conferences on related topics: WPP equivalencing, fault analysis of a wind plant, WTG dynamic model validation methodology, power system stability, and short circuit behavior of WPP.

The list of technical papers and publications related to this project is listed in Appendix I. The list of workshops, and short courses is given in Appendix II. An interim report describing the equivalencing is included in Appendix III, an interim report describing the data collection is given in the Appendix IV, and the interim report on dynamic model validation is given in the Appendix V. Copies of WECC guides are given in the Appendices VI and VII.

7.0 Future Plan

The topic of dynamic modeling of WPP needs to be expanded. This continuation is necessary because of the wind technology is changing rapidly − it requires continues model adaptation to reflect the latest turbine implementation. Parameter sensitivities, identification, and tuning of WTG dynamic models for different manufacturers are needed to help manufacturer derived parameters for generic dynamic models representing their turbines.

In the next phase, it is also necessary to revise/improve dynamic models to include droop, ramp-limit, reserve management, preprogrammed frequency/inertial response, relay protection. These capabilities will soon be implemented by turbine manufacturers and the existing models may have to be upgraded to reflect new capabilities. Some of new turbine concepts may be designed and installed in the near future. The new turbine concept should also be represented especially if their presence in the power grid and the size are significant.

In order to facilitate the adaptation of generic models by other software vendors, we need to support other software vendors (e.g., Powertech Lab, Inc., Operation Technology, Inc.) to implement WTG dynamic models on their platforms.

The availability and use of future PMU data collected by different agencies (WECC, BPA, ERCOT etc) will be accessed to validate dynamic models, predict WPP stability, design possible new WPP controls and protection.

Finally, we need to interact with the IEEE, the IEC, WECC, and UWIG for standard/guide development and public dissemination.

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.

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[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

Appendix I - List of Publications

1. R. Piwko, E. Camm, A. Ellis, E. Muljadi, R. Zavadil, R. Walling, M. O'Malley, G. Irwin, and, S. Saylors, "A Whirl of Activity", the IEEE Power and Energy Magazine, November/December 2009
2. D. Burnham, S. Santoso, E. Muljadi, "Variable Rotor Resistance Control of Wind Turbine Generators," presented at the IEEE Power Engineering Society, General Meeting, Calgary, Alberta, Canada, July 26-30, 2009.
3. M. Singh, K. Faria, S. Santoso, E. Muljadi "Validation and Analysis of Wind Power Plant Models using Short-Circuit Field Measurement Data," presented at the IEEE Power Engineering Society, General Meeting, Calgary, Alberta, Canada, July 26-30, 2009.
4. E. Muljadi, T. Nguyen, M.A. Pai, "Transient Stability of the Grid with a Wind Power Plant," to be presented at the IEEE Power System Conference and Exposition, Seattle, WA, Mar. 15-18, 2009.
5. E. Muljadi, T. Nguyen, M.A. Pai, "Impact of Wind Power Plants on Voltage and Transient Stability of Power Systems," presented at the IEEE Energy2030 conference, Atlanta, Georgia, Nov. 17-18, 2008.
6. A. Ellis, E. Muljadi, "Wind Power Plant Representation in Large-Scale Power Flow Simulations in WECC," presented at the IEEE Power Engineering Society, General Meeting, Pittsburgh, PA, July 20-24, 2008.
7. E. Muljadi, A. Ellis," Validation of Wind Power Plant Dynamic Models", invited panel discussion presented at the IEEE Power Engineering Society, General Meeting, Pittsburgh, PA, July 20-24, 2008.
8. E. Muljadi, Z. Mills, R. Foster, J. Conto, A. Ellis, " Fault Analysis at a Wind Power Plant for a One Year of Observation", presented at the IEEE Power Engineering Society, General Meeting, Pittsburgh, PA, July 20-24, 2008.
9. E. Muljadi, S. Pasupulati, A. Ellis, D. Kosterov," Method of Equivalencing for a Large Wind Power Plant with Multiple Turbine Representation", presented at the IEEE Power Engineering Society, General Meeting, Pittsburgh, PA, July 20-24, 2008.
10. R. Zavadil, N. Miller, A. Ellis, E. Muljadi, E. Camm, and B. Kirby, "Queuing Up", the IEEE Power and Energy Magazine, November/December 2007
11. E. Muljadi, C.P. Butterfield, B. Parsons, A. Ellis, "Characteristics of Variable Speed Wind Turbines Under Normal and Fault Conditions", presented at the IEEE Power Engineering Society, Annual Conference, Tampa, Florida, June 24-28, 2007.
12. M. Behnke, A. Ellis, Y. Kazachkov, T. McCoy, E. Muljadi, W. Price, J. Sanchez-Gasca "Development and Validation of WECC Variable Speed Wind Turbine Dynamic Models for Grid Integration Studies" presented at the Windpower 2007, WINDPOWER 2007 Conference & Exhibition, Los Angeles, CA, June 24-28, 2007.
13. E. Muljadi, C.P. Butterfield, B. Parsons, A. Ellis, "Effect of Variable Speed Wind Turbine Generator on Stability of a Weak Grid", published in the IEEE Transactions on Energy Conversion, Vol. 22, No. 1, March 2007.
14. 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.

Appendix II - List of Short Courses and Workshops

1) WECC – 2009 Generator Model Validation Workshop, held at Tristate Generator and Transmission Association, Westminster, CO May 18-19, 2009
2) WECC - 2009 Modeling Workshop for Planning Engineers, held at PG&E, San Francisco, CA, April 16-17 2009
3) IEEE Dynamic Performance of Wind Power Generation Task Force (DPWPGTF) “Tutorial on Wind Generation Modeling and Controls,” IEEE PSCE Conference, Seattle, WA, USA – March 2009
4) Tutorial “Wind Energy Boot Camp” organized by New Mexico State University, PNM, and NREL at Albuquerque, NM, Nov 12-14, 2008
5) IEEE Dynamic Performance of Wind Power Generation Task Force (DPWPGTF) “Tutorial on Wind Generation Modeling and Controls,” IEEE PES General Meeting, Pittsburgh, PA, USA – July, 2008
6) “WECC Wind Generator Modeling Project “, Policy Advisory Committee, California Energy Commission (CEC), Irwindale, CA, 8/20/2007 and Kick off meeting for the, Los Angeles, CA, 8/21/2007
7) “Wind Generator Modeling”, CEC-PIER-TRP Technical Advisory Committee Meeting, Sacramento, CA, October 3, 2006
8) “Equivalencing Large Wind Power Plant”, WECC 2006 Modeling Workshop, Las Vegas, NV, June 14-15, 2006

FINAL PROJECT REPORT

WECC WIND GENERATOR DEVELOPMENT

Appendix III
WIND POWER PLANT EQUIVALENCING

Prepared for CIEE By:

National Renewable Energy Laboratory

A CIEE Report

Acknowledgments

This work is part of a larger project called WECC Wind Generator Modeling. The support of the U.S. Department of Energy, the Western Electric Coordinating Council, and the California Energy Commission's PIER Program are gratefully acknowledged.

The author expresses his gratitude to the members WECC WGMG and MVWG, General Electric, Siemens PTI who have been instrumental in providing technical support and reviews, and, in particular to Dr. Abraham Ellis of Sandia National Laboratory, who works with us on this project as the Chair of WECC-WGMG and continuously provides technical guidance during the development of this project.

Table of Contents

Appendices

List of Figures

List of Tables

Abstract and Keywords

Wind energy continues to be one of the fastest growing technology sectors. This trend is expected to continue globally as we attempt to fulfill a growing electrical energy demand in an environmentally responsible manner. As the number of wind power plants (WPPs) continues to grow and the level of penetration reaches high levels in some areas, there is an increased interest on the part of power system planners in methodologies and techniques that can be used to adequately represent WPPs in the interconnected power systems.

WPPs can be very large in terms of installed capacity. The number of turbines within a single WPP can be as high 200 turbines or more, and the collector system within the WPP can have several hundred miles of overhead and underground lines. It is not practical to model in detail all individual turbines and the collector system for simulations typically conducted by power system planners. To simplify, it is a common practice to represent the entire WPP with a small group of equivalent turbine generators or a single turbine generator.

In this report, we describe methods to derive and validate equivalent models for a large WPP. FPL Energy's 204-MW New Mexico Wind Energy Center, which is interconnected to the Public Service Company of New Mexico (PNM) transmission system, was used as a case study. The methods described are applicable to any large WPP. We will illustrate how to derive a simplified single-machine equivalent model of a large WPP (that includes an equivalent collector system model), preserving the net steady state and dynamic behavior of the actual installation. Another part of this report describes methods to derive equivalent models for a WPP with different types and sizes of wind turbine.

To verify the derivations, we compared the performance of the equivalent model against a detailed model of the WPP, which contains all the wind turbine generators and associated collector system.

The objective of this task was to provide methodology of equivalecing WPPs for power system dynamic studies. This report discusses the derivation of the equation used to equivalent major components of WPP (i.e., collector systems, pad mounted transformer, and wind turbine etc.). The procedure is illustrated with specific examples, both for a uniform WPP or for a power plant with different turbine types and sizes.

Keywords: Dynamic model, equivalencing, equivalent circuit, 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 (WPPs) has also increased significantly. In the past, a typical wind power plant consisted of several turbines. Today, WPP 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 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 WPPs has been acceptable in the past (i.e., 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 WPP in a dynamic model may lead the transmission planners to erroneous conclusions.

The Wind Generator 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 WPP in power system studies. These goals will be accomplished through of the development and validation of standard models, development of an equivalent method for an array of wind generators, and recommended practices for modeling a WPP. 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 (i.e., generic, non-proprietary) dynamic models would 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 (e.g., 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 conduct research without the need to provide for non-disclosure agreements from turbine manufacturers.

With the appropriate dynamic models available for wind turbines, planners could more accurately study transmission congestion or other major grid operating constraints, either from a real-time grid operating 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 electricity supply of grid instabilities and outages, or reduces the amount of power that can be imported into and transported within California and the region within the WECC footprint.

Wind Plant Equivalencing is one of the final reports for the WECC Wind Generator Development Project (WGDP), contract number #500-02-004, work authorization number MR-065, a project sponsored by the WECC WGMG, California Energy Commission (Energy Commission), and National Renewable Energy Laboratory (NREL).

1.0 Introduction and Scope

Although it is very important to understand the dynamics of individual turbines, the collective behavior of the wind power plant (WPP) and the accuracy in modeling the collector systems are also very critical in assessing WPP characteristics. Among other aspects, the design of collector systems for WPPs seeks to minimize losses and voltage drops within budgetary constraints. This philosophy is generally applied regardless of the size of the WPP, the types of the turbines and reactive power compensation. The calculation of the equivalent network should take place before performing power flow and dynamic simulation.

Within a WPP, wind turbines are placed optimally to harvest as much wind energy as possible. The turbine layout in a large WPP on a flat terrain is different from the layout of a WPP located on mountain ridges. The different layouts will have different impacts on the line impedances to the grid interconnection bus.

A WPP may contain up to several hundred individual wind generators and miles of underground and overhead collector network. An equivalent model (e.g., a single generator behind an equivalent collector system) is needed for the large-scale simulations that are typically conducted in planning studies. It is not generally understood to what degree this model reduction degrades the faithfulness of the models. This report is intended to assess how the aggregate behavior of several tens to several hundred generators comprised in a WPP should be captured using the Western Electricity Coordinating Council (WECC) generic models.

The method developed here is independent of the power system simulation programs such as PSLF and PSS/E. It is also independent of the type of turbines used. New WPPs usually consists of uniform turbines supplied by the same turbine manufacturers, however, older WPPs may have different turbines types or different turbine manufacturers. Thus, WPP equivalencing must be considered on a case-by-case basis.

The scope of this document is focused on the methodology of equivalencing a WPP consisting of hundreds of turbines to its simplified equivalent. This report is organized as follows:

- Section 1 – Introduction and Scope
    - Section 1 is devoted to the introduction and the scope of the project.
- Section 2 – Background
    - This section provides historical background and the need to perform equivalencing for a large WPP.
- Section 3 – Equivalencing Method.
    - This section derives method to perform equivalencing of a WPP with uniform turbines (all turbines within the WPP are of the same type, size, and manufacturers).

- Section 4 – Comparison between Single Turbine Representation and the Full System Representation
    - A comparison between single turbine representation and full system representation (136 turbines) is presented in this section.
- Section 5 –Multiple Turbine Representation
    - This section describes the method used to represent WPP with different types (non-uniform) of wind power turbine within the same WPP.
- Section 6 – Summary
    - This section gives a summary of the equivalencing methodology for wind turbine generator (WTG).

2.0 Background

As the size and number of WPPs increases, power system planners will need to study their impact on the power system in more detail. As the level of wind power penetration into the grid increases, the transmission system integration requirements will become more critical [1-2].

A very large WPP may contain hundreds of megawatt-size wind turbines. These turbines are interconnected by an intricate collector system. While the impact of individual turbines on the larger power system network is minimal, collectively, wind turbines can have a significant impact on the power system during a severe disturbance, such as a nearby fault [3-4]. Power flow analysis and dynamic analysis are commonly performed by utility system planners, and WPP developers during various stages of WPP development. Although it is important to model a WPP to be as close as possible to the actual implementation, representing hundreds of turbine and the corresponding hundreds of branches are not practical, so a simplified equivalent representation is usually used.

This report focuses on our effort to develop an equivalent representation of a WPP collector system for power system planning studies. The layout of the WPP, the size and type of conductors used, and the method of delivery (overhead or buried cables) all influence the characteristic and performance of the collector system inside the WPP. Our effort to develop an equivalent representation of the collector system for WPPs is an attempt to simplify power system modeling for future developments or planned expansions of WPPs. Although we use a specific large WPP as a case study, the concept is applicable for any type of WPP. The concepts described in this report are based on the work presented in reference [5-6].

In new WPPs, the wind turbine used is generally of the same type and supplied by the same manufacturers. Often the characteristic of a WPP can be represented by a single generator equivalent or single turbine representation. Generally, a full system representation (FSR, where all turbines are represented) of a WPP shows the same behavior at the point of interconnection (POI) as a WPP with a single turbine representation (STR). During the fault (4 – 10 cycles) minor differences between FSR and STR behaviors may be visible on the plots, however, these differences are mainly caused by the diversity of collector system impedance among the turbines, which tends to smooth out the response seen at the POI. The post transient region is the more important period of simulation because it gives an indication of survivability of the system. In the post transient response, generally the STR and FSR show the same response (damping, settling time, etc.).

Validation requires that both the system network (equivalencing) and the dynamic models represent the actual WPP. Reference [7-9] gives more insights on the dynamic simulations and dynamic model validation. More references on wind power turbines, WPPs and distribution networks can be found in references [10-13].

Occasionally, the diversity of a WPP needs to be represented. In an old WPP, some of the turbines are replaced by bigger modern turbines to harvest more energy. Or even in any WPP, the same type of turbine could be deployed using different types of control algorithms. For example, a variable-speed doubly fed induction generator can be controlled to provide a constant power factor or a constant voltage. Different control strategies deployment are sometimes implemented to optimize the controllability of the WPP or to minimize losses within the WPP. In order to capture the unique characteristics of the WPP, the unique characteristics of the wind turbine must be represented. Thus, in some cases, we may want to represent the WPP with a multiple turbine representation.

3.0 Develop Equivalencing Methodology

A typical modern wind power plant consists of hundreds of turbines of the same types. A WTG is usually rated at low three phase voltage output (480 – 600 V). A pad mounted transformer at the turbine step-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 a desired transmission level (e.g., 230 kV). A very large WPP consists of several substations with sizes of 50 MVA or higher for substation transformers. These substations are connected with 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 WPP layout can be seen in Figure 1.

Within a WPP, there are a lot of diversities in the line feeder and the wind speed at each turbine. Line impedance in the line feeder connecting each wind turbine to the POI differs from each other. The wind speed experienced by one turbine can be significantly different from another turbine located at another part of the WPP. The diversity of a WPP is a good attribute in many ways. For example, the interaction between a WPP with the grid is determined by the collective behavior of the WPP. 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 WPP may loose a small percentage of the total generation, depending on the location of each wind turbine with respect to the fault origin.

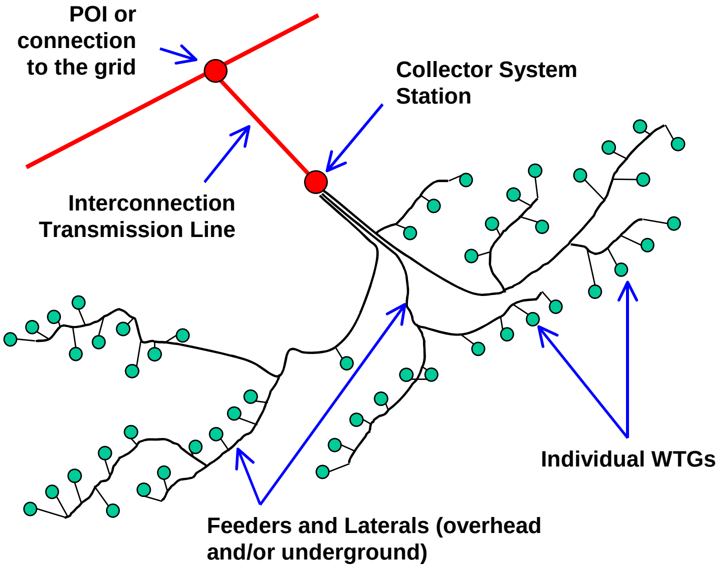


Figure 1. Physical diagram of a typical WPP

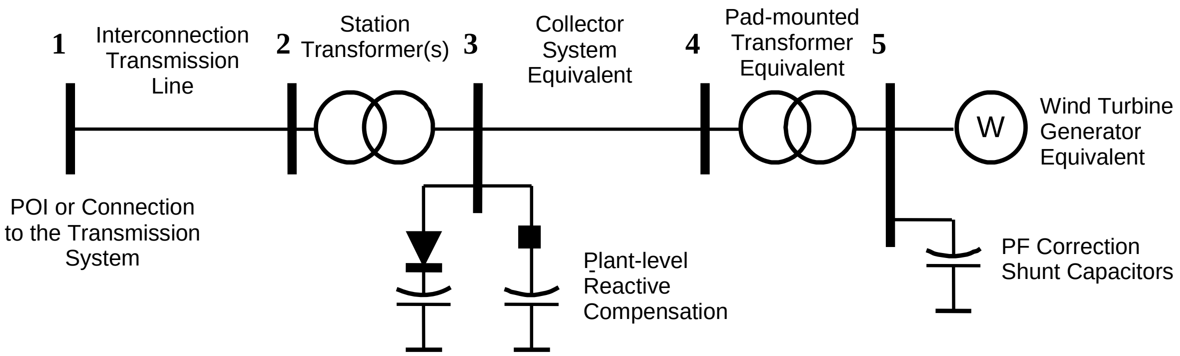
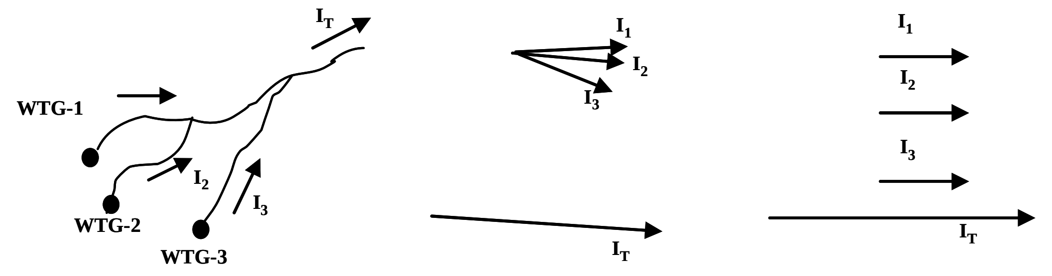


Figure 2. Single turbine representation for a WPP

3.1. Single Turbine Representation (STR)

The Wind Generator Modeling Group (WGMG) of WECC recommends the use of the single-machine equivalent model shown in Figure 2 to represent WPPs in WECC base cases. This representation is recommended for transient stability simulations and power flow studies [10].

All the components shown in Figure 2 are represented in a power flow calculation. It is important to understand the significance of compatibility of power flow input data (sav files in PSLF or raw files in PSSE) and the dynamic data file (dyr file in PSLF and dyd files in PSSE).



(a) Currents entering a Node

b) Phasor Summation (assume unique phase angles)

(c) Algebraic Summation (assume equal phase angles)

Kirchhoff Current Law (KCL)

$$I_T = I_1 + I_2 + I_3$$

Figure 3. Illustration of current injection from each WTG

3.1.1. General overview and assumptions

In the following derivation, we based our equivalent circuit on apparent power losses (i.e., real power losses and reactive power losses). We made the following assumptions to derive the general equation for a circuit within a WPP:

- The current injection from all wind turbines is assumed to be identical in magnitude and angle (see Figure 3).
- Reactive power generated by the line capacitive shunts is based on the assumption that the voltage at the buses is one per unit.

3.1.2. Derivation of equivalent impedance for a group of turbines

The first step is to derive the equivalent circuit for two or more turbines connected in a daisy-chain configuration. The equivalent circuit of the daisy-chain network shown in Figure 4 is represented in Figure 5. Note that the pad-mounted transformer is considered to be part of the generator itself. At this stage, we are only interested in the equivalent impedance of the collector system, excluding the pad-mounted transformers. Each of the currents shown is a phasor quantity, as follows:

$$\mathbf{I_m} = I_m \angle \theta_m$$

In this report, a boldfaced variable indicates a phasor quantity. For instance, $\mathbf{I_1}$ represents the current out of the wind turbine 1. The magnitude and angle of the phasor $\mathbf{I_1}$ are I_1 and θ_1, respectively. Since current injections from each turbine are assumed to be identical, we obtain the following:

$$\mathbf{I_1} = \mathbf{I_2} = \mathbf{I_3} = \mathbf{I_4} = \mathbf{I_5} = \mathbf{I_6} = \mathbf{I}$$

Therefore, the total current in the equivalent representation is given by:

$$\mathbf{I_S} = n\,\mathbf{I}$$

The voltage drop across each impedance can be easily derived as follows

The voltage drop across

$$Z_1 = \Delta\mathbf{V_{Z1}} = \mathbf{I_1}\,\mathbf{Z_1} = \mathbf{I}\,\mathbf{Z_1}.$$

The voltage drop across

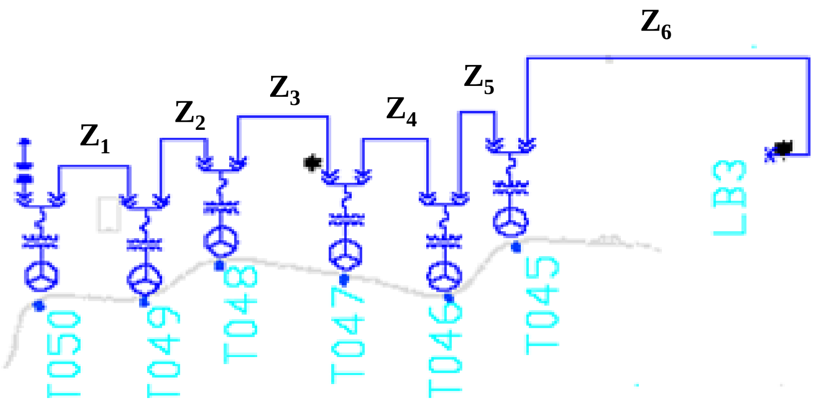
$$Z_2 = \Delta\mathbf{V_{Z2}} = (\mathbf{I_1}+\mathbf{I_2})\,\mathbf{Z_2} = 2\,\mathbf{I}\,\mathbf{Z_2}$$

.

.

The voltage drop across

$$Z_6 = \Delta\mathbf{V_{Z6}} = (\mathbf{I_1}+\mathbf{I_2}+\mathbf{I_3}+\mathbf{I_4}+\mathbf{I_5}+\mathbf{I_6})\,\mathbf{Z_6} = 6\,\mathbf{I}\,\mathbf{Z_2}$$



n = 6 turbines connected in daisy-chain

Figure 4. Wind turbines connected in a daisy-chained string

The real and reactive power loss at each impedance, can be computed as:

$$\mathbf{S}_{\mathbf{Loss\_Z1}} = \Delta\mathbf{V}_{\mathbf{Z1}}\ \mathbf{I}_{\mathbf{1}}^{*} = \mathbf{I}_1\mathbf{I}_1^{*}\ \mathbf{Z}_{\mathbf{1}} = I^2\ \mathbf{Z}_{\mathbf{1}}$$

$$\mathbf{S}_{\mathbf{Loss\_Z2}} = \Delta\mathbf{V}_{\mathbf{Z2}}\ \mathbf{I}_{\mathbf{2}}^{*} = (\ \mathbf{I}_{\mathbf{1}}+\mathbf{I}_{\mathbf{2}})\ (\mathbf{I}_{\mathbf{1}}+\mathbf{I}_{\mathbf{2}})^{*}\ \mathbf{Z}_{\mathbf{2}} = 2^2\ I^2\ \mathbf{Z}_{\mathbf{2}}$$

.

.

$$\mathbf{S}_{\mathbf{Loss\_Z6}} = \Delta\mathbf{V}_{\mathbf{Z6}}\ \mathbf{I}_{\mathbf{6}}^{*} = \Delta\mathbf{V}_{\mathbf{Z6}}\ (\ \mathbf{I}_{\mathbf{1}} + \mathbf{I}_{\mathbf{2}} + \mathbf{I}_{\mathbf{3}} + \mathbf{I}_{\mathbf{4}} + \mathbf{I}_{\mathbf{5}} + \mathbf{I}_{\mathbf{6}})^{*} = 6^2\ I^2\ \mathbf{Z}_{\mathbf{6}}$$

Since $\mathbf{I}_{\mathbf{S}} = n\ \mathbf{I}$, the power loss equation can be simplified as follows:

$$S_{\mathrm{Tot\_loss}} = I^2\ (Z_1 + 2^2\ Z_2 + 3^2\ Z_3 + 4^2\ Z_4 + 5^2\ Z_5 + 6^2\ Z_6)$$

$$S_{\mathrm{Tot\_loss}} = I^2 \sum_{m=1}^{n} m^2\ Z_m$$

where

I = output current of a single turbine

m = index

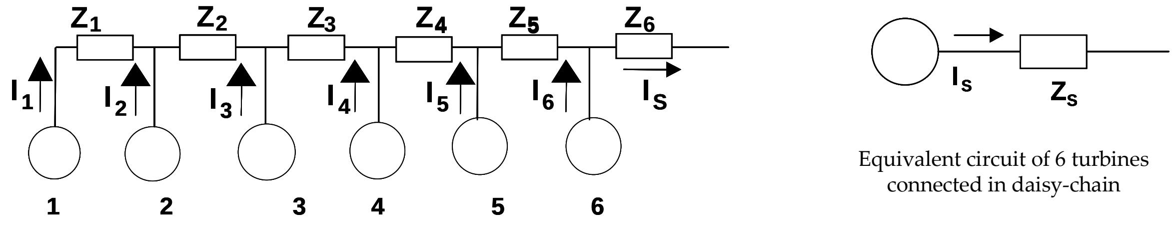
n = number of turbines in a daisy-chain string

The equations for the simplified equivalent circuit can be written as follows:

$$S_{\mathrm{Tot\_loss}} = I_S^{\ 2}\ Z_S$$

$$Z_S = \frac{\sum_{m=1}^{n} m^2\ Z_m}{n^2}$$

Z_m represents the individual series impedances.



Equivalent circuit of 6 turbines connected in daisy-chain

Figure 5. Equivalent circuit and its simplified representation

The concept developed here is based on the conservation of real power consumed and reactive power consumed/generated by the collector systems. The above equation representing the turbines connected in daisy chain can be expanded to develop the equivalent of the collector system for the entire WPP. It is computed by using the total losses in the collector system.

$$Z_{EQ} = \frac{\sum_{k=1}^{l} \sum_{m=1}^{n_k} m^2 Z_m}{{n_{wtg}}^2}$$

where

n_k = the number of turbines in line k

m = an index of the branch within a line

k = an index of the line considered

l = the total number of lines considered

n_{wtg} = number of the turbines considered

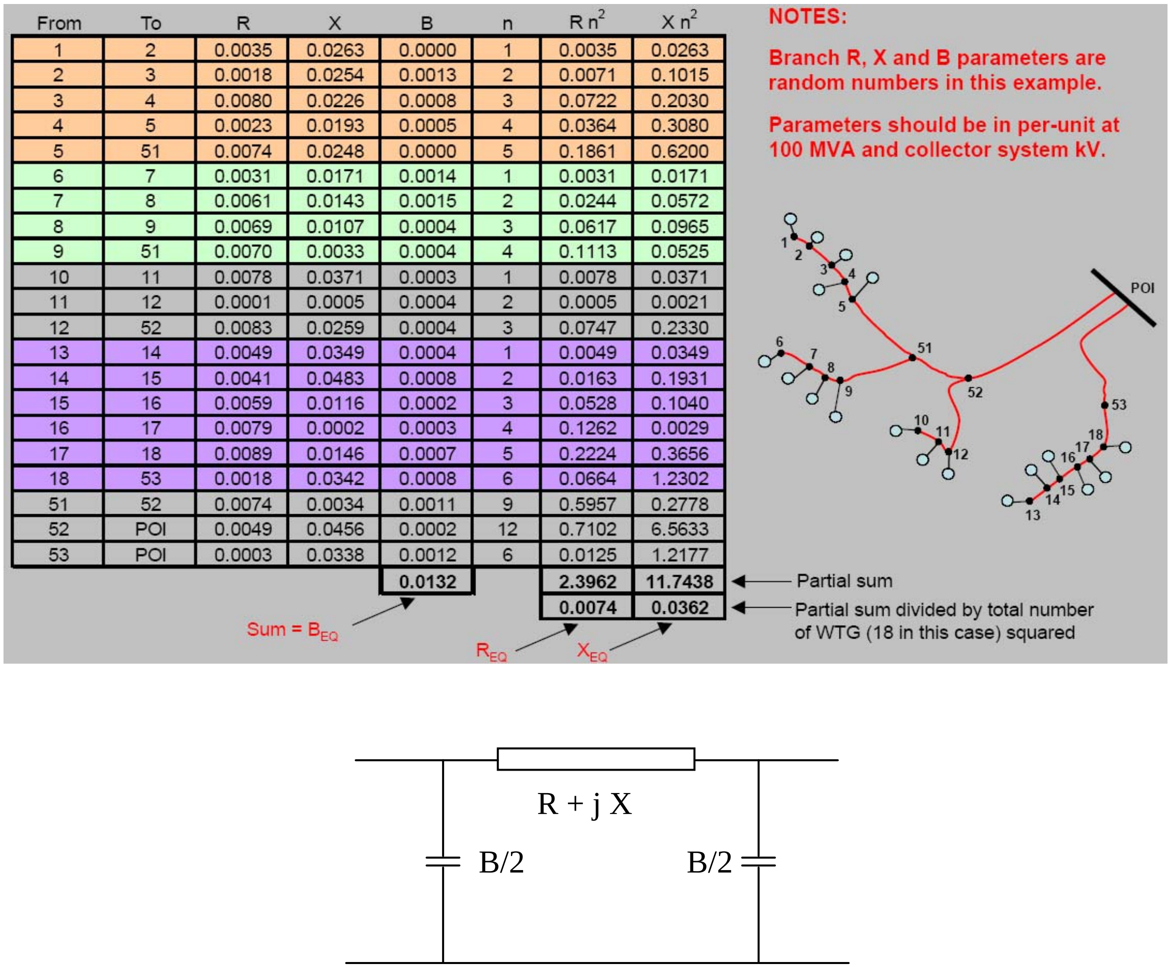
Z_m = the impedance of a branch

Thus, for each branch, the equation presented in the previous section can be modified. A simple network example will be presented here to illustrate the approach. A simple spreadsheet is included to get a clearer idea about the concept developed here.

A simple illustration of calculation is given in the spreadsheet. For example the number of turbines served by branch 2-3 (between bus 2 and bus 3) is 2 and the equivalent $m^2 Z_m$ is computed as 2^2 (0.0018+j0.0254) = (0.0071+j0.1015).

Similarly, we can perform the calculation for the rest of the branches and we can get the total (i.e., 2.3962+j11.7438). To get the equivalent of this simple network, we divided the total by the square of the number of turbines (18 turbines) within the WPP.

Z_{eq} = (2.3962+j11.7438)/182 = (0.0074+j0.0362)



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 6. Representing the line capacitance of a collector system

3.2. Shunt representation

Consider an equivalent circuit for the transmission line shown below. Because the nature of the capacitance generates reactive power that is proportional to the square of the voltage across them, and considering that the bus voltage is close to unity under normal conditions, the representation of the shunt B can be considered as the sum of all the shunts in the power systems network.

Figure 6 above shows a typical representation of the collector system equivalent represented as a pi circuit. This assumption is close to reality under normal condition. With the assumption presented, we can compute the total shunt capacitance within the WPP as follows:

$$B_{tot} = \sum_{i=1}^{n} B_i$$

where

B_i = the capacitance of individual branch (in p.u. system base, Sbase)

n = the number of branches

3.3. Pad-mounted transformer representation

The pad-mounted transformer must be represented to process the entire WPP. The equivalent circuit can be scaled so that the resulting voltage drop across the impedances (leakage) and the reactive and real power losses are equal to the sum of individual reactive and real losses of the turbines.

The equivalent representation for the entire WPP can be computed as the impedance of a single transformer divided by the number of the turbines. Note, that the

$$Z_{PMXFMR\_WF} = Z_{PMXFMR\_WTG} / n_{turbine}$$

where

Z_{PMXFMR_WF} = the equivalent impedance of pad mounted transformer (in p.u. system base, Sbase)

Z_{PMXFMR_WTG} = the impedance of a single turbine pad mounted transformer (in p.u. system base, Sbase)

$n_{turbine}$ = the number of turbines

As an example, the pad-mounted transformer impedance for the NMWEC is:

$$Z_{PMXFMR\_WTG} = (0.3572 + j\,3.3370) \text{ p.u.}$$

The number of turbines is $n_{turbine}$ = 136 turbines.

Using the equation above, and using the same system base ((V_{Base}, I_{Base}, S_{Base})), the equivalent impedance for the pad-mounted transformer represented by a single turbine for the entire WPP is:

$$Z_{PMXFMR\_WF} = Z_{PMXFMR\_WTG} / n_{turbine}$$

$$Z_{PMXFMR\_WF} = (0.0027 + j0.0245) \text{ p.u.}$$

Note, that this equation is valid using the actual values of the impedance (ohms) or using the system base value. However, it is recommended to use the system base value for the pad-mounted transformer to prepare the input for power flow modeling.

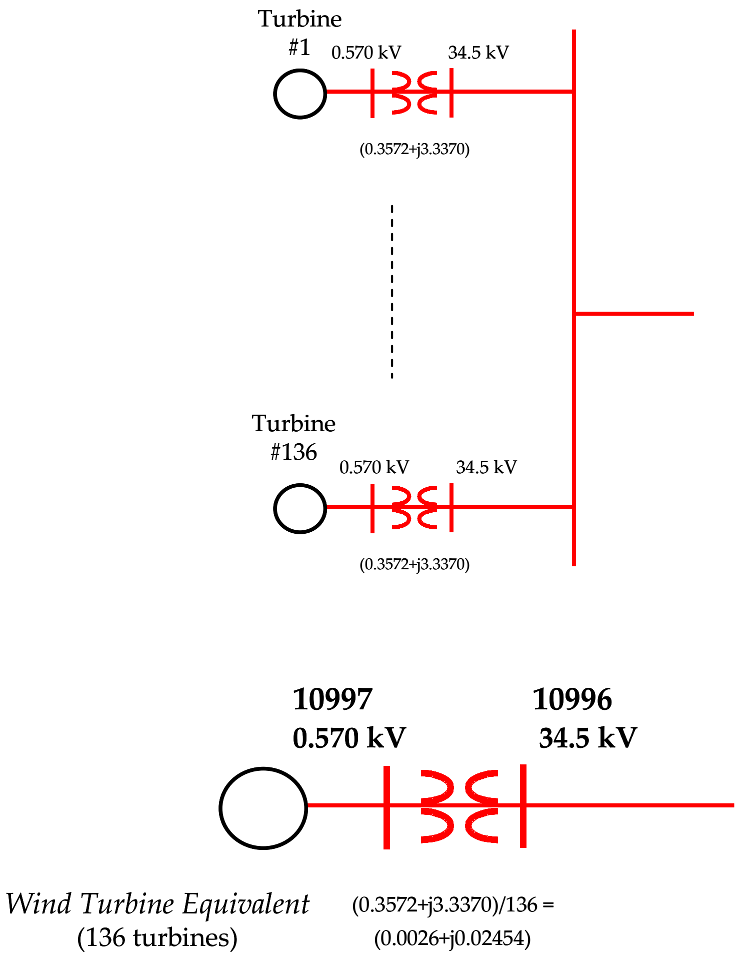


Figure 7. Representing the pad mounted transformer equivalent impedance

New Mexico Energy Center (NMEC) Wind Power Plant (Taiban Mesa)

The WPP equivalent circuit for the NMEC Wind Power Plant is shown in Figure 8. This equivalent is a single turbine representation. The WPP consists of 136 turbines with a total capacity of 204 MW. Each wind turbine is rated at 1.5 MW. The wind turbine used is a variable-speed wind turbine (doubly fed induction generator). Most of the collector systems are underground cables. The method of equivalencing described previously was used to find the equivalent impedances of the collector systems, pad-mounted transformer, and station transformer. The system base used is 100 MVA.

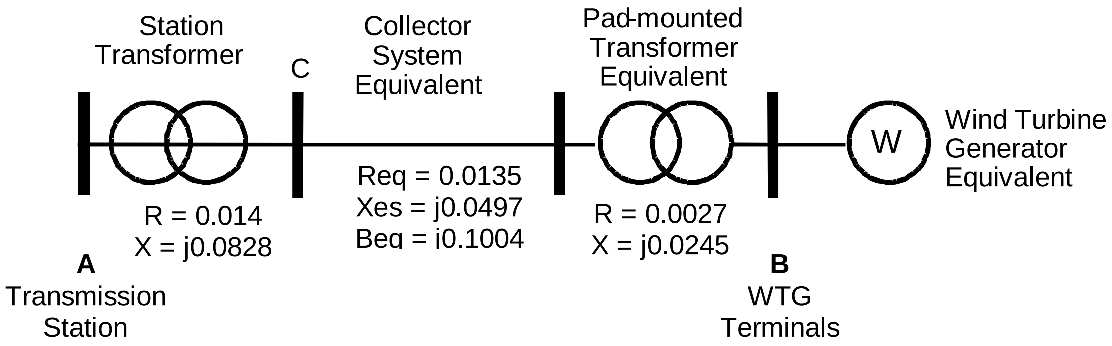


Figure 8. Single-machine equivalent impedance of NMEC wind power plant

Limited WPP collector system impedance data is presented in Appendix II. From what we've gathered so far, we can say that the WPP is usually designed to have a low real-power loss. This value is reflected from the size of the collector system resistance. It is desirable to have a low loss within the collector system (e.g., 1% to 2%). The size of the reactive power loss is shown by the size of the collector system reactance, and it is influenced by the type of collector system conductor used. For example, with an underground cable, we can expect to have a range of reactance around 2%, but if there is some overhead wire used within the WPP, the reactance value can go up to 8%. These values are expressed in per unit using the MBASE (MVA base = the rating of the WPP).

4.0 Comparison between Single Turbine Representation and the Full Turbine Representation

To validate the results of the calculation from equivalencing the collector systems, we can compare the results from the dynamic simulation. Based on the same transient condition, the two-systems single turbine representation (STR) and the full system representation (FSR) of 136 turbines are compared. The NMEC wind plant is represented as an STR and as an FSR (all 136 turbines).

In the next few sections, we attempt to recreate a fictitious fault at the Taiban Mesa 345-kV substation using a guidelines provided by AWEA. According to the AWEA-LVRT, the WPP must be connected to the grid as long as the voltage at the POI is at or above the specified voltage profile. The voltage profile starts at 1.0 p.u. at t = 0 and drops to 0.15 p.u. at t = 625 msecs, and the voltage slowly ramps up to 0.9 p.u. at t = 3.0 secs. The wind turbine must be connected indefinitely as the voltage drops down to 0.9 p.u. The low voltage ride-through voltage profile can be seen in Figure 9. This voltage profile is proposed by AWEA as it appears in the FERC NOPR, January 24, 2005.

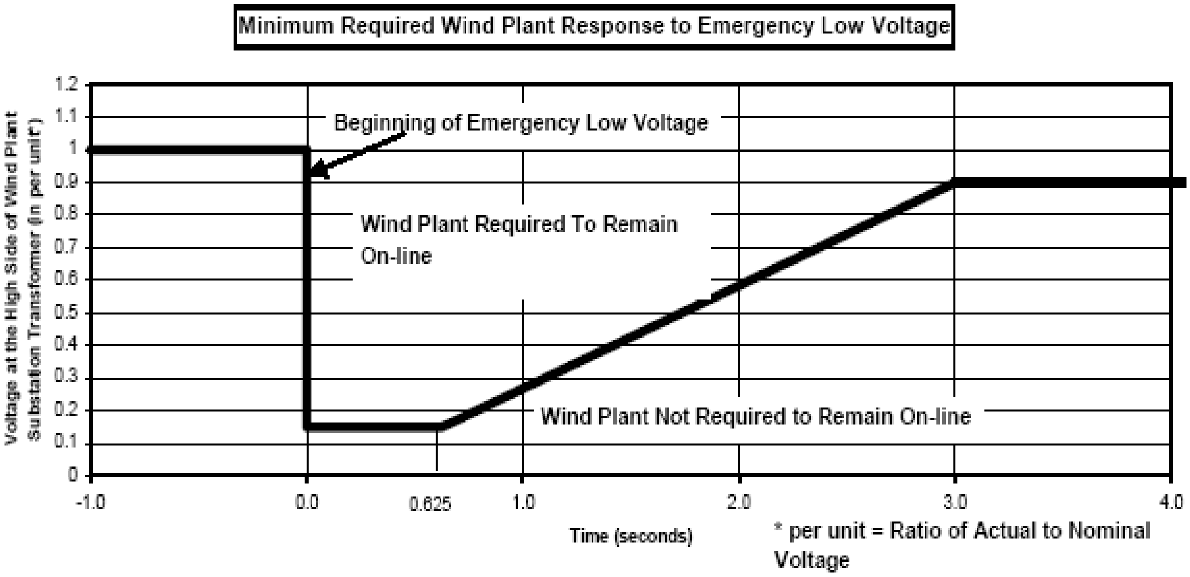


Figure 9. Test voltage profile (ref. from FERC NOPR, Jan. 24, 2005)

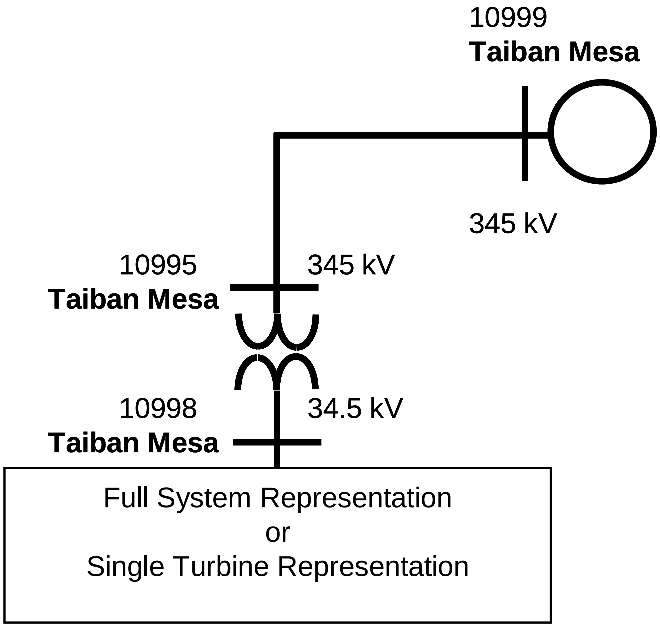


Figure 10. Single line diagram of the WPP for two types of collector system configurations

The purpose of applying this voltage profile is more to test the wind turbine behavior than to test the power system integrity. Under normal circumstances, this type of fault will be cleared within 4 – 5 normal clearing cycles. Since the relay protection of most of generators installed in the field is not set to survive this voltage profile, we will temporarily disable the protection systems for under/over voltage protection and under/over frequency protection. The voltage profile is applied at the Taiban Mesa substation using a generator classic (GNCLS) PSLF model with a voltage profile readable from an input file. This LVRT requirement does not consider frequency changes, thus, only the voltage magnitude is modulated according to this voltage profile shown in Figure 9.

The comparison is conducted by interchanging the wind plant representation between the STR and FSR as shown in Figure 10 using the same voltage profile to as the voltage source at bus 10999.

4.1. Single Turbine Representation (STR)

4.1.1. Bus 10999 (Taiban Mesa, 345 kV)

Figure 11 shows the result of the simulation. The voltage profile representing a fictitious fault based on AWEA – LVRT proposed voltage profile is shown. The real power and reactive power traces are also shown on the same figure. The direction of the power flows shown in this figure is from Taiban Mesa to the WPP, thus, the actual flows from the WPP to Taiban Mesa is the mirror image of the traces shown.

4.1.2. Bus 10701 (Wind Turbine, 0.57 kV)

Figure 12 shows the traces of voltage, real power, and reactive power output of the wind turbines represented by a single turbine. Since this simple circuit is a single series circuit connecting the wind turbine and the Taiban Mesa substation, the traces shown in Figure 11 and Figure 12 are very similar in shape. The voltage trace in Figure 12 shows the response of the WTG to the fault simulated by the voltage profile at bus 10999. The difference between the voltage at the terminal voltage and at the bus 10999 is the voltage drop across the collector system and transformer impedances. The difference between real and reactive power at bus 10999 and the generator output is the losses in the collector system and the transformer impedances. Note, that when we use STR to represent a WPP, we lose the information on individual turbines. The single wind turbine represents only the "average" wind turbine within the WPP.

The post-fault (steady state) condition returns the terminal voltage and output power (real and reactive) to the same level as its pre-fault condition within a relatively short time. Note that

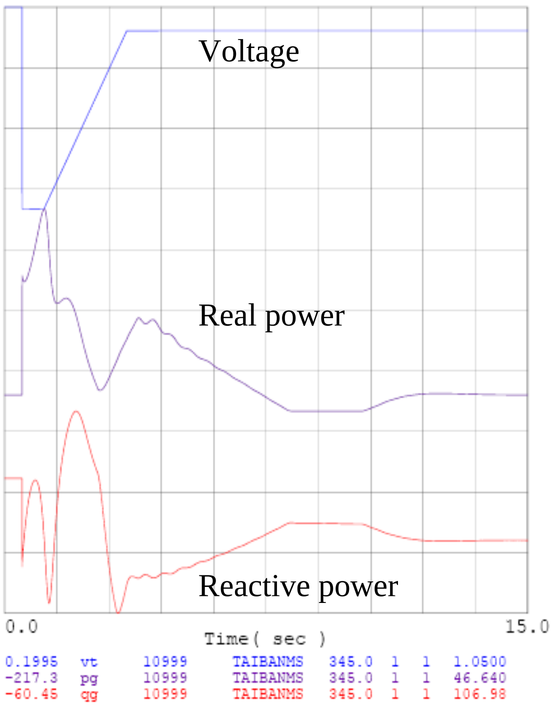


Figure 11. Voltage, real power and reactive power response to the fault at the Taiban Mesa 345-kV substation

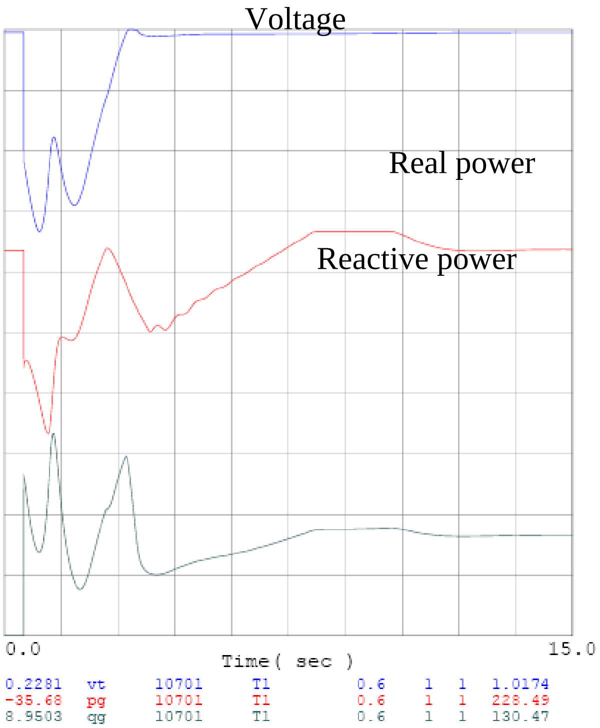


Figure 12. Voltage, real power and reactive power response to the fault at the wind turbine terminals

both the real and reactive power output of the wind turbine is the mirror image of the real and reactive power shown at the Table Mesa substation.

4.2. Full System Representation (FSR)

4.2.1. General Description

In this section, the entire 136 turbines in the WPP is represented. Each turbine, each line connecting turbine to turbine, and each pad-mounted transformer are represented. The same fault condition applied to the STR is also applied to this FSR. The fault is applied to the same bus at the Taiban Mesa 345-kV substation (10999) by generating the voltage profile as in the single turbine equivalent. The same setting is applied to the relay protection to disable them during this simulation. From the simulation results, we can observe the behavior of individual turbines as well as the collective behavior of the entire WPP. With FSR, it is possible to probe each turbine response to transient events.

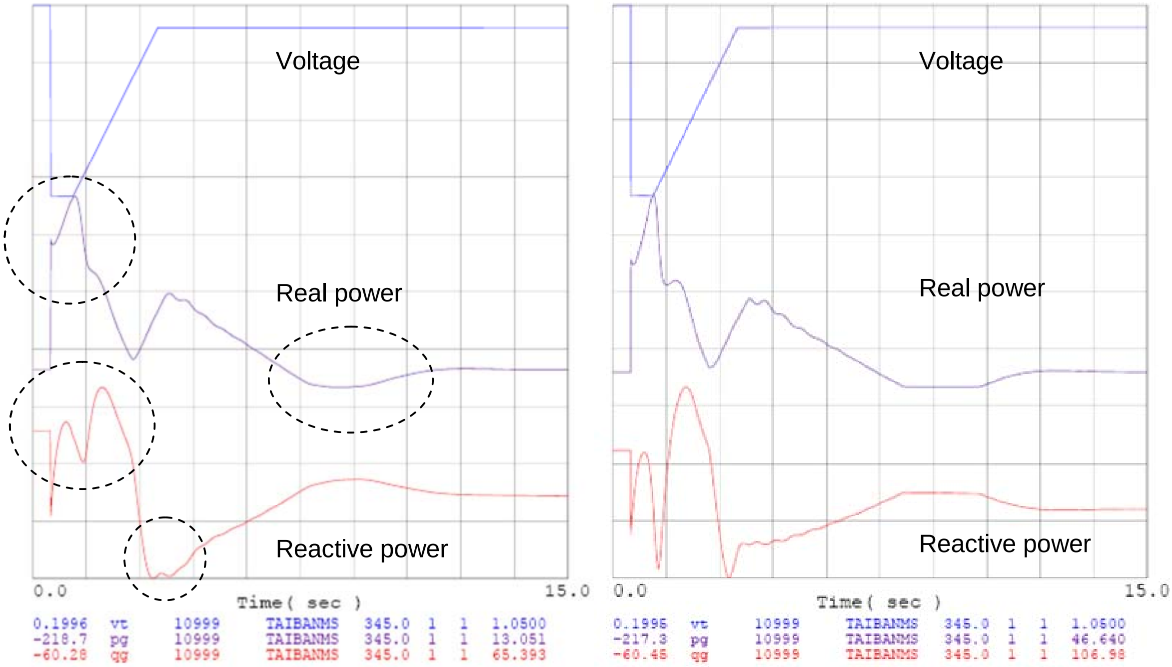
The dynamic model of each generator consists of the wind turbine prime mover model, generator-power converter model, and the relay protection model, all of which must each be represented in the dynamic file. Thus, for the entire 136 turbines, these models must be repeated and represented creating many variables that must be computed at each time step. One disadvantage of representing all the turbines installed in the WPP is the data preparation and debugging, and the computing time can be very long.

4.2.2. Bus 10999 (Taiban Mesa 345 kV):

At the pre-fault condition, there is 204 MW of power generation from the WPP. When the fault occurs, the severity of the fault shows how the power flow is affected. Figure 13a illustrates the behavior of the voltage, real, and reactive power at bus 10999 (Taiban Mesa Substation) when subjected to a voltage profile (AWEA-LVRT). For an easy comparison between FSR and STR, Figure 13b is brought here from the previous section (at the right hand side). The voltage waveform is the same preset voltage read from an input file. From Figure 13a, it is shown that the traces for real and reactive power for an FSR is rounder or smoother than the traces for the STR, indicating that there is some cancellation effect among the 136 turbines. Note that in the FSR, the wind speed driving each turbine is the same, thus the only diversity considered here is the impedance of the collector system. The range of variation of real power for an FSR is narrower than the range of variation for an STR.

We can see that the use of STR assumes that all turbines respond instantaneously and are in sync with the rest of the turbines in the wind power plant, thus there is no cancellation or no smoothing effect in place. Sharp rise of high ramp rates is amplified by 136 times. On the other hands, for FSR, the diversity in the wind power plant collector system is fully employed thus the smoothing effects from the slightly different responses from each turbine revealed in the output shown at the point of interconnection (bus 10999, Taiban Mesa).

From this table we can also see that the range of real power exceeds the allowable range of wind power plant output. For example, the output ranges of wind power plant for real power output is 0 MW to 204 MW, and the reactive power output ranges from –70 MVAR to +70 MVAR. This deviations occur during the fault where only the magnitude of the power converter currents are restrained by the current capability of the power converter by its system protection, while the phase angle of the voltage during transient can swing unpredictable.



(a) Full System Representation (136 WTGs) (b) Single Turbine Representation

Figure 13. Voltage, real power and reactive power at Bus 10999

4.3. Comparison among the turbines

All of the 136 turbines are simulated with the same wind speed input, the same initial conditions of the pitch angle, real input power, etc. The difference in conditions among the turbines, are strictly based on their line impedances among the turbines.

To observe the impact of line-impedances among the wind turbines, we compare one turbine with index number 10701 with another turbine with index number 10836. This choice of turbines observed here is random with consideration based only on the index number (the first one and the last one). It is neither based on the electrical distance nor physical distance. Also, it is neither based on the choice of line impedances nor the choice of bus voltage magnitude and phase angle. Having said that, we should be aware that there is a difference in the Thevenin line impedance (between the turbine and the infinite bus) of the turbines being compared that warrant significant behavior differences observable on the traces shown.

Considering that the only diversity considered is the collector system impedances, it is expected that the electrical behavior of the turbines will be different. First, let's consider the voltage at the terminals of two buses mentioned above. Note that the two turbines are set to control the voltage at the low voltage side of the substation transformer (bus 10998). Figure 14 shows that the two wind turbines experience different voltage at any instant of time. The dashed circles indicate the notable difference in the electrical characteristics between the two turbines. The voltage difference is reflected by the difference in reactive power. The reactive power changes with the voltage as a consequence of the control systems trying to fix the deviation of the voltage away from the reference value. Note that the voltage controller indicates that the PID (both the voltage error and the rate of voltage error) components are controlling the reactive power. The real power trace has a very subtle difference between the two turbines. The shape is very similar between the two traces, with the exception that there is some time delay between the two traces.

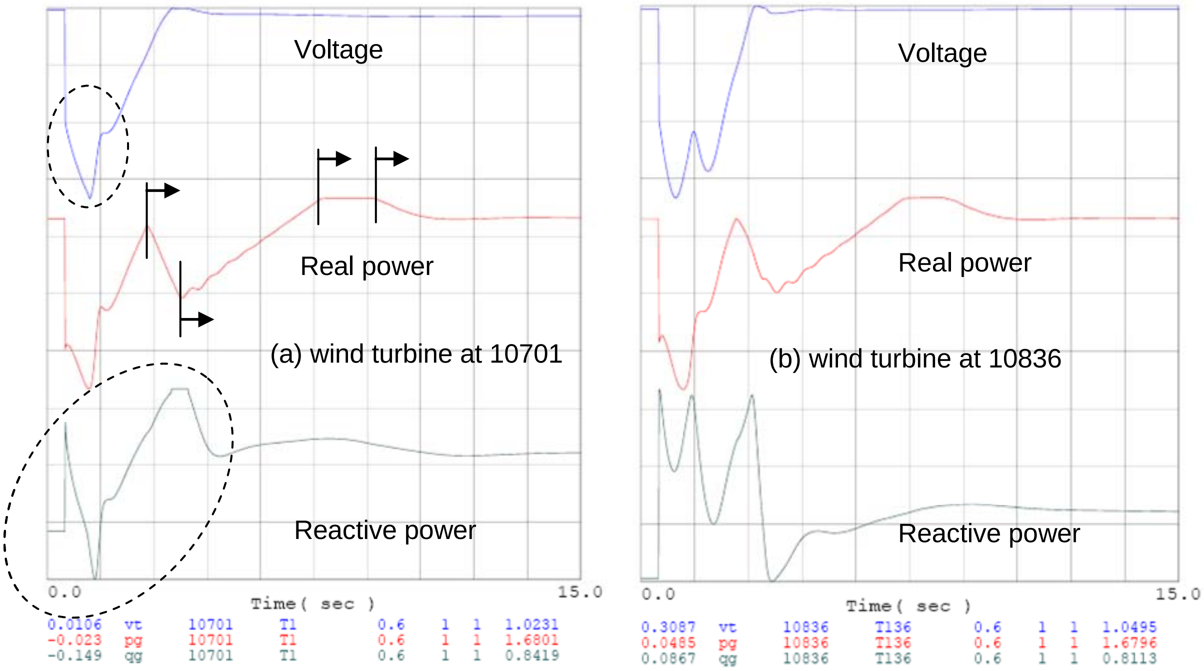


Figure 14. Voltage, real power, and reactive power at two different turbines

5.0 Multiple Turbine Representation

Although it is very important to understand the dynamics of individual turbines [3-5], the collective behavior of the WPP and the accuracy in modeling the collector systems are also very critical in assessing WPP characteristics. Among other aspects, the design of collector systems for WPPs seeks to minimize losses and voltage drops within budgetary constraints. This philosophy is generally applied regardless of the size of the WPP, the types of the turbines, and reactive power compensation.

Within a WPP, wind turbines are placed optimally to harvest as much wind energy as possible. Turbine layout in a large WPP on flat terrain is different from the layout of a WPP located on mountain ridges. Different layouts will have different impacts on the line impedances to the grid interconnection bus. Some preliminary work on equivalencing is based on single turbine representation as presented in the previous section. Some WPPs are built with different types of wind turbines for different reasons. For example:

- Recent unavailability of new turbines because wind turbine supply lags behind demand
- The economic benefit of mixing wind turbine types within the same WPP
- Re-powering old WPPs with newer and bigger turbines.

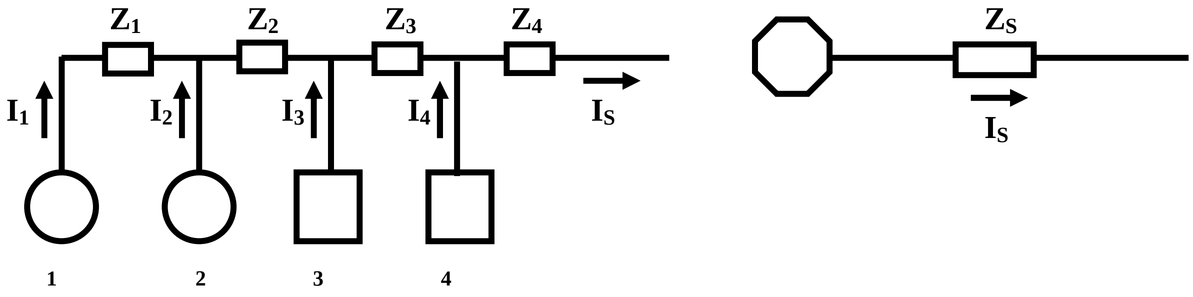
When this problem arises, analysis of WPPs must take into account that the WPP can no longer be represented by a single generator. Obviously, the representation must be based on several considerations.

5.1. Derivation of Equivalent Impedance for Different Sizes of WTGs

In this section we will describe an analytical approach that can be used to derive the equivalent representation of a WPP collector system. Many textbooks on distribution system modeling are available [7], but this report focuses on modeling WPP collector systems in particular. To illustrate the methodology, we used data from the proposed WPP to be built in Tehachapi, California, and interconnected to the transmission grid owned and operated by Sothern California Edison (SCE).

Let's consider a WPP consisting of different types of wind turbines of different sizes. Consider the equivalent circuit shown in Figure 15 where we have 4 turbines connected in a daisy chain fashion. Let's first consider the voltage drops across the line impedances. Across Z_1, the voltage drop can be written as:

$$\Delta V_{Z1} = I_1 Z_1 = (S_1/V) Z_1 = (P_1/V) Z_1$$



a) Daisy-chain representation b) Equivalent circuit representation

Figure 15. Equivalencing four turbines of different sizes

Note that I_1 is substituted with S_1/V where S_1 is the rated apparent power of wind turbine #1. Based on the assumption that most wind turbines are compensated to have a very close unity power factor, the apparent power S_1 can be substituted by the rated power of wind turbine 1, P_1. The rest of the equations can be used to describe the voltage drop across Z_1 through Z_4.

$$\begin{aligned}\Delta V_{Z2} &= (I_1 + I_2)\, Z_2 \\ &= (P_1/V + P_2/V)\, Z_2 \\ &= (P_1 + P_2)\, Z_2/V\end{aligned}$$

$$\begin{aligned}\Delta V_{Z3} &= (I_1 + I_2 + I_3)\, Z_3 \\ &= (P_1/V + P_2/V + P_3/V)\, Z_3 \\ &= (P_1 + P_2 + P_3)\, Z_3/V\end{aligned}$$

$$\begin{aligned}\Delta V_{Z4} &= (I_1 + I_2 + I_3 + I_4)\, Z_4 \\ &= (P_1/V + P_2/V + P_3/V + P_4/V)\, Z_4 \\ &= (P_1+P_2+P_3+P_4)\, Z_4/V\end{aligned}$$

Next, we'll define a new variable, P_{Zi}, as the total power flow in the line segment represented by $\mathbf{Z_i}$. The power loss in each line segment can be written as:

$$\begin{aligned}S_{Loss\_Z1} &= \Delta V_{Z1} I_1^* \\ &= (P_1/V)\,(P_1/V)^* Z_1 \\ &= (P_1/V)\,(P_1^*/V^*)\, Z_1 \\ &= P_1^2\, Z_1/\, V^2 \\ &= P_{Z1}^2\, Z_1/\, V^2\end{aligned}$$

$$\begin{aligned}S_{Loss\_Z2} &= \Delta V_{Z2} I_2^* \\ &= (P_1 + P_2)^2\, Z_2/V^2 = P_{Z2}^2\, Z_2/V^2\end{aligned}$$

$$\begin{aligned}S_{Loss\_Z3} &= \Delta V_{Z3}\, I_3^* \\ &= (P_1 + P_2 + P_3)^2\, Z_3/V^2\end{aligned}$$

$$= P_{Z3}^{2}\,\mathbf{Z_3}/V^2$$

$$\begin{aligned}\mathbf{S_{Loss\_Z4}} &= \Delta\mathbf{V_{Z4}}\,\mathbf{I_4}^{*}\\ &= (P_1 + P_2 + P_3 + P_4)^2\,\mathbf{Z_4}/V^2\\ &= P_{Z4}^{2}\,\mathbf{Z_4}/V^2\end{aligned}$$

Note that $\mathbf{Z_4}$ is the last line segment in the daisy chain branch. The total loss can be computed as:

$$\mathbf{S_{Loss}} = P_{Z1}^{2}\,\mathbf{Z_1} + P_{Z2}^{2}\,\mathbf{Z_2} + P_{Z3}^{2}\,\mathbf{Z_3} + P_{Z4}^{2}\,\mathbf{Z_4}$$

From Figure 3b, we can compute the voltage drop across the equivalent impedance as:

$$\Delta\mathbf{V_{ZS}} = \mathbf{I_S}\,\mathbf{Z_S}$$

where

$$\mathbf{I_S} = (P_1 + P_2 + P_3 + P_4)/\mathbf{V}$$

The total loss in the equivalent impedance can be computed as:

$$\begin{aligned}\mathbf{S_{Loss\_ZS}} &= \Delta\mathbf{V_{ZS}}\mathbf{I_S}^{*}\\ &= \mathbf{I_S}\,\mathbf{I_S}^{*}\mathbf{Z_S}\\ &= \{(P_1 + P_2 + P_3 + P_4)/\mathbf{V}\}\{(P_1 + P_2 + P_3 + P_4)/\mathbf{V}\}^{*}\,\mathbf{Z_S}\end{aligned}$$

or

$$\mathbf{S_{Loss\_ZS}} = (P_1 + P_2 + P_3 + P_4)^2\,\mathbf{Z_S}/V^2$$

or

$$\mathbf{S_{Loss\_ZS}} = P_{Z4}^{2}\,\mathbf{Z_S}/V^2$$

By equating the loss calculation, we get:

$$\mathbf{S_{Loss\_ZS}} = \mathbf{S_{Loss}}$$

$$P_{Z4}^{2}\mathbf{Z_S}/V^2 = (P_{Z1}^{2}\mathbf{Z_1} + P_{Z2}^{2}\mathbf{Z_2} + P_{Z3}^{2}\,\mathbf{Z_3} + P_{Z4}^{2}\,\mathbf{Z_4})\,/V^2$$

Note:

P_{Z1} = the total power flowing through impedance $Z_1 = P_1$

.

.

P_{Z4} = the total power flowing through impedance $Z_4 = (P_1 + P_2 + P_3 + P_4)$

The general expression can be written as:

$$Z_S = \frac{\sum_{m=1}^{n} {P_{Zm}}^2 Z_m}{{P_{Zs}}^2}$$

where

Z_S = the equivalent impedance

P_{Zm} = the total power flowing through impedance Z_m

P_{Zs} = the total power flowing through equivalent impedance Z_s

5.2. Wind Turbine Grouping

In this section, a method for grouping of turbines will be explored. For a large WPP, there is a need to form small groups of wind turbines signifying the size of the group with respect to the size of the entire wind power plant.

5.2.1. Groupings based on the diversity of the WPP

This grouping criterion is based on the diversity generally found in a very large WPP. For a very large WPP, the area within the power plant is very large. The number of turbines within the WPP can be a very high number, and sometimes it is not easy to get the same types of turbines due to limited supply. Or, the WPP is expanded due to re-powering program.

- Diversity in wind speed; instantaneously, the wind speed at one corner of the WPP might be significantly different from the wind speed at the other corner of the WPP. Similarly, altitude diversity may be found in a large WPP that will lead to differences in wind speeds experienced by each wind turbine.
- Diversity in line impedance; in some WPPs, especially with significant diversity in the altitudes (WPPs with many hills), the locations of turbines are chosen based on the best wind resource. Thus, groups of turbines will be installed on top of one hill with significant distance with respect to the other groups of turbines. This diversity creates significant diversity in the size of the impedances connecting the groups of turbines to the POI.
- Diversity in turbine types; if there are almost equal numbers of different turbines types, it is appropriate to represent each turbine type within the WPP.
- Diversity in control algorithms; even within the same type, there could be different control algorithms implemented, thus creating groups of turbines with different

response to the same excitations. For example, for type 3 and type 4 turbines, the wind turbine can be controlled to operate in voltage control mode or in power factor mode.

5.2.2. Groupings based on the transformer size

This is a convenient way to group wind turbines within large WPPs. WPP sizes are getting larger and larger. Presently, a 300-MW WPP size is considered typical. The step-up transformer used, however, is normally divided into smaller sizes for economic, reliability, and redundancy reasons. A 30 to 60-MVA transformer is commonly used to step up the voltage of a group of turbines. This method of grouping will probably be the most common type of grouping used in most new power plant cases.

5.2.3. Groupings based on the short circuit capacity

For a very large WPP, a STR or multiple turbine representation (MTR) should be used. MTR is chosen if there is a significant diversity within the WPP in terms of type of wind turbines, impedance levels of the line feeder, different control algorithms, or different wind turbine manufacturers.

In many cases, newer WPPs are represented by a single wind turbine representation because the wind developer usually chooses the same type of wind turbine within the same WPP. If MTR is chosen, the WPP must be represented by several wind turbines. Each wind turbine represents a group of turbines with the same characteristics. The number groups within a single WPP can be determined based on the size of the generated rated power of the group.

A WPP connected to a grid with MTR must be represented by groups of wind turbines. Since short circuit capability (SCC) determines the level of grid stiffness, which also governs its stability characteristic (both voltage and phase angle), and the impact of the WPP on the power grid, it is convenient to express the grouping of the wind turbines by its group size in percentage of its SCC at the POI. For example, a 150-MW WPP might include 75 MW of turbine type 1, 5 MW of turbine type 2, 60 MW of turbine type 3, and 10 MW of turbine type 4. With the system base of 100 MVA and the grid at an SCC = 5, there are four groups of wind turbines within a 150-MW WPP. In terms of its SCC, we can divide the group of turbines into:

Type 1: 75/(5*100) = 15% SCC

Type 2: 5/(5*100) = 1% SCC

Type 3: 60/(5*100) = 12% SCC

Type 4: 10/(5*100) = 2% SCC

Note that the impact of type 4 WTGs is very small (1% SCC) compared to the impact of type 1 WTGs. In this case, it might be useful to combine type 4 into another group with similar characteristics. From the nature of its behavior, we recommend that type 1 and type 2 be considered to have similar behavior, and types 3 and 4 be considered to have similar behavior. We do not recommend combining type 1 and type 3, or type 2 and type 3, or type 2 and type 4, or type 1 and type 4. By regrouping type 2 turbines into the type 1 group as shown in the example below, the number of turbine representations can be reduced, thus simplifying the calculation.

Type 1: 80/500 = 16% SCC

Type 3: 60/500 = 12% SCC

Type 4: 10/500 = 2% SCC

The planner may decide that a group of wind turbines with a total output power of less than 5% of the SCC can be combined into a group with a similar type of turbines to reduce the number of turbine representations. In this case, for a stiffer grid, the grouping allocation will change.

For example, the above list of groups can be rewritten for SCC = 10 as follows:

Type 1: 75/1000 = 7.5% SCC

Type 2: 5/1000 = 0.5% SCC

Type 3: 60/1000 = 6% SCC

Type 4: 10/1000 = 1% SCC

Which can be simplified into;

Type 1: 80/1000 = 8% SCC

Type 3: 70/1000 = 7% SCC

This can be considered to be the simplest form of wind turbine representation without loosing the significant characteristics of the major turbine contributions. The proportion of the wind turbine types representing the turbine group indicates the influence of the WPP on the power grid (i.e., a WPP with the stiffer grid will have a lower impact on the power grid).

Case Study: Multiple Turbine Representation

In this section, an example of equivalencing a WPP is presented in Figure 16. This WPP consists of non-uniform turbines. In this power plant, only two kinds of wind turbines will be considered; 1 MW of type 1 (fixed-speed induction-generator wind turbine) and 3 MW of type 4 (variable-speed wind turbine with full power converter).

The basic assumptions used in the equivalencing method are:

- Assume that all turbines generate rated power at rated current
- Equate the losses within the branch to the total losses
- Find the equivalence impedance
- Assume that inter-turbine cables required are equal to 400 feet.

Since we are interested only on the impedance between two turbines, and for simplicity, we use 400 feet as the distance between two turbines. This number is sufficient for the 3.16 MW-turbine chosen (the distance between these two turbines is more than 3 times the blade diameter).

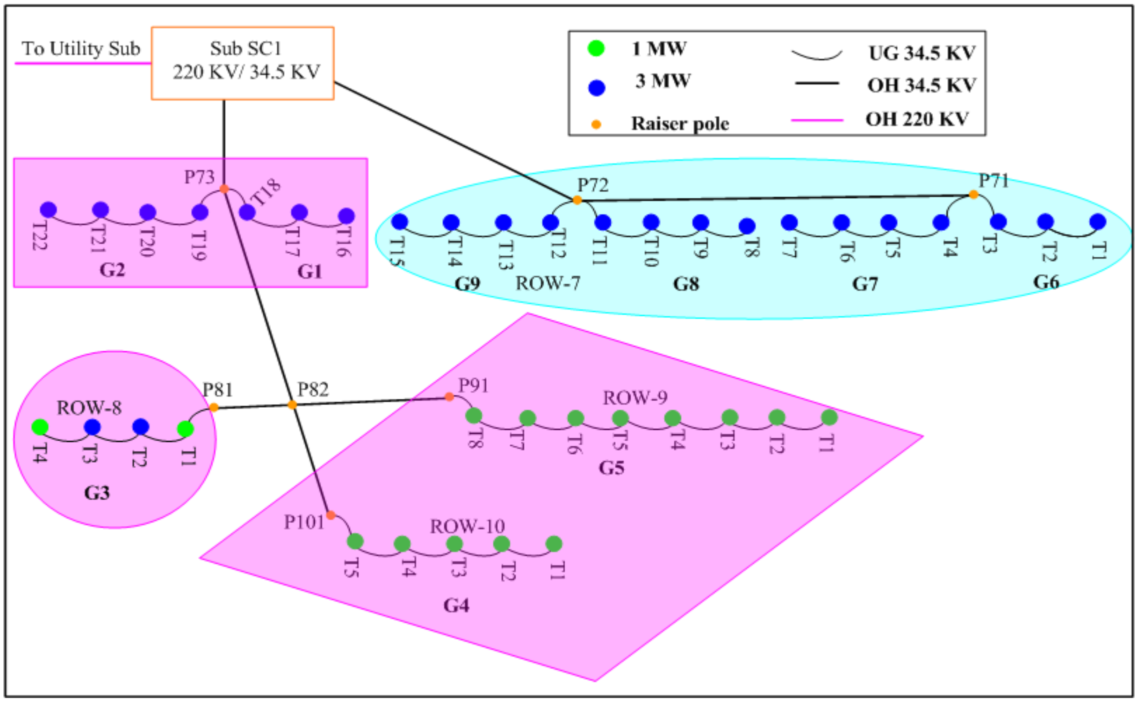


Figure 16. Groups of turbines within a wind power plant

In this equivalencing method, the impedance calculation is taken from the data provided (based on the cable chosen). Using the collector medium voltage of 34.5 kV as our base voltage, and the base apparent power of 100 MVA, we can find the base impedance Z_{base} in Table I.

Table 1. Base at the Collector System

	KVLL (kV)	SBASE (MVA)	Zbase (ohms)
Base	34.5	100	11.9025

Table 2. Typical Values of Impedance Used

34.5 kV	R ohm/ft	X ohms/ft	R pu/ft	X pu/ft
Under Gr.	1.150E-04	9.200E-05	9.662E-06	7.729E-06
Over Head	2.220E-05	1.181E-04	1.865E-06	9.920E-06

Table 3. Daisy Chain Equivalencing

Branch		Gen MW	Dist. in Feet	R in pu	X in pu	Power flow in branch	P^2 R	P^2 X
From	To							
34.5 kV UG - Group 3								
T3	T4	1	400	0.0039	0.0031	1	0.00386	0.00309
T2	T3	3	400	0.0039	0.0031	4	0.06184	0.04947
T1	T2	3	400	0.0039	0.0031	7	0.18937	0.1515
P81	T1	1	400	0.0039	0.0031	8	0.24734	0.19787
Total Gen		8						
34.5 KV OVER HEAD								
P82	P81		1774	0.0033	0.0176	8	0.21173	1.12623
Total							0.71415	1.52817
							0.01116	0.02388
							Req	Xeq

Table 4. Pad-Mounted Transformer Equivalencing

Transformer		Gen Rating MW	Transf. Imp	R in pu	X in pu	Power Flow in Transf.	P^2 R	P^2 X
From	To							
Group 3								
T3	T4	1	ZT4	0	6.8182	1	0	6.81818
T2	T3	3	ZT3	0	3.0063	3	0	27.057
T1	T2	3	ZT2	0	3.0063	3	0	27.057
P81	T1	1	ZT1	0	6.8182	1	0	6.81818
Total		8					0	67.7503
							0	1.0586
							Req	Xeq

Table 5. Summary of Groups Impedance

Group Name	Tot. Pwr MW	# of Turb	Type	Turb. MW	Collector Impedance Z(p.u.)	Trafo Reactance X(p.u.)
Rectangle	21	7	1	4	0.0312+j0.025	0.4295
Circle	8	4	1,3	1,4	0.0112+j0.024	1.0586
Diamond	13	13	1	1	0.0074+j0.018	0.5245
Ellipse	45	15	4	4	0.0064+j0.026	0.2004

Table 6. Summary of Overhead Impedance

Branch Desription		Power Flow (MW)	Distance (Feet)	R in pu	X in pu
From	To				
34.5 KV OVER HEAD					
P101	P82	5	1577	0.0029	0.0156
P91	P82	8	3075	0.0057	0.0305
P82	P81	8	1774	0.0033	0.0176
P82	P73	21	1576	0.0029	0.0156
P72	SUB A-3-1	42	1200	0.0022	0.0119

The typical values of the underground cable and overhead wire impedance in ohms and in per unit are given in Table 2.

As shown in Figure 16, the WPP is divided into 9 groups of turbines connected in daisy chain fashion. The number of turbines within each group varies from 3 to 8 turbines. From this layout, we can configure the WPP into four turbine representations. Different geometrical shapes are used to form the boundary of each turbine representation. There are two types of turbines installed in this WPP. One type of turbine is a type 1 WTG rated at 1 MW, and another type is type 4 WTG with a rating of 3 MW.

Two major feeders connect the groups of turbines to two transformers. The first feeder connects the three turbine representations; the rectangle representation, the circle representation, and the diamond representation. Another feeder connects the groups of turbines enclosed by the ellipse shape. The turbine representation enclosed the ellipse (from G6 through G9) are connected to this feeder. Each group consists of three to four turbines and each type 4 turbine is rated at 3 MW. Turbine representation enclosed by the diamond shape consists of type 1 1-MW wind turbines. Group G4 consists of 5 turbines of 1 MW each connected in a daisy chain, and group G5 consists of 8 turbines of 1 MW each connected in daisy chain. Turbine representation enclosed by the circle consists of only one group G3, which is made of mixed types of turbines (two 1-MW wind turbines of type 1 and 2 and two 3-MW wind turbines of type 4). Since G3 has 75% of the total output represented by wind turbine type 4, the group G3 will be treated as type 4 turbines in the analysis and dynamic simulation, because the contribution of the type 1

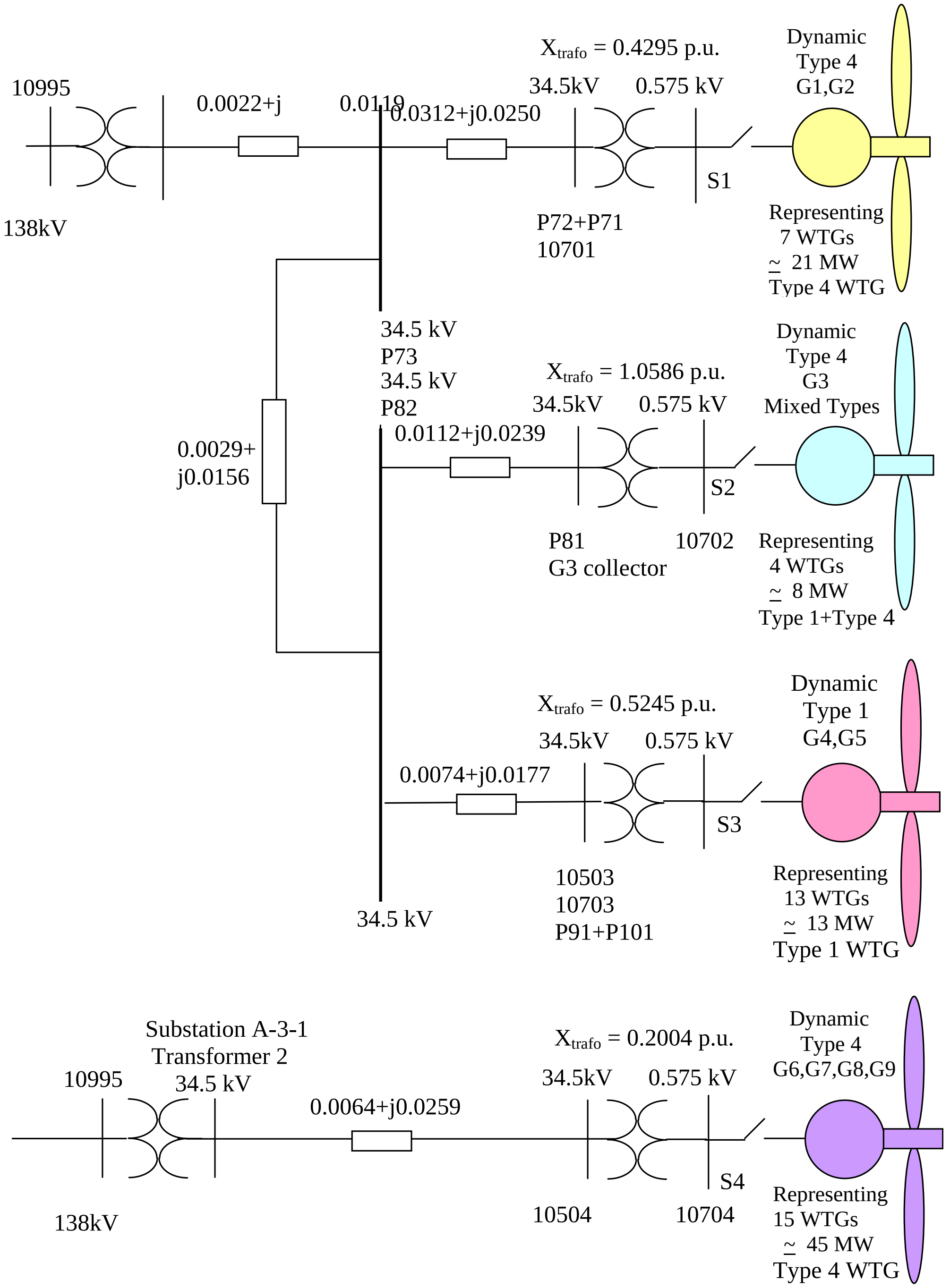


Figure 17. A WPP equivalent with a four-turbine representation

turbine within this group is much smaller than the contribution of type 4 turbines. The rest of the turbines enclosed by the rectangle represented by groups G1 and G2 consist of type 4 3-MW wind turbines.

An example of the calculation for a daisy chain turbine representation is presented in Table 3. This example is taken from the group G3 illustrated as a group of turbines within the circular boundary shown in Figure 16. Note that this group is represented as 8 MW of wind turbine capacity using type 4 instead of type 1 machines.

Table 4 shows the calculation for pad-mounted transformer impedance for group 3 (G3). The calculation for the rest of the turbine representations (rectangle, diamond, and ellipse) can be performed the same way.

Table 5 shows the calculation of the underground cables for the groups of turbines. For example, row 2 (turbines bounded by circle) of the Table 5 is the result calculated from Table 1. Using similar calculations derived in Table 1, representation of the other turbines bounded by rectangle, diamond, and ellipse can be derived.

Table 6 contains the impedances of overhead lines interconnecting the rectangle, circle, diamond, and ellipse shapes, and the substation transformer shown in Figure 16.

The summary of the calculations for the collector system representation is presented in the Table 4 and Table 5. From Tables 4, 5, and 7, we can draw the four turbine representations of the WPP shown in Figure 17.

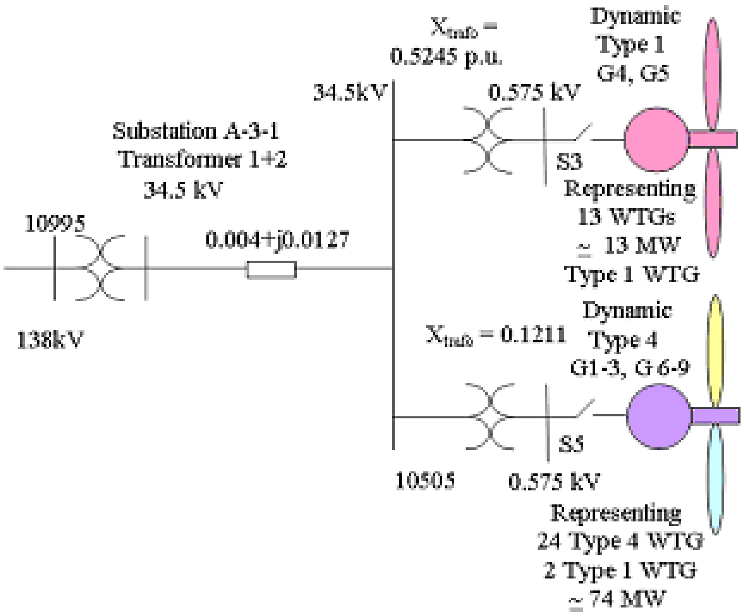


Figure 18. A simplified WPP equivalent with a two-turbine representation

Further simplifications might be considered in lieu of the complete circuit presented previously and based on the assumption that the simplification will not affect the accuracy of the simulation significantly. We can use the equivalent circuit shown in Figure 7 as the starting point. Figure 18 shows the two turbine representations of the WPP. The first turbine representation is of type 1 wind turbines, and the second one is of type 4 wind turbines. Note that there are 2 turbines of type 1 being lumped into the 24 type 4 wind turbines.

The calculations to convert from the “four-turbine representation” as shown in Figure 17 into the “two-turbine representation” as shown Figure 18 are listed in Appendix 1.

6.0 Summary

This report describes methods of equivalencing collector system in a large WPP. We simplified a WPP with 136 wind turbines into a single turbine representation. There are two methods we used in the process of simplification from 136 turbines into a single representation.

The full system representation (FSR) and the single turbine representation (STR) are compared in dynamic performance. To verify the resulting equivalent circuit, we compared the two different turbine representations by using dynamic analysis. The simulation program used is the PSLF package program. The dynamic model used was the detailed model of type 3 WTG available in the library of the PSLF program used. A simple low voltage ride-through (LVRT) voltage profile was used as a test case. Both system representations are subject to this voltage profile and the responses were compared.

What we found advantageous to the STR is that we had the advantage of representing the entire WPP as a simple single turbine. This type of simplification tends to be on the conservative side, especially when the relay protection is included in the simulation run. Thus, if there is a severe fault, there are really only two choices; either the WPP is disconnected or the WPP stays connected. With the FSR, the entire WPP is represented in detail. Thus, the WPP diversity in the line impedances, relay protection setting, and wind speed on each individual turbine can be represented. When a severe fault occurs, we can find out how many turbines will be disconnected from the grid and how many turbines will stay connected to the grid.

This report describes methods used to represent WPPs by equivalence. For various reasons, some WPPs are built with different wind turbines. This diversity of WPPs needs to be represented.

One important aspect of equivalencing is to find a way to group wind turbines into larger groups that sufficiently represents the overall characteristics of WPPs. Several methods of grouping consideration are also presented in this report.

As an example, a case study of a WPP (100 MW) with two substation transformers was presented. Step–by-step equivalencing of the impedances and shunt capacitances was shown to represent the WPP into a four-turbine representation. Further reduction into a two-turbine representation is also shown.

Finally, the decision to represent the WPP in a power system study depends on the power system planners. Any major diversity in the WPP with major contributions to the total output power of the WPP should be represented in the WPP model.

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Glossary

The following acronyms are used in this report:

AWEA	American Wind Energy Association
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
MTR	Multiple Turbine Representation
NMEC	New Mexico Energy Center
NDA	Non Disclosure Agreement
NEC	National Electrical Code
NERC	North American Electric Reliability Council
NOPR	Notice of Proposed Rulemaking
NREL	National Renewable Energy Laboratory
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
SCC	Short Circuit Capability
SCE	Southern California Edison
STR	Single Turbine Representation
TSO	Transmission System Operator
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

Appendix I

Calculation performed to transfer the WPP from a four-turbine representation to a two-turbine representation.

Branch Desription		Group Rating (MW)	R in pu	X in pu	Power Flow in Branch	P^2 R	P^2 X
From	To						
34.5 kV OH							
G1_G2	P73	21	0.0312	0.0250	21	13.7739	11.0191
G3	P82	8	0.0112	0.0239	8	0.7141	1.5282
G4_G5	P82	13	0.0074	0.0177	13	1.2531	2.9933
P82	P73	21	0.0029	0.0156	21	1.2961	6.8943
P73	SUB A-3-1	42	0.0022	0.0119	42	3.9476	20.9978
		Total Output Power of WPP			42	20.9849	43.4327
						0.0119	0.0246
						Req	Xeq
G1_G5	SUB A-3-1	42	0.0119	0.0246	42	20.9849	43.4327
G6_G9	SUB A-3-1	45	0.0064	0.0259	45	12.9487	52.5281
		Total			87	33.9336	95.9608
						0.0045	0.0127
						Req	Xeq

Transformer Description		Group Rating (MW)	R in pu	X in pu	Power Flow in Transf.	P^2 R	P^2 X
	Imped.						
G1_G2	ZT1	21	0.0000	0.4295	21	0.0000	189.3987
G3	ZT2	8	0.0000	1.0586	8	0.0000	67.7503
G6_G9	ZT4	45	0.0000	0.2004	45	0.0000	405.8544
	Total Gen	74					
		Total				0.0000	663.0035
						0.0000	0.1211
						Req	Xeq

Transformer Description		Group Rating (MW)	R in pu	X in pu	Power Flow in Transf.	P^2 R	P^2 X
	Imped.						
G4_G5	ZT3	13	0.0000	0.5245	13	0.0000	88.6364
	Total Gen	13					
		Total				0.0000	88.6364
						0.0000	0.5245
						Req	Xeq

Appendix II

Typical Values of Collector System Impedance

In a power system calculation, it is common to use a system base to compute the per unit values of the impedances. The system base (Sbase) is an arbitrarily chosen size to define, however, the assigned value can also be the same as the size of the WPP. A common value used in many power flow studies is 100 MVA.

To give a general sense of the impedance size of the collector system relative to the WPP, it is convenient to compare the losses (real and reactive power losses) to the size of the WPP. In this section, we will present the per unit values of the collector system impedance versus the size of the WPP. We will use the machine base (MBase), which is the size of WPP rating. The data presented in this section is computed in per unit values and plotted against the rating of the WPP.

Collector System Impedance in p.u. (MBASE)

Plant Size (MW)	Voltage (kV)	Feeder	R pu (pu)	X pu (pu)	B pu (pu)	B/X pu	X/R pu	B/R pu
50	34.5	All UG	*0.014*	*0.011*	*0.032*	*2.33*	*0.77*	*3.02*
100	34.5	All UG	*0.017*	*0.014*	*0.030*	*1.79*	*0.83*	*2.16*
100	34.5	33% OH	*0.018*	*0.079*	*0.030*	*1.67*	*4.37*	*0.38*
100	34.5	All UG	*0.012*	*0.011*	*0.036*	*3.14*	*0.91*	*3.43*
110	34.5	All UG	*0.013*	*0.012*	*0.033*	*2.59*	*0.92*	*2.83*
103	34.5	All UG	*0.009*	*0.018*	*0.044*	*4.59*	*1.88*	*2.45*
112	34.5	All UG	*0.007*	*0.005*	*0.019*	*2.79*	*0.72*	*3.89*
114	34.5	All UG	*0.012*	*0.015*	*0.037*	*3.12*	*1.25*	*2.49*
116	34.5	All UG	*0.012*	*0.016*	*0.039*	*3.13*	*1.30*	*2.40*
200	34.5	Some OH	*0.013*	*0.051*	*0.028*	*2.07*	*3.79*	*0.55*
200	34.5	25% OH	*0.021*	*0.078*	*0.050*	*2.38*	*3.73*	*0.64*
230	34.5	All UG	*0.012*	*0.016*	*0.038*	*3.12*	*1.28*	*2.44*
300	34.5	Some OH	*0.020*	*0.078*	*0.050*	*2.56*	*4.02*	*0.64*
300	34.5	Some OH	*0.015*	*0.060*	*0.028*	*1.94*	*4.08*	*0.47*

The table shown in Appendix II shows the list of collector system impedance values. The shaded row contains overhead lines within the WPP. From the table presented below, we can estimate the size of the real power losses in from the size of the resistive component of the collector impedance (R), and the reactive power losses can be estimated from the size of the reactance. From the data presented in the above table, we can conclude that most of the WPP is designed to have a range of 1% to 2% real power losses in the collector system. The reactive power loss is about 1 – 8%, and is dependent on the type of conductor used in the collector system. A WPP with underground cables has a reactance between 1% and 2%. The ones with overhead wires have reactance values between 5% and 8%. The underground cable tends to have a small size reactance, and the existence of the overhead wires increases the size of the reactance. The effect of overhead conductor can also be seen on X/R ratio size. The overhead wire influences the size of the reactance and it has a larger X/R ratio. The size of the WPP does not seem to influence the size of the collector system impedance.

From the table above, we can find the approximate value of the capacitor compensation needed for a large WPP. For example, if we build a 400-MW WPP with some overhead lines, we can expect to compensate the reactive losses within the WPP by about 8% or 32 MVAR. If the wind plant uses mostly underground cable, the reactive power needed to compensate for the reactive loss is around 2% or 8 MVAR. The expected real power loss in the collector system for a good design within a 1% resistance will be about 4 MW. Obviously, more detailed calculation should be performed to include the transformers and other components within the WPP

FINAL PROJECT REPORT

WECC WIND GENERATOR DEVELOPMENT

Appendix IV
WIND POWER PLANT DATA COLLECTION

Prepared for CIEE By:

National Renewable Energy Laboratory

University of California
ciee
A CIEE Report

Acknowledgments

This work is part of a larger project called WECC Wind Generator Modeling. The support of the U.S. Department of Energy, the Western Electric Coordinating Council, and the California Energy Commission's PIER Program are gratefully acknowledged.

The author expresses his gratitude to the members WECC WGMG and MVWG, General Electric, Siemens PTI who have been instrumental in providing technical support and reviews, and, in particular to Dr. Abraham Ellis of Sandia National Laboratory, who works with us as the Chair of WECC-WGMG and continuously provides technical guidance during the development of this project.

Table of Contents

Appendices

List of Figures

List of Tables

Abstract and Keywords

Wind energy continues to be one of the fastest growing technology sectors. This trend is expected to continue globally as we attempt to fulfill a growing electrical energy demand in an environmentally responsible manner. As the number of wind power plants (WPPs) continues to grow and the level of penetration reaches high levels in some areas, there is an increased interest on the part of power system planners in methodologies and techniques that can be used to adequately represent WPPs in the interconnected power systems.

WPPs can be very large in terms of installed capacity. The number of turbines within a single WPP can be as high as 200 turbines or more, and the collector system within the WPP can have several hundred miles of overhead and underground lines. It is not practical to model in detail all individual turbines and the collector system for simulations typically conducted by power system planners. To simplify, it is a common practice to represent the entire WPP with a small group of equivalent turbine generators or a single turbine generator.

In this report, we will describe the data preparation to validate equivalent models for a large WPP. FPL Energy's 204-MW New Mexico Wind Energy Center (NMEC), which is interconnected to the Public Service Company of New Mexico (PNM) transmission system, was used as a case study. The data requirement for both steady state (power flow) and dynamic models are described in detail. Other reports related to this project will be listed in the references. One report describes methods to derive equivalent models for a WPP with different types and sizes of wind turbine, another report describes the method of wind turbine model validation.

The objective of this report is to describe the data required to perform steady state and dynamic analysis of a WPP. Steady state analysis includes power flow and voltage stability. Dynamic analysis includes the transient, switching, or other dynamic events.

Keywords: Data collection, data acquisition, dynamic model, equivalencing, equivalent circuit, power system, renewable energy, variable-speed wind turbine generation, wind farm, wind power plant, wind turbine, wind integration, systems integration, 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 (WPPs) has also increased significantly. In the past, a typical wind power plant consisted of several turbines. Today, WPP 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 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 WPPs has been acceptable in the past (i.e., 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 WPP in a dynamic model may lead the transmission planners to erroneous conclusions.

The Wind Generator Modeling Group (WGMG) has initiated and will complete the research and development of generic 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 WPP in power system studies. These goals will be accomplished through of the development and validation of standard models, development of an equivalent method for an array of wind generators, and recommended practices for modeling a WPP. 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 (i.e., generic, non-proprietary) dynamic models would 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 (e.g., 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 conduct research without the need to provide for non-disclosure agreements from turbine manufacturers.

With the appropriate dynamic models available for wind turbines, planners could more accurately study transmission congestion or other major grid operating constraints, either from a real-time grid operating 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 electricity supply of grid instabilities and outages, or reduces the amount of power that can be imported into and transported within California and the region within the WECC footprint.

Wind Plant Data Collection is one of the final reports for the WECC Wind Generator Development Project (WGDP), contract number #500-02-004, work authorization number MR-065, a project sponsored by the WECC WGMG, California Energy Commission (Energy Commission), and National Renewable Energy Laboratory (NREL).

1.0 Introduction and Scope

Wind Power Plant Data Collection is one of the final reports for Wind Generator Model Development Project, contract number #500-02-004, work authorization number MR-065, a project sponsored by Western Electric Coordinating Council (WECC) – Wind Generator Modeling Group (WGMG), California Energy Commission (CEC), and National Renewable Energy Laboratory (NREL).

To perform dynamic analysis of a wind power plant (WPP), steady state data must be acquired. Steady state data is the power system network data needed to perform power flow analysis. It is the network between the wind turbine generator (WTG) to the point of interconnection (POI) where the WPP is connected to the rest of the grid. Depending on the type of studies conducted, the boundary of the power system network can encompass a very large region (reliability council such as WECC) or within one control area (Electricity Reliability Council of Texas – ERCOT) or a small set of data to study local power systems, or even a single WPP.

The scope of this document is focused on the WPP data collection related to the project WECC Wind Generator Model Development (WGMD). Thus, the wind turbine model used is the WECC Generic Dynamic Model of Wind Turbines. The software used is the PSLF and PSSE. The examples used in this report are based on model validation performed on a WPP at New Mexico Energy Center.

- Section 1 – Introduction and Scope
    - Section 1 is devoted to the introduction and the scope of the project.
- Section 2 – Background
    - This section provides historical background of the project.
- Section 3 – WPP Data Collection
    - This section describes the two types of data needed (steady state and dynamic).
- Section 4 – Data for Steady State Analysis
    - In this section, the steady-state data requirement for WPP studies for both the power flow analysis and the dynamic analysis is discussed.
- Section 5 – Data for Dynamic Analysis
    - This section describes the data requirement for dynamic analysis covering dynamic models and the corresponding parameter data needed.
- Section 6 – Summary
    - This section gives the summary of the data requirement for WPP studies.

2.0 Background

The size and number of WPPs has dramatically increased and in the United States, there is a potential for 20% of wind energy penetration by 2030. As the level of wind power penetration into the grid increases, the transmission system integration requirements will become more critical [1-2]. Power system planners will need to study the impact of WPPs on the power system in more detail.

A very large WPP may contain hundreds of megawatt-size wind turbines. These turbines are interconnected by an intricate collector system. While the impact of individual turbines on the larger power system network is minimal, collectively, wind turbines can have a significant impact on the power systems during a severe disturbance such as a nearby fault [3-4]. Power flow analysis and dynamic analysis are commonly performed by utility system planners and WPP developers during various stages of WPP development.

There are several types of data needed to study WPPs within the power system environment. The steady state analysis (e.g., power flow, voltage stability) requires the power system network data. The power system network of a WPP collector system consists of the interconnections among the turbines within a group and the connection between the groups of turbines and the POI. The analysis of hundreds of turbines is usually simplified by finding the equivalent of the WPP [5, 7]. This conversion from hundreds of turbines into single turbine representation is not difficult to do and this process needs to be done only once. The dynamic analysis requires representation of generators, loads, and reactive compensations in a dynamic environment. Dynamic models are required to represent the power system components dynamically.

In the past, when the number and the size of WPPs were very small, the analysis of a WPP was very simple. It was common to represent a WPP as a negative load or a simple induction generator. Later, as the size of wind turbines and WPPs became significantly larger, the impact of WPPs could no longer be ignored. In addition, the entry of modern wind turbines equipped with power converters makes them more tolerant to power system transients and fault events. These new types of wind turbines and WPPs must be properly represented in the power system analysis.

Another challenge when studying WPPs was availability of wind turbine models for power system planners. Many wind turbine manufacturers develop and fund their own wind turbine models. Unfortunately, access to these models is typically restricted. Usually, a non-disclosure agreement is needed to get access to these models.

Collaboration among WECC, CEC, and NREL was initiated to develop generic wind turbine dynamic models and make them available for public access. These models are non-proprietary and represent simplified versions of the dynamic models developed by wind turbine manufacturers. These models are also known as WECC generic models.

There are four types of wind turbine dynamic models developed under this collaboration. Type 1 is the induction generator or fixed-speed wind turbine. Type 2 is the wound-rotor induction generator with adjustable external resistor or variable-slip wind turbine. Type 3 is the doubly-fed induction generator (also known as doubly-fed asynchronous generator) or variable-speed wind turbine. Type 4 is a variable-speed wind turbine with an ac generator connected to a power converter, or full-converter WTG.

This report focuses on our effort to prepare data for steady state and dynamic model analysis. In this report, an example of data for a dynamic model validation effort is presented.

3.0 Wind power plant data collection

A typical modern wind power plant consists of hundreds of turbines of the same types. A WTG is usually rated at low three phase voltage output (480 – 600 V). A pad mounted transformer at the turbine step-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 a desired transmission level (e.g., 230 kV). A very large WPP consists of several substations with sizes of 50 MVA or higher for substation transformers. These substations are connected with 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 WPP layout can be seen in Figure 1.

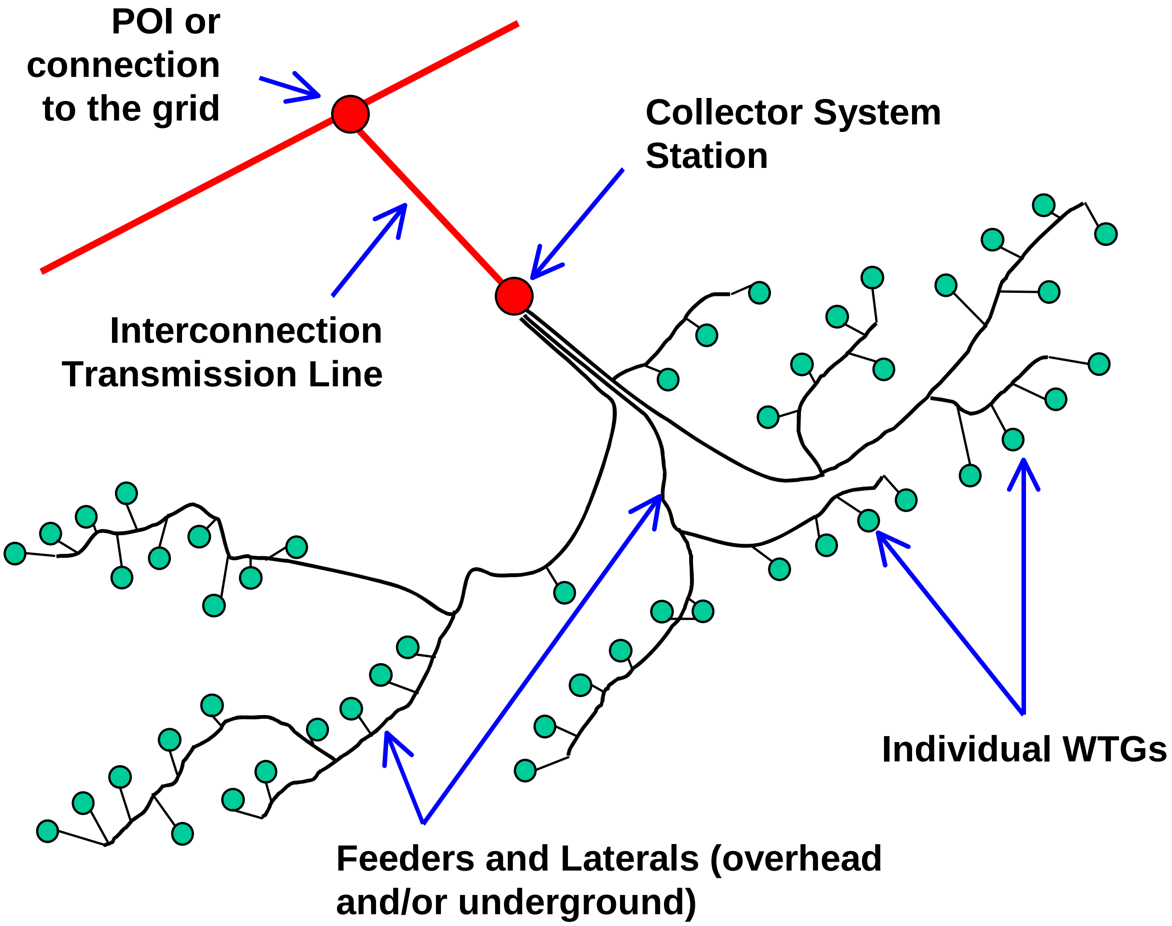


Figure 1. Physical diagram of a typical WPP

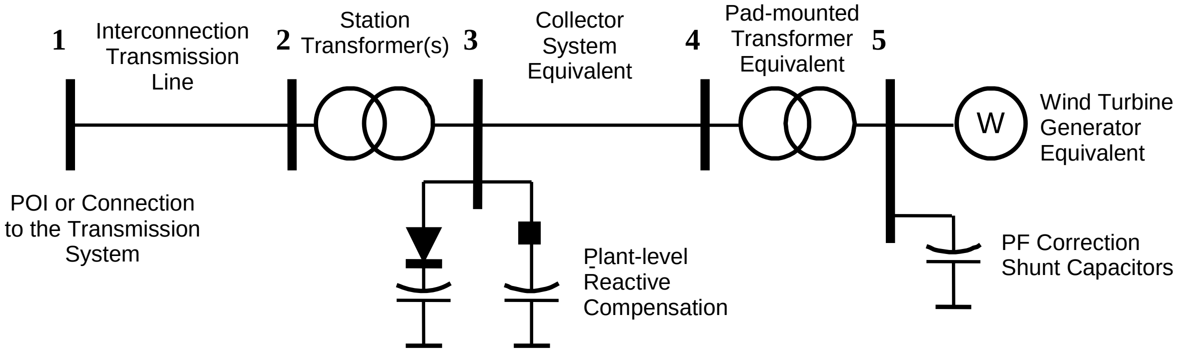


Figure 2. Single turbine representation for a WPP

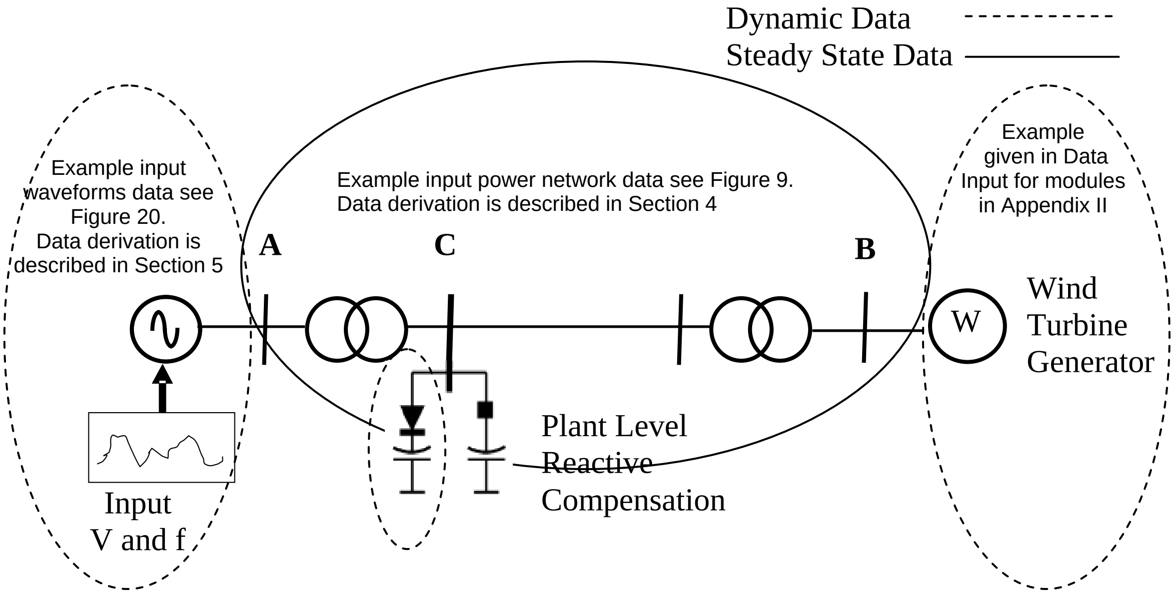


Figure 3 – Steady state and dynamic data groupings.

The power system network operates in a voltage-source environment. In a normal situation, the voltage and frequency at buses are maintained at rated values (voltage = 1.0 per unit, and frequency = 1.0 per unit). Equipment (loads) connected to the grid is designed to operate near its rated value (1.0 per unit). The allowable voltage and frequency deviation is a very limited range. Generally and under normal conditions, voltage can vary in a very limited range (max. 5% under normal conditions and 10% under transient conditions). The frequency variation follows even more strict rules. The narrow range of operation will ensure that the equipment connected to the grid will perform optimally, and the lifetime of the equipment will not be shortened due to overload or over temperature operation (i.e., degrading insulation life). It will ensure the performance of precision equipment, and it will not degrade the quality of the end products of the factory. To maintain normal voltage and frequency, the balance of energy must be maintained at all times. Imbalance in the system degrades the quality of the power system performance. Steady state and dynamic analysis are performed to measure the margin of stability and power system performance under transient events.

The Wind Generator Modeling Group of WECC recommends the use of the single-machine equivalent model shown in Figure 2 to represent WPPs in WECC base cases. This representation is recommended for transient stability simulations and power flow studies [6-7]. In Figure 3, the dashed line circumscribes the power system elements that may require dynamic models. The solid line circumscribes the power system network of a WPP representation.

3.1. Steady State Data Structure

3.1.1. POI

The POI is the point (node, bus) where the utility company grid connects. At this bus, the measuring equipment is usually installed to measure the power flow in and out of the WPP. The transaction between the buyer and seller of produced power is accounted here. The power quality of the WPP demanded by the utility is also determined at this bus. The reactive power or power factor requirement is also determined at this bus.

The location of POI for different sizes of WPPs [8]:

- For a small project (several MW) projects, the POI is Node 3. Thus, the utility owns the substation transformer (between Node 2 and Node 3).
- For a larger project (several hundred MW) projects, the POI is Node 2, thus, the WPP developer or owner owns the substation transformer.
- For very large projects (several hundred MW to several GW), the POI is Node 1. Thus, the developer must install the interconnection transmission line (Node 2 to Node 1) to the low-voltage side of the transmission substation at Node 1. At Node 1, the utility connects its transmission substation to transmit power out of the WPP.

3.1.2. Interconnection Transmission Line (Node 1 – Node 2)

The interconnection transmission line is the line connected from the substation transformer to the utility grid at the transmission substation (Node 1). For a very large WPP, the developer is usually required to build and own this line. Voltage is at the high-voltage level. A major substation (owned by utility) is located at Node 1 and serves as the collection point of several WPPs, and the transformer at this major substation steps the voltage up from a high-voltage level (e.g., 230 kV) to extra high voltage (e.g., 500 kV) to send the wind power over long distance.

3.1.3. Substation Transformer (Node 2 – Node 3)

Substation transformer is the gateway of the WPP to the outside grid. It is the collection point of all generated power by the turbines within the WPP. The substation transformer is located in a WPP at the junction of all feeders from the collector system. Real estate, optimized feeder design, and proximity to transmission lines are considered when determining the location of the substation transformer. The transformer steps up the voltage from the sub-transmission level (e.g., 34.5 kV) to a transmission level voltage (e.g., 230 kV).

3.1.4. Plant Level Reactive Power Compensation (at Node 3)

The plant-level reactive power compensation is usually installed at the low- voltage side of the substation transformer (i.e., Node 3). This node is usually rated at a sub-transmission level (e.g., 34.5 kV). Installation of capacitors or other reactive power compensation at this voltage level is usually more economical. Thus, the reactive power or power factor requirement (e.g., PF = 0.95 under and over excited conditions) at the POI is usually computed based on location of POI, and an approximation of the reactive losses inside the transformers and lines connecting Node 3 to the POI is usually computed based on the name-plate data of the transformer and lines. This calculation should be included in sizing the reactive compensation at Node 3.

3.1.5. Collector System Equivalent Impedance (Node 3 – Node 4)

The collector system in a WPP is a very complex network. The analysis of WPPs using a full system representation (representing all the wind turbines including the interconnected wiring) can be very tedious. It is common to represent a collector system by its equivalent.

Most modern WPPs use underground cable to implement the collector system. The equivalent impedance of a collector system is shown in Figure 4. It is represented as a pi circuit with the resistance representing the real power losses in the WPP and the reactance representing the reactive power losses in the WPP. The capacitance represents the shunt capacitance of the cables. A more detailed derivation of equivalencing the WPP collector system can be found in reference [5, 7].

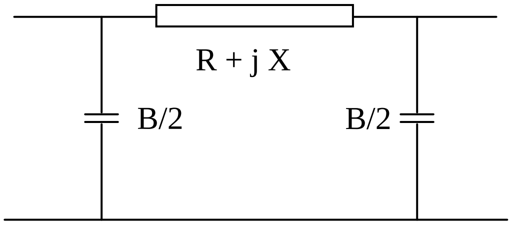


Figure 4. Representation of the collector system line impedance in a WPP

In power system calculations, it is common to use a System Base to compute the per unit values of impedances. The System Base (Sbase) is an arbitrarily chosen defined size, however, the assigned value can also be the same as the WPP size. A common value used in many power flow studies is 100 MVA. To give a general sense of the collector-system impedance size relative to the WPP size, it is convenient to compare losses (real and reactive power losses) to the WPP size. In this section, we will present the per unit values of the collector system impedance versus the WPP size. We will use the Machine Base (MBase), which is the size of the WPP rating. The data presented in this section is computed in per unit values and plotted against the rating of the WPP.

Table 1 – Collector system impedance in p.u. (MBASE)

Plant Size (MW)	Voltage (kV)	Feeder	R pu (pu)	X pu (pu)	B pu (pu)	B/X pu	X/R pu	B/R pu
50	34.5	All UG	*0.014*	*0.011*	*0.032*	*2.33*	*0.77*	*3.02*
100	34.5	All UG	*0.017*	*0.014*	*0.030*	*1.79*	*0.83*	*2.16*
100	34.5	33% OH	*0.018*	*0.079*	*0.030*	*1.67*	*4.37*	*0.38*
100	34.5	All UG	*0.012*	*0.011*	*0.036*	*3.14*	*0.91*	*3.43*
110	34.5	All UG	*0.013*	*0.012*	*0.033*	*2.59*	*0.92*	*2.83*
103	34.5	All UG	*0.009*	*0.018*	*0.044*	*4.59*	*1.88*	*2.45*
112	34.5	All UG	*0.007*	*0.005*	*0.019*	*2.79*	*0.72*	*3.89*
114	34.5	All UG	*0.012*	*0.015*	*0.037*	*3.12*	*1.25*	*2.49*
116	34.5	All UG	*0.012*	*0.016*	*0.039*	*3.13*	*1.30*	*2.40*
200	34.5	Some OH	*0.013*	*0.051*	*0.028*	*2.07*	*3.79*	*0.55*
200	34.5	25% OH	*0.021*	*0.078*	*0.050*	*2.38*	*3.73*	*0.64*
230	34.5	All UG	*0.012*	*0.016*	*0.038*	*3.12*	*1.28*	*2.44*
300	34.5	Some OH	*0.020*	*0.078*	*0.050*	*2.56*	*4.02*	*0.64*
300	34.5	Some OH	*0.015*	*0.060*	*0.028*	*1.94*	*4.08*	*0.47*

Table 1 lists the collector system impedance for different sizes of typical WPPs. The shaded row contains overhead lines within the WPP. From Table 1, we can estimate the size of the real power losses from the resistive component size of the collector impedance (R), and the reactive power losses can be estimated from the size of the reactance. From the data presented in Table 1, we can conclude that most of the WPP is designed to have a range of 1% to 2% real power losses in the collector system. The reactive power loss is about 1 – 8%, and is dependent on the type of conductor used in the collector system. WPPs with underground cables have a reactance between 1% and 2%. WPPs with overhead wires have a reactance between 5% and 8%. Underground cable tends to have a small reactance size, and existence of overhead wires increases reactance size. The effect of overhead conductors can also be seen on the X/R ratio size. Overhead wires influence the size of reactance and they have a larger X/R ratio. The WPP size does not seem to influence the collector-system impedance size.

From Table 1, we can find the approximate value of the capacitor compensation needed for a large WPP. For example, if we build a 400-MW WPP with some overhead lines, we can expect to compensate the reactive losses within WPP by say 8% or 32 MVAR. If the wind plant uses mostly underground cable, the reactive power needed to compensate for the reactive loss is around 2% or 8 MVAR. The expected real power loss in the collector system with a good design within a 1% resistance will be about 4 MW. Obviously, more detailed calculations should be performed to include the transformers and other components within the WPP.

3.1.6. Pad-mounted transformer representation

The pad-mounted transformer is located at the turbine base, although some wind turbine manufacturers place the transformer in the turbine nacelle next to the generator. The transformer is connected to the generators with the proper circuit breaker.

The equivalent of the pad-mounted transformer represents hundreds of transformers connected to the turbines. It must be represented to process the entire WPP output. The equivalent circuit can be scaled so that the resulting voltage drop (leakage) across the impedances and reactive and real power losses are equal to the sum of individual reactive and real losses of the turbines.

The equivalent representation for the entire WPP can be computed as the impedance of a single transformer divided by the number of turbines. Using the same base (SBASE), we can compute the equivalent impedance of the pad- mounted transformer as follows.

$Z_{PMXFMR\_WF} = Z_{PMXFMR\_WTG} / n_{turbine}$

Where:

$n_{turbine}$ = number of turbines represented by Z_{PMXFMR_WF}

Z_{PMXFMR_WF} = impedance of the equivalent of pad-mounted transformer in per unit (System Base) representing $n_{turbine}$

Z_{PMXFMR_WTG} = impedance of single pad-mounted transformer in per unit (System Base)

Note that this equation is valid using the actual values of the impedance (ohms) or using the System Base value. However, use the System Base value for the pad-mounted transformer is recommended when preparing the input for power flow modeling.

3.2. Data for Dynamic Analysis

Dynamic simulation requires that we use the dynamic modules available from the library or user written model [9]. These modules must be present in the dynamic files. The dynamic files are commonly used with a specific extension (i.e., file.dyd for PLSF and file.dyr for PSSE). In the past, many wind turbine dynamic models were not included in the software library. Currently, both PSLF and PSSE include the WECC generic models for wind turbines in the library. Other conventional generators are also available in the library. The input to the dynamic model, as will be described later, is unique for each different turbine manufacturer. Some types of turbines (Type 3 and Type 4) can be operated differently to control the reactive power, or the power factor, or the voltage. For these types of turbines, the user must know the control strategy implemented at the wind plant under investigation and adjust the input accordingly.

3.2.1. Different types of wind turbine models:

As stated above, there are four types of WECC generic models available for WPP dynamic modeling studies. Figure 5 shows the block diagram of a Type 1 WTG.

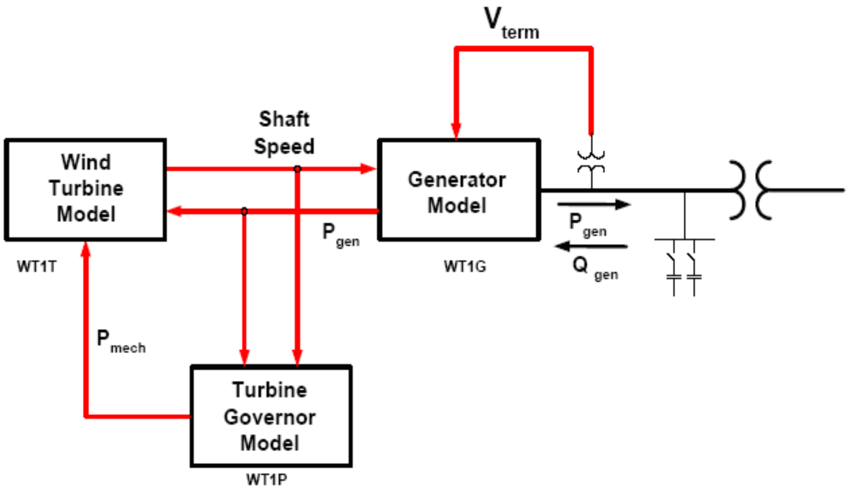


Figure 5 – Type 1 WTG dynamic connectivity.

The Type 1 WTG WECC generic dynamic model consists of a generator model, wind turbine model, and turbine governor model. The pseudo-governor module is a simplified representation of the pitch control. The wind turbine module is a simplified representation of aerodynamic characteristics of the turbine. Thus, no proprietary information is revealed. The generator module consists of induction machine parameters used for the specific turbine.

- The input to the Type 1 WTG must be unique for different manufacturers.
- There is no specific wind-plant control adjustment needed for this model.
- Plant level reactive power compensation, if it is installed, and its dynamic model should be included in the dynamic file.

Figure 6 shows the Type 2 WTG WECC generic model that consists of generator model, rotor resistance control model, wind turbine model and turbine governor model. The additional block diagram WT2E is used to control constant output power in the high wind region by varying the effective external rotor resistance.

- The input to the Type 2 WTG must be unique for different manufacturers.
- There is no specific wind-plant control adjustment needed for this model.
- Plant-level reactive power compensation, if it is installed, and its dynamic model should be included in the dynamic file.

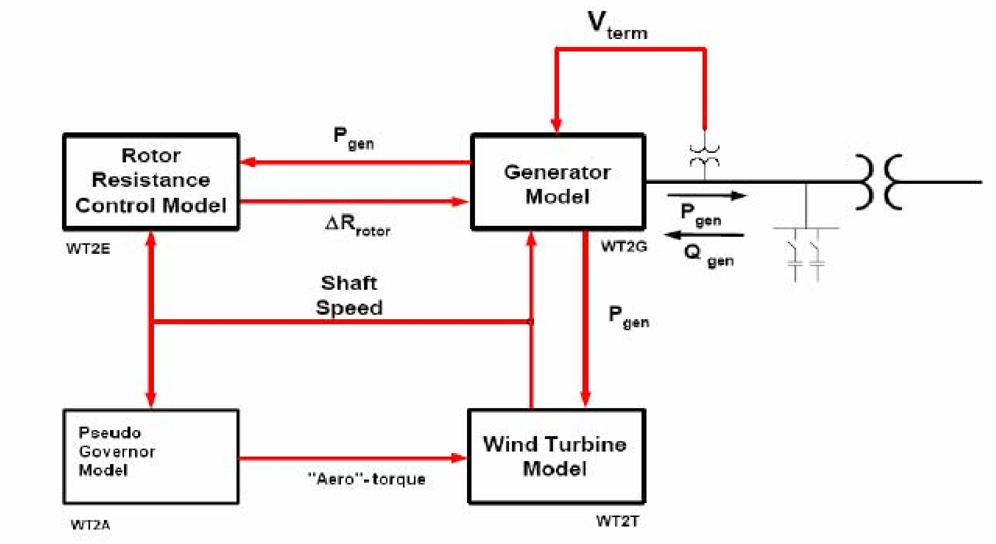


Figure 6 – Type 2 WTG dynamic connectivity

Figure 7 shows the block diagram for a Type 3 WTG WECC generic model. It consists of a doubly-fed induction generator (DFIG). The power converter is used to process the slip power. Because there is electromagnetic coupling between the stator and the rotor, the mechanical dynamic has some influence on the total output power of the generator. In many wind plants with Type 3 WTG, plant-level reactive compensation is not used. However, in a weak grid, it may be used and the corresponding model (if any) should be included in the dynamic file.

The input to the Type 3 WTG must be unique for different manufacturers.

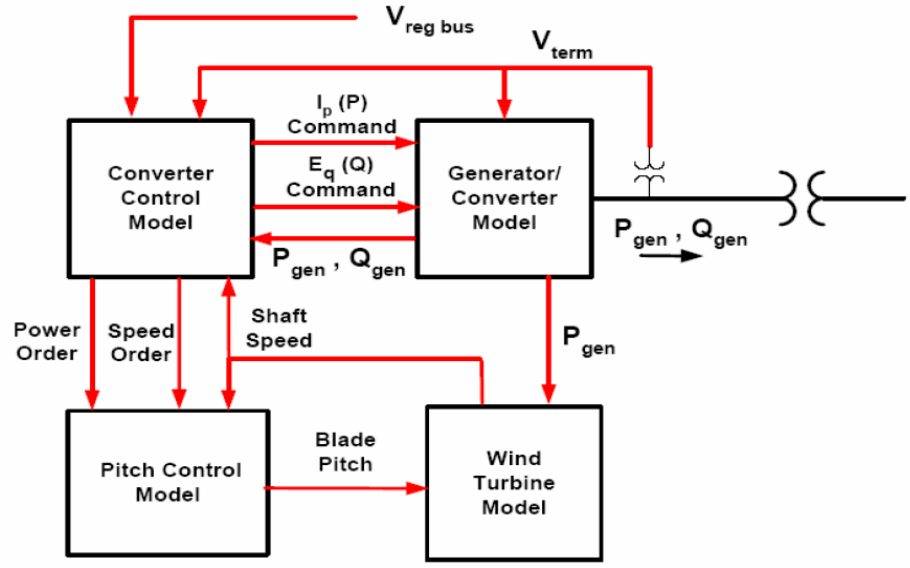


Figure 7 – Type 3 WTG dynamic connectivity

There is flexibility in Type 3 WTGs where a wind plant control-specific adjustment is available for this model.

Separate plant-level reactive power compensation, if it is installed, and its dynamic model should be included in the dynamic file.

Figure 8 shows a Type 4 WTG WECC generic model that consists of a converter model because the interface between the wind turbine and the utility grid is the power converter. All the power generated by the wind turbine is processed by the power converter. The control of the power converter is very dominant in determining the system behavior as it is presented to the grid. The power converter serves as a buffer between the wind turbine and the grid. The power converter is sized to the same rating as the turbine.

Although this type of WTG is able to control the reactive power output and/or the voltage at the POI, plant-level reactive compensation may still be used in case the grid is very weak or if the WTG is controlled to operate at a constant power factor. If the reactive power compensation at the plant level is included, the corresponding dynamic model (if any) should be included in the dynamic file.

The input to the Type 4 WTG must be unique for different manufacturers.

There is flexibility in a Type 4 WTG where a wind plant control-specific adjustment is available for this model.

Separate plant level reactive power compensation, if it is installed, its dynamic model should be included in the dynamic file.

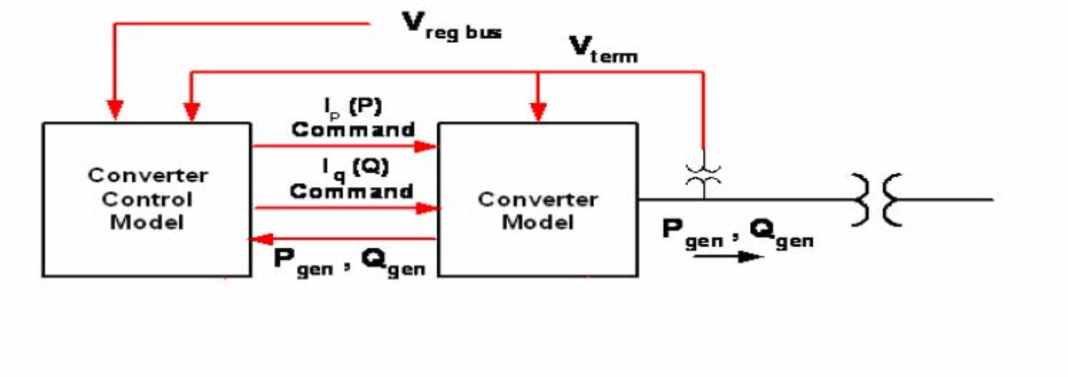


Figure 8 – Type 4 WTG dynamic connectivity

The list of modules for the four types of wind turbine generators described in this section is presented in Table 2.

Table 2 – List of modules for four types of WTGs

WTG Type	PSSE		PSLF		Description
	Module	# input	Module	# input	
Type 1 **(Fixed Speed)**	WT1G1 WT1T1 WT1A1	10 5 8	WT1G1 WT1T1 WT1A1	10 5 8	Generator model Wind turbine model Pseudo turbine-governor model
Type 2 **(Variable Slip)**	WT2G1 WT2E1 WT2T1 WT2A1	19 16 5 10			Generator model Rotor resistance control model Two mass turbine model Pseudo-governor model
Type 3 **(Variable Speed)** **DFIG**	WT3G1 WT3E1 WT3T1 WT3P1	5 37 8 9	WT3G WT3E WT3T WT3P	2 36 7 9	Generator/Converter Mode Converter Control Model Two mass turbine model Pseudo-governor model
Type 4 **(Variable Speed)** **Full Converter**	WT4G2 WT4E1	4 32			Generator/Converter Mode Converter Control Model

4.0 Data for steady state analysis

The term steady state analysis in this section refers to the power flow or load flow analysis commonly performed in power system studies. The data represents the equivalent circuit of the network to be analyzed, different types of buses i.e., generator bus or P-V bus, load bus or P-Q bus, and infinite bus or swing bus.

4.1. Data acquisition

The data needed to perform steady state analysis are as follows:

- The power system network data
    - Outside the WPP
    - Inside the WPP
- Auxiliary components within the WPP
    - Pad-mounted transformer
    - Wind turbine
    - Reactive power compensation (turbine level or plant level)
    - Substation transformers
- Method of operation of the WPP
    - Type of WTG used
    - Method of VAR compensation or voltage control
    - Relay protection settings
- Initialization of the simulation or initial condition.

The power system network data consists of the network outside the WPP and inside WPP. The boundary of the power system network of interest depends on the level of study. For example, to study the inter-area stability between two areas, it may require a very large power system network. On the other hand, to study the interaction between two zones or more, a smaller sized power network can be isolated, and the rest of the outside world can be netted or can be replaced by its equivalent. Data for the power system network can be found and downloaded from the database of the reliability councils or system operators (e.g., ERCOT, MISO, CAISO, and WECC etc.). In many cases, the detailed network is reduced to only major buses to study different aspects of power systems.

The power system network inside WPPs can be acquired from the wind plant developer, owner, or the utility companies at which the WPP is located. However, this information is not easily accessible and in many cases, is considered to be proprietary information.

The following list is the recommended data requested of the wind plant developer or owner needed to study a WPP. The list is taken from the WECC Power Flow Guide [7]:

4.1.1. Interconnection Transmission Line

Line voltage = ______ kV

R = ________ ohm or _______ p.u. on 100 MVA and line kV base (positive sequence)

X = ________ ohm or _______ p.u. on 100 MVA and line kV base (positive sequence)

B = ________ uF or _______ p.u. on 100 MVA and line kV base

4.1.2. Substation Transformer

(NOTE: If there are multiple transformers, data for each transformer should be provided)

- Rating (ONAN/FA/FA): ______/_____/_____ MVA
- Voltage ratio (low side/high side/tertiary): _______/_______/______ kV
- Winding connections: ________/________/________ (Wye or Delta)
- Available taps: ______________ (indicated fixed or ULTC)
- Positive sequence Z: _____%, ____X/R on transformer self-cooled (ONAN) MVA
- Zero sequence Z: _____%, ____X/R on transformer self-cooled (ONAN) MVA

4.1.3. Collector System Equivalent Impedance

This can be found by applying the equivalencing methodology described in Attachment 1; otherwise, typical values can be used.

- Collector voltage = ________ kV
- R = _________ ohm or _______ p.u. on 100 MVA and collector kV base
- X = _________ ohm or _______ p.u. on 100 MVA and collector kV base
- B = _________ μF or _______ p.u. on 100 MVA and collector kV base

4.1.4. Pad-Mounted Transformer

Note: These are typically two-winding air-cooled transformers. If the proposed project contains different types or sizes of pad-mounted transformers, please provide data for each type.

- Rating: ______ MVA
- Voltage Ratio (Low side/High side): _______/_______kV
- Winding Connections: _______/_______ (Wye or Delta)
- Available taps: __________ (please indicated fixed or ULTC)
- Positive sequence impedance (Z1) _____%, ____X/R on transformer self-cooled MVA
- Zero sequence impedance (Z0) _____%, ____X/R on transformer self-cooled MVA

4.1.5. WTG Power Flow Data

Proposed projects may include one or more WTG types (see NOTE 1 below). Please provide the following information for each:

- Number of WTGs: _______
- Nameplate rating (each WTG): ________ MW
- WTG make and model: _______________
- WTG type: __________

For Type 1 or Type 2 WTGs:

- Uncompensated power factor at full load: _______
- Power factor correction capacitors at full load: ______MVAr
- Number of shunt stages and size ___________
- Please attach capability curve describing reactive power or power factor range from 0 to full output, including the effect of shunt compensation.

For Type 3 and Type 4 WTGs:

- Maximum under-excited power factor at full load: _______
- Maximum under-excited power factor at full load: _______
- Control mode: _______________ (voltage control, fixed power factor)
- Please attach capability curve describing reactive power or power factor range from 0 to full output.

NOTE 1:

WTG Type can be one of the following:

- Type 1 – Squirrel-cage induction generator
- Type 2 – Wound-rotor induction machine with variable rotor resistance
- Type 3 – Doubly-fed asynchronous generator
- Type 4 – Full converter interface

NOTE 2:

- Type 1 and Type 2 WTGs typically operate on a fixed power-factor mode for a wide range of output levels, aided by turbine-side power factor correction capacitors (shunt compensation), with a suitable plant-level controller
- Type 3 and Type 4 WTGs may be capable of dynamically the varying power factor to contribute to voltage-control mode operation, if required by the utility. However, this feature is not always available. The data requested must reflect the WTG capability that can be used in practice. Please consult with the manufacturer when in doubt. The interconnection study will determine the voltage control requirements for the project. Plant-level reactive compensation requirements are engineered to meet specific requirements. WTG reactive capability data described above could significantly impact study results and plant-level reactive compensation requirements.

4.2 Data Assembling and Processing

Before we assemble the data to run power flow studies, we need to know the exact location of WPP within the power system network. Typically, these studies are conducted on an existing power flow case.

4.2.1. Power Flow Network Data

The input data to the power flow program is usually available for the rest of the power system network. If possible, use an existing power flow data before the addition of the WPP. Creating power flow input data from the scratch can be very time consuming. The following steps can be followed:

- The WPP information needs to be obtained. The bus number to which the WPP is connected should be indentified. Then, the next step is to compute the data acquired. Choose the corresponding bus number, bus name, kV, and bus ID for WPP buses.

- Convert the actual data (ohm, volt, or amp) into per unit data using the uniform system base (e.g., 100 MVA).
- If the acquired data is already expressed in per unit, but if it uses different bases, convert the old per unit data into the new per unit data using the uniform System Base chosen (e.g. 100 MVA).
- The data for the interconnection transmission line, substation transformer, collector system equivalent and, pad-mounted equivalent impedances must be computed in per unit (using the System Base chosen).
- Assemble the wind plant power-system network data.
- The P_{gen} Q_{gen}, Q_{max}, Q_{min}
    - At the turbine level:
        - Type 1 and Type 2, use the method suggested in WECC Power Flow Guidelines.
            - If data is not provided, set the Q_{gen} by setting the $Q_{max} = Q_{min} = 50\% P_{gen}$.
            - Fixed capacitor is chosen to compensate the reactive power. Usually, it is compensated based on a constant power factor (e.g., PF = 1). $Q_{cap} = 50\% P_{gen}$
        - Type 3 and Type 4
            - Usually, it is set to compensate for reactive power based on the capability of the generator; for example, PF = 0.95 under excited to overexcited.
            - $Q_{max} = P_{max}$*tan(acos(0.95);
            - $Q_{min} = - P_{max}$*tan(acos(0.95))
            - Set the regulated bus number and the regulated bus voltage according to the actual set up (refer to the bus table for V_{sched}, and refer to the generator table to I_{reg}.(bus number to be regulated). Note that this setting must match the dynamic data (*dyd*) file if dynamic simulation is to be performed.
    - At the plant level
        - Use the appropriate model for the reactive power compensation used.

4.2.2. Example of Power Flow Data

The WPP equivalent circuit for the New Mexico Energy Center (NMEC) WPP is shown in Figure 9. This equivalent is a single turbine representation. The WPP consists of 136 turbines with a total capacity of 204 MW [6]. Each wind turbine is rated at 1.5 MW. The wind turbine used is a variable-speed wind turbine (doubly-fed induction generator). Most of the collector systems are underground cables. The method of equivalencing described previously was used to find the equivalent impedances of the collector systems, the pad-mounted transformer, and the station transformer. The System Base used is 100 MVA.

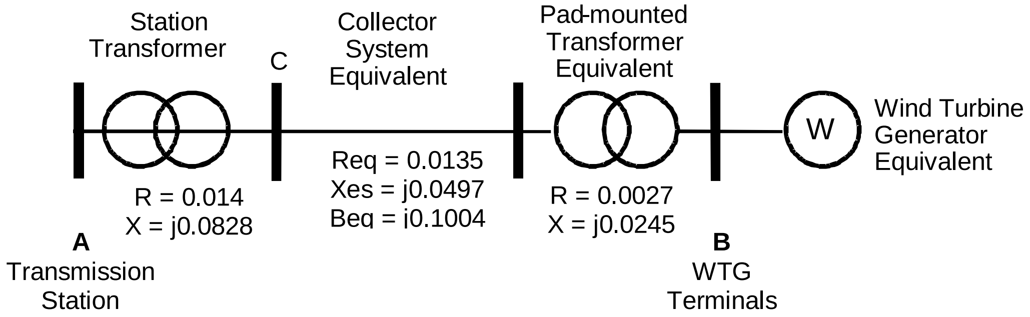


Figure 9 – Single-machine equivalent impedance of NMEC WPP

4.2.3. Power Flow Initialization

In this section, we will describe an initialization process of power flow for dynamic analysis of Type 3 WTGs. The process described here is intended for model validation with field-measured data monitored and recorded at the WPP POI. The data recorded are the instantaneous voltages and currents at high sampling rates.

The approach that can be used to initialize can be prescribed by referring to the single-line diagram shown in Figure 9. The corresponding values of the impedances shown were computed by the equivalencing technique presented in [5, 7].

The following steps should be followed to initialize the power flow program:

- The power network data should be set and predetermined. The simulation should be initialized before running the dynamic simulation.
- Set the bus A voltage to match the recorded pre-fault voltage at bus A.
- This is done by setting the bus A voltage, which is the infinite bus, to the voltage recorded at the pre-fault condition. For this particular event, the voltage at this point is $V_A = 1.05$ p.u.
- Set the level of power generation of the WTG:
- Here, we adjust the WTG generation level. Note that this is data is not available because it is not measured. However, the data recorded at the bus A monitoring equipment during the prefault condition is 115 MW. Since the losses in the substation transformer, collector systems, and the pad-mounted transformer are unknown, we use trial and error to adjust the WTG's P_{gen} to match the pre-fault power at bus A to be equal to $P_{measured} = P_{simulated} = 115$ MW at bus A

- Adjust the regulated voltage V_{reg} at bus C to match the initial $Q_{measured} = Q_{simulated} = 23$ MVAR at bus A

Since the WPP is controlled to keep the voltage at the POI and the voltage at the generator terminal constant, the dynamic model was set to VARFLG = VLTFLG = 1. The regulated voltage (bus C) setting was not recorded. We can use the reactive power output at the POI bus A to determine the setting of the regulated bus voltage. After trial and error, we adjust the regulated voltage at bus C so that the output reactive power at bus A is 23 MVAR.

5.0 Data for Dynamic Analysis

Power system stability is the ability of the system to reach equilibrium after a disturbance with most system variables bounded so that practically the entire system remains intact. Power system stability has been an area of interest since the initial development of interconnected power systems, particularly following the advent of long-distance transmission. The importance of the subject cannot be overstated. Loss of stability can result in severe economic, technical, and social upsets [10-11].

To study power system stability, dynamic analysis is usually performed for the system under investigation. In general, the dynamic data required is the input data for the WTG. The dynamic data is usually contained in an input file with extension .dyd. The input file will have the description of the wind turbine dynamic modules with the appropriate input data for the corresponding wind turbine to be simulated.

For WPP dynamic stability analysis, we are interested in the time scale of seconds to minutes, and in particular, in the post-fault recovery. In this report, we use the GE-PSLF program and PSSE programs. There are many other power system analysis programs available from different vendors. The default time step used in the PSLF is a quarter of a cycle (4 ms). Thus, the program is not intended to study higher frequency components of the events.

5.1. Dynamic Data Acquisition

If the dynamic data is not available from the WECC data base or other public information, you must contact the turbine manufacturers to get the input parameter data of the specific turbine of interest. Since the input data is intended for the Generic WECC model, most manufacturers will consider the information contained in this dynamic data as non-proprietary information (see example provided in Appendix II).

5.2. Wind Turbine Dynamic Data

Referring to Figure 10, the WTG dynamic data for the model and parameter data required for dynamic analysis is specific to each WTG make and model. An example of input parameter for a Type 3 WTG WECC generic model is presented in Appendix II.

As stated in the WECC Power Flow Guide [7], the dynamic models must be in an approved WECC format, or in a PSSE or PSLF format that is acceptable to the transmission provider. Typical values of the generic WECC models can be found in the manual of the PSSE or PSLF.

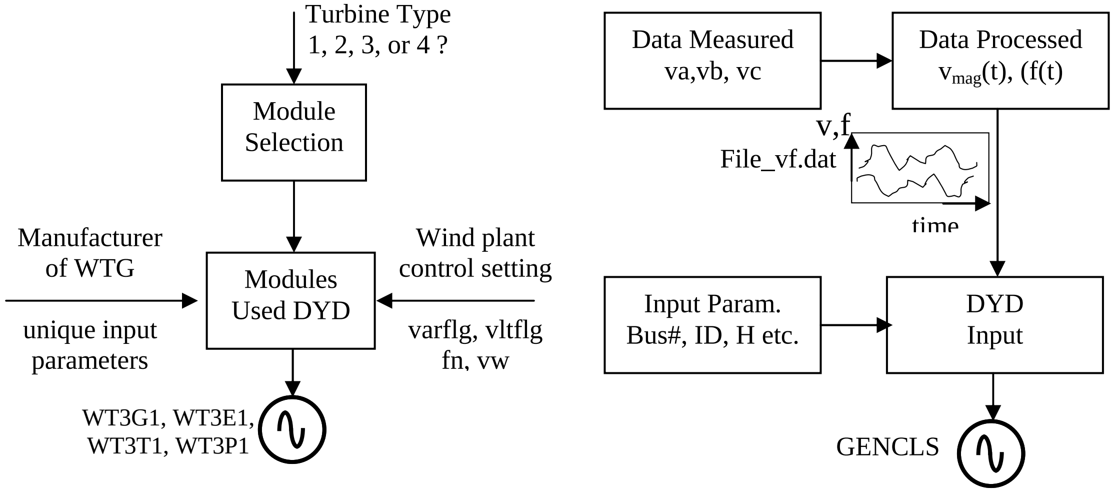
However, to simulate an actual turbine for a specific type and from a specific manufacturer of a WTG, WECC strongly suggests that the manufacturers provide this information.

- Library model name: ______________
- Model type (standard library or user-written): ___________
- Model access (proprietary or non-proprietary): ___________
- Attach full model description and parameter data

5.2.1. The process of creating a dynamic file for a WTG

The process of creating a dynamic file (.dyd or .dyr) for a WPP is illustrated in the flow chart shown in Figure 10a. It consists of several steps:

1) Choose the type of wind turbines use in the simulation
2) Find the corresponding input parameters related to the turbines chosen (manufacturer specific).
3) Wind plant specific controllability:
    a) Voltage control or power factor control or reactive power control
    b) If there is voltage control capability (terminal voltage and remote bus), specify the remote bus to be controlled.



a) Wind Turbine Generator

b) Infinite Bus as a fault simulator represented by GENCLS

Figure 10 – Dynamic model input preparation

Step 1.

For example, we will use PSSE software we will select a WPP with GE-1.5 turbines used. This is a Type 3 wind turbine. We then know the dynamic modules used for GE turbines in PSSE and will have four modules (WT3G1, WT3E1, WT3T1, WT3P1).

Another WPP 30 mile away may be using a different type of wind turbine for example Type 4 turbines. The modules used for this particular WPP will be WT4G1 and WT4E1.

Step 2.

Next, we can find the input parameters for the modules (WT3G1, WT3E1, WT3T1, and WT3P1). Note that the input parameters to these modules are unique to a specific turbine manufacturer. For example, manufacturer X sells a Type 3 WTG, and manufacturer Y also makes a Type 3 WTG. The input parameters to the modules (WT3G1, WT3E1, WT3T1, and WT3P1) for manufacturer X will be different from the input parameters for manufacturer Y.

Step 3.

If the turbine has the capability to control reactive power, determine the type of control setting used for the specific WPP settings being investigated. Set the flags (input parameter to the modules) appropriately (see reference [15] for a more detailed explanation). For example, wind plant A consists of Type 3 WTGs and is set to control voltage at the POI, and wind plant B also consists of Type 3 WTGs, but it is set to generate at a unity power factor at the turbine level.

5.2.2. Unique set of module for the WTG Type and corresponding input parameter

Let's consider the NMEC as an example. The wind turbines installed are Type 3 WTGs (GE 1.5-MW WTG) manufactured by GE. The WECC generic modules for the Type 3 WTG are WT3G1, WT3E1, WT3T1, and WT3P1. The input parameter for a GE-1.5 Type 3 WTG is given in Appendix II. This set of input parameters is presented in Appendix II and is unique to GE-1.5 Type 3 WTGs. The same type of turbine produced by other manufacturers will have a different set of input parameters.

5.2.3. Unique voltage control setting for NMEC WPP

The reactive power control for Type 3 WTG can be used to control the voltage, the power factor, or the reactive power. The NMEC WPP is set to have capability to control the voltage at node C (refer to Figure 9) and the terminal voltage (node A). Thus, there are some changes that must be made to the input parameter of module WT3E1. For this particular WPP, the settings of the flags are:

VARFLG = 1

VLTFLG = 1

The combination of different flags can be found in reference [9] and reference [14].

Another setting the user can specify is the input parameter fn located in module WT3E1 as Fn. Fn is the fraction of WTGs within the wind plant that are on-line. It is used only for VAR control gain adjustment. Since all the turbines are operating in the pre-fault condition, we set Fn = 1

5.2.4. Unique control setting to simulate the initial condition of the blade pitch

The dynamic model Type 3 Generic Model allows the user to set the wind speed condition at the initial condition. This setting is derived from the condition to be simulated. For example, the rated output power of the WPP is 204 MW and the generated power to be simulated is 115 MW. The input parameter Vw, located in module WT3T1, can be used to adjust the initial blade pitch condition. Note that if Vw > 1, the blade pitch will be adjusted to a certain pitch angle. Since the output power is less than rated value (115 MW < 204 MW), we can set the value of Vw < 1 (e.g., Vw = 0.2 p.u.). The value itself is not important for Vw<1 because when Vw < 1, the blade pitch angle is set to $\theta = 0^o$.

5.3. Infinite bus representation

Referring to Figure 10b, the infinite bus is represented by a generator classic GENCLS (Appendix II lists the input example of GENCLS). This module allows the voltage and frequency profiles to be specified. The input data to this module is an input file containing three columns. The first one is the time indicator. The second column is the time series of voltage, and the third column is the time series of the frequency.

5.3.1. Field Measurement for Dynamic Data for Model Validation

Occasionally, field-data measurement is needed to verify or validate a dynamic model. The field data is a set of data measured at the POI. The data is recorded at high sampling rates and the recording is triggered by transient event and used to record the event from pre-fault to post-fault, or approximately 2 – 4 seconds of data. The data measured is used to drive the simulation, and the response of the wind plant model simulated is compared to the actual measured data.

5.3.2. Location of data monitoring equipment

The location of data monitoring equipment is usually at the substation POI. At this location, the output of the WPP is measured by the utility and the transaction is conducted based on the measured data. This location is accessible to the utility personnel. Because of the level of the voltage at this point, the maintenance of the monitoring equipment should be coordinated with the utility company to which this WPP is connected. Usually, if there is a problem with the monitoring equipment and we need to reset or restart the equipment, we need to send someone to perform this action with utility permission and accompanied by utility staff. Sometimes the utility will volunteer to reset the equipment.

An example of the diagrams showing the location of monitoring points and an example of the data flow from monitoring equipment in a WPP are shown in Figures 11 and 12, and based on reference [12].

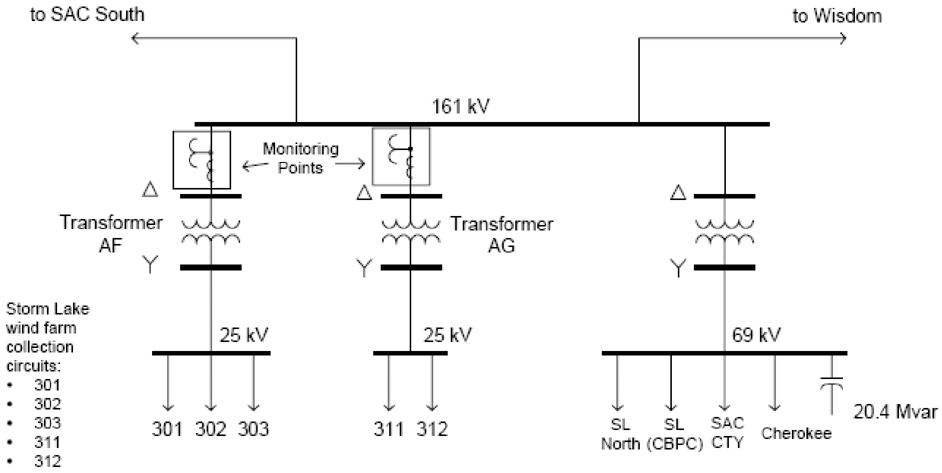


Figure 11 – Example of one-line diagram of the substation connected to collector systems.

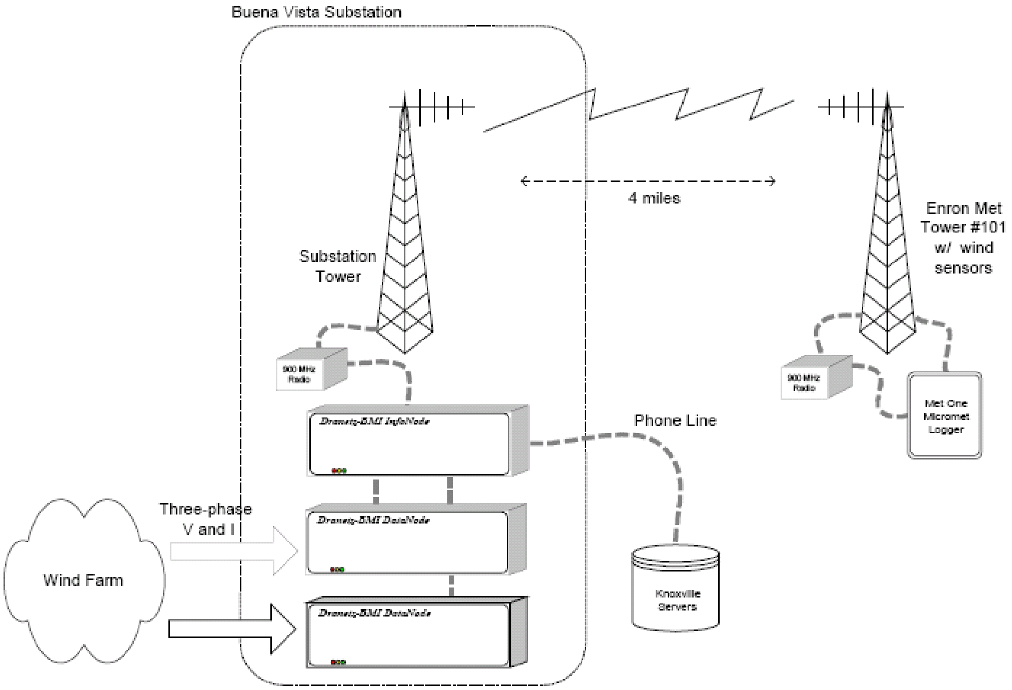


Figure 12 – An example of the data flow of monitoring equipment in a WPP.

5.4. High-Speed Data Collected

The high-speed data collected at the POI consists of the following:

- Per phase voltages (V_{an}, V_{bn}, V_{cn})
- Line Currents (I_a, I_b, I_c)
- Sampling rates (5 kHz – 10 kHz)

This data collected will be preprocessed to drive the simulation as input to the generator classic GENCLS representing the infinite bus.

5.4.1. The per phase voltage waveforms

It can be seen in Figure 13 that the three-phase voltage currents v_{an}, v_{bn} , and v_{cn} recorded are symmetrically balanced voltages in the pre-fault condition. The fault occurs in the transmission lines in the vicinity of the WPP. It can be seen that the three-phase voltage becomes an unbalanced voltage with phase B dropping significantly for a period of four cycles, before the fault is cleared. The post-fault condition shows that the three-phase voltages recover to normal again and a small oscillation is shown on the three-phase waveforms.

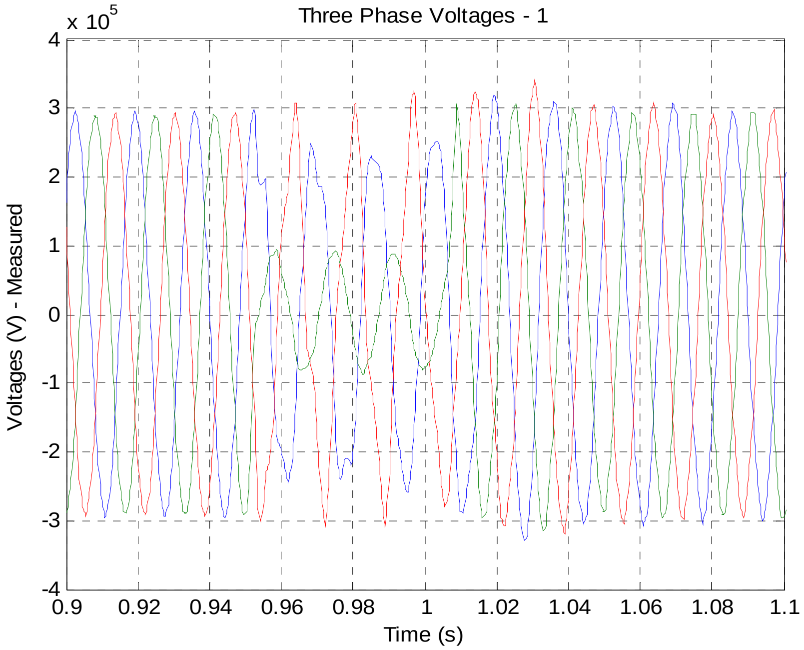


Figure 13 – The per phase voltages van, vbn , and vcn as recorded

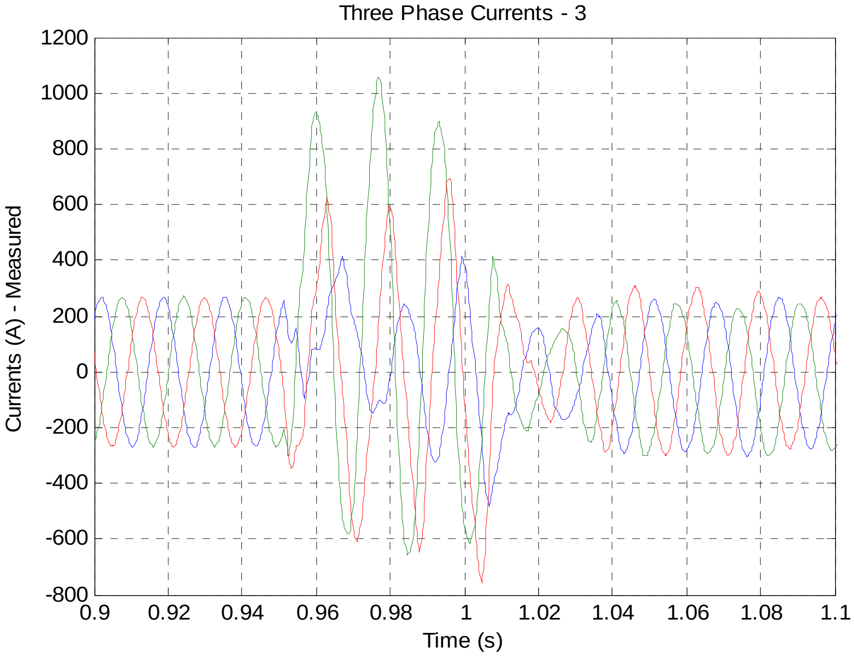


Figure 14 The line currents ia, ib , and ic as recorded

5.4.2. The Line Current Waveform

The three line currents are shown in Figure 14. The line currents are seen to increase momentarily during the fault event. Figure 14 shows that the largest current increase is the phase B line current corresponding to the lowest voltage drop. It is also shown that the corresponding response of line currents shows the time when the fault is removed from the grid after about 4 cycles. The corresponding post-fault condition indicates a similar oscillation as shown in the voltage response.

5.5. Data Processing

To validate the model representing the WPP under investigation, we perform pre processing of the data. The sequence of the analyses is as follows:

1) Identify the power system network data where the WPP power system network is identified and the collector system equivalence is found and represented in the power system network
2) Simplify the outside power system network by representing it as a voltage source.
3) Represent the voltage source by its voltage magnitude and frequency.

The power system network is represented properly. The fault and the outside power system network are represented by its equivalent voltage source. In the PSLF, we found GENCLS models that can represent the voltage magnitude and the frequency. Since we do not have the information for frequency, we convert the frequency from the phase angle.

5.5.1. Processing Data for PSLF Simulation

The dynamic model to be validated is available in PSSE and PSLF programs. To use PSLF program, we need to get the input data to be fed to the simulator. The input data will be the captured voltage waveform at the POI representing the fault and the outside power system network. The PSLF program can only take the voltage magnitude and frequency as a function of time. Thus, conversion from the sinusoidal voltage waveform into the voltage magnitude and frequency needs to take place. The process of converting monitored voltage data into input data is illustrated in Figure 15. More detail information can be found in Reference [13].

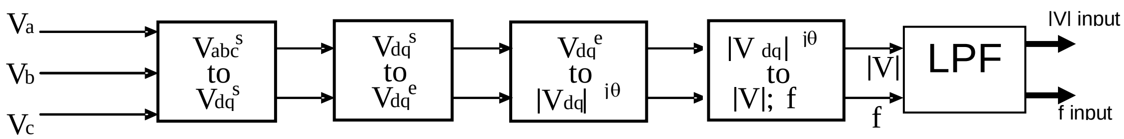


Figure 15 – Block diagrams indicating the flow process to convert the monitored voltage into the input data for GENCLS module

In the first step, raw data is processed from the sinusoidal wave forms in the a, b, and c axis in the estationary reference frame into the d-q axis component in the stationary reference frame. The equation used to convert abc to dq can be expressed by the following equations:

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

Where:

f = a variable that can be substituted by voltage or current.

s = subscript used to indicate the stationary reference frame.

The voltages in d-q axis and stationary reference frame are shown in Figure 16.

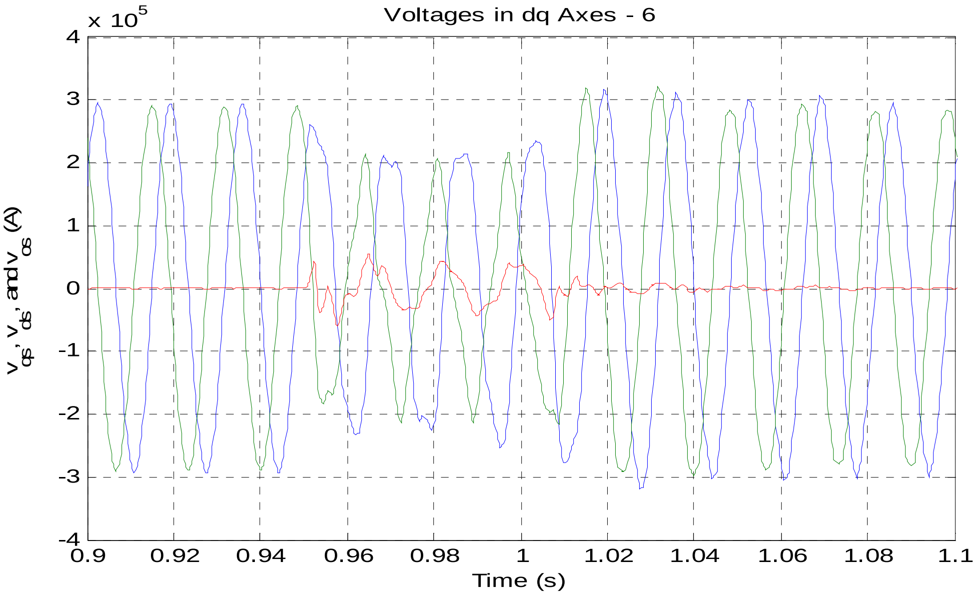


Figure 16 – The voltages expressed in the dq axis in a stationary reference frame

The PSLF program allows the user to simulate the voltage and frequency by using the generator classic module (GENCLS). This module takes the voltage magnitude and frequency as the input read from an input file. To convert from data recorded, which is in sinusoidal form, we need to convert the data from a stationary reference frame into a rotating reference frame, or more precisely, to a synchronous reference frame. The conversion can be expressed in the following equation.

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

Where:
s = subscript used to indicate the stationary reference frame.
e = subscript used to indicate the synchronous reference frame.

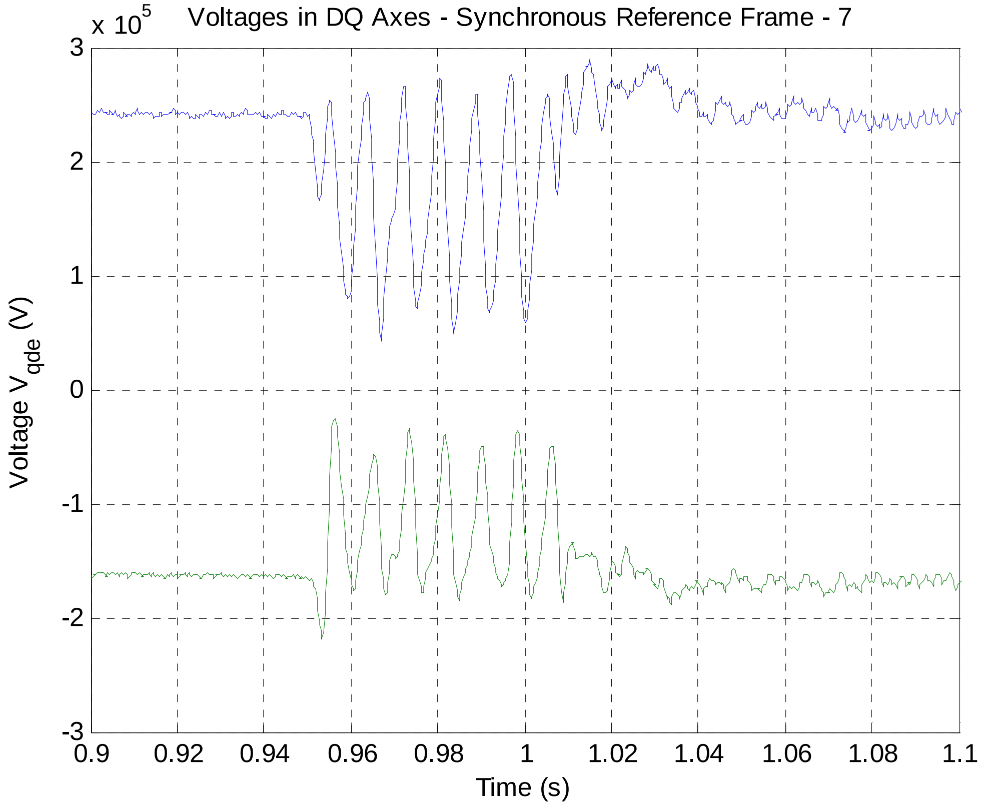


Figure 17 – The voltages expressed in the dq axis in a synchronous reference frame

The resulting dq voltage in the synchronous reference frame is given in Figure 17. It is shown in the pre-fault to post-fault events, and it shows that the voltage is steady in the pre-fault condition. It changes during the fault, and it settles down during the post-fault event.

To use the dq voltage for the input to the program, we convert the voltage in the synchronous reference-frame phasor quantities using the following equation:

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

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

The resulting voltage waveform (its magnitude and its phase angle) is shown in Figure 18. The trajectory of the voltage phasor is presented in Figure 19, where both the voltage magnitude and phase angle can be traced in the polar coordinates.

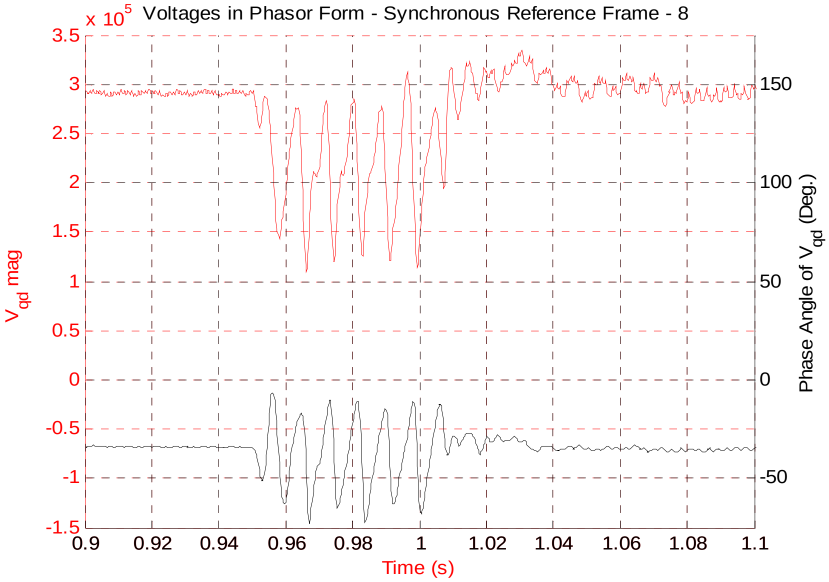


Figure 18 – The voltage expressed in its magnitude and phase angle

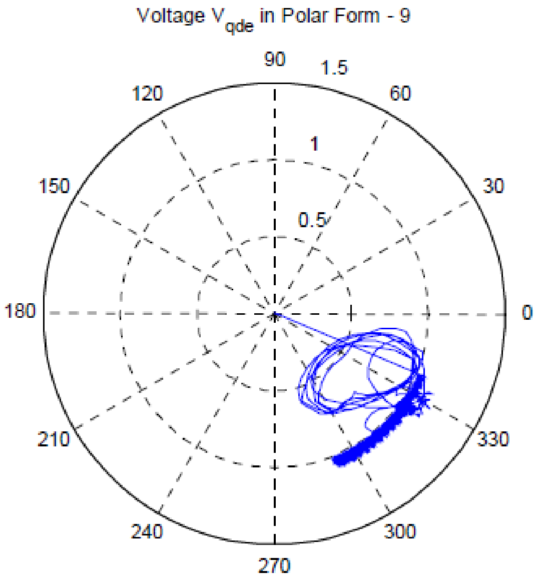


Figure 19 – The trajectory of voltage expressed in its polar form as time progressed from 0 to 4 seconds

Since the module simulating the voltage source GENCLS uses the voltage magnitude and its frequency, we need to convert the phase angle information to the corresponding frequency changes. The frequency changes can be computed from the phase angle changes divided by the time step.

$\Delta f\,(t) = \Delta\theta_{qde} / \,(2\pi\,\Delta t)$

Another aspect of PSLF program is that the program is not designed to estimate the high frequency component of the transient event (time step ~ 4 milliseconds), and the voltage and frequency input data needs to be filtered by a low pass filter to remove the high frequency components. Finally, the input data (voltage and frequency) ready to be used in module GENCLS is presented in Figure 20. An example of an input file containing voltage and frequency for the GENCLS is given in Appendix II.

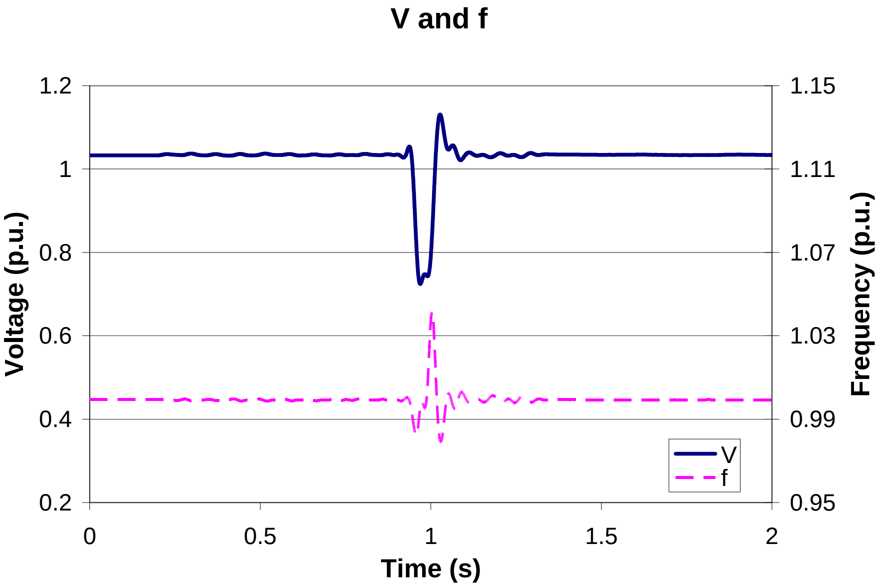


Figure 20 – Input data to GENCLS to perform the dynamic simulation

6.0 Summary

This report describes the data required to study a WPP. The example taken is a specific WPP at the NMEC with a case study based on validating the WPP. The validation method used can be found in reference [15].

The data required can be divided into two parts; the steady state data needed to solve the power flow portion of dynamic simulation, and the dynamic data needed to solve the electro-mechanical interaction between the grid and the WTGs.

The steady state data is mostly power system network data of the WPP. Since a WPP consists of hundreds of turbines, the collector system is simplified by equivalencing thee WPP into a simple representation (e.g., single turbine representation). A report on the equivalencing method can be found in reference [16].

The dynamic data consists of the wind turbine dynamic model and the infinite bus dynamic model.

- The wind turbine model requires the use of several modules corresponding to the turbine type used in the simulation. The input to these modules is unique for each turbine manufacturer.
- Special flags and several parameter values of the WTG modules need to be set to reflect the unique characteristic of the WPP voltage/reactive power control strategy, and the wind speed condition to initialize the pitch angle.
- The infinite bus dynamic model requires the use of the GENCLS model that allows the user to simulate a fault condition by using the time series of voltage and frequency contained in a file. The voltage and frequency used are captured by a field measurement at the POI.
- However, the raw data from the monitoring equipment cannot be used directly by the GENCLS. It must be pre processed before we can use it to simulate the fault event captured at the POI.

Glossary

The following acronyms are used in this report:

AWEA	American Wind Energy Association
CEC	California Energy Commission
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
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
NMEC	New Mexico Energy Center
NDA	Non Disclosure Agreement
NREL	National Renewable Energy Laboratory
PF	Power Factor
PIER	Public Interest Energy Research
PNM	Public Service of New Mexico
POI	POI
PSLF	Positive Sequence Load Flow
PSSE	Power System Simulator for Engineers
STR	Single Turbine Representation
TSO	Transmission System Operator
WECC	Western Electricity Coordinating Council
WGMG	Wind Generator Modeling Group
WTG	Wind Turbine Generator
WF	Wind Farm
WPP	WPP

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Appendix I
An Example of the Collector System Impedance Calculation

An example of collector system data usually provided in a spread sheet format in an excel file by the wind plant planner. Table A.I-1 and Table A.I-2 are typical spread sheet used to compute the line impedance. The size of the cable impedance can be calculated and given the length and the type of the line feeder.

A single-line diagram of the layout of the WPP will be needed to compute the equivalence of the collector system.

Table A I-1. Example of specific impedance values for different cables and conductors

Circuit Arrangement	Cable Size	R ohm/K ft	X ohm/K ft	C uMHO/K ft	Ampacity	C ohm x 1000'
dbl ckt strs >	795-2	0.0244	0.118	1.297	989	2.74E+04
single ckt >	795-1	0.0244	0.117	1.31	989	2.77E+04
	1000	0.040	0.058	31.90	605	3.14E+04
	4/0	0.112	0.083	17.89	267	5.59E+04

Table A.I-2. Example calculation of impedance given the length and type of feeder

Feeder Number	fr bus number	fr bus name	to bus number	to bus nm name	Length Ft	cable size	R1 per unit	X1 per unit	Bc per unit	Rating MVA
12	106	H1	107	H2	1945	4/0	0.01827	0.01362	0.000414	16
3	107	H2	108	H3	970	4/0	0.00911	0.00679	0.000206	16
3	108	H3	151	LB1	590	4/0	0.00554	0.00413	0.000126	16
3	151	LB1	109	H4	755	4/0	0.00709	0.00529	0.00016	16
3	109	H4	110	H5	1200	4/0	0.01127	0.00840	0.00026	16
3	110	H5	111	H6	1300	4/0	0.01221	0.00910	0.00028	16
3	111	H6	112	H7	550	4/0	0.00517	0.00385	0.00012	16
3	151	LB1	198	SUB	30000	1000	0.10160	0.14622	0.01139	36

Appendix II

An Example of the Dynamic Data in PSLF Format

a) Type 3 GE 1.5 MW Wind Turbine Generator

b) Generator Classic GENCLS

a) An example of dynamic data for a GE 1.5-MW Type 3 Wind Turbine (for PSLF WECC Generic Model) is given below.

```
#
#  Generator
#
wt3g   40015 "WIND 3  "  0.600 "W " : #9 mva=670.0 /
"lpp"     0.8
#
#  Generator and Converter
#
wt3e   40015 "WIND 3  "  0.600 "W "  40013 "WIND 3  " 34.5  "1 "  1 : #9   mwcap=670.0 /
"varflg"   1.0          /
"vltflg"   1.0          /
"tsp"      5.0          /
"kptrq"    3.0          /
"kitrq"    0.6          /
"tpc"      0.05         /
"pmax"     1.12         /
"pmin"     0.1          /
"pwrat"    0.45         /
"ipmax"    1.1          /
"wpmin"    0.69         /
"wp20"     0.78         /
"wp40"     0.98         /
"wp60"     1.12         /
"pwp100"  0.74          /
"wp100"    1.20         /
"kqi"      0.10         /
"kqv"      120.0        /
"qmax"     0.436   "qmin"    -0.436   /
"vmax"     1.10    "vmin"     0.900   /
"xiqmax"   1.55    "xiqmin"   0.55    /
"tp"       0.05         /
"xc"       0.0          /
"tr"       0.050        /
"fn"       1.00         /
"kiv"      5.0          /
"kpv"      18.0         /
"tv"       0.05         /
"tc"       0.15
```

```
#
#  Turbine
#
wt3t    40015 "WIND 3  "  0.600 "W " : #9   /
"vw"      0.44           /
"h"       4.95           /
"d"       0.0            /
"kaero"   0.007          /
"theta2"  21.98          /
"htfrac"  0.8747         /
"freq1"   1.80           /
"dshaft"  1.50
#
# Pitch controller
#
wt3p    40015 "WIND 3  "  0.600 "W " : #9   /
"kpp"    150.0           /
"kip"     25.0           /
"kpc"      3.0           /
"kic"     30.0           /
"pimax"   27.0           /
"pimin"    0.0           /
"pirat"   10.0           /
"tpi"      0.3           /
"pset"     1.0
```

b) An example of dynamic data for generator classic GENCLS (for PSLF WECC Generic Model) is given below. GENCLS is a synchronous machine represented by "classical" modeling or Thevenin voltage source to play back known voltage/frequency signal.

```
gencls  10999 "TAIBANMS" 138.00 "1 " : #9 mva=99999.0000 "h" 999999.0000 "d"
0.0000 "ra" 0.0000 "lppd" 0.200 "vbias" 0. "fbias" 0. "to" 0.0 "plyfil" vsteps2a.txt
```

The file vstep2a.txt is the input file consists of 129 data points with the columns of time in seconds, voltage in per unit, frequency in per unit. The file can be displayed as follow:

```
        129
           0.         1.03285    0.99941    0.000    0.000    0.000
           0.20020    1.03285    0.99941    0.000    0.000    0.000
           0.20046    1.03287    0.99942    0.000    0.000    0.000
           0.92638    1.03284    1.00012    0.000    0.000    0.000
           0.92664    1.03331    1.00016    0.000    0.000    0.000
           0.93314    1.04843    1.00029    0.000    0.000    0.000
           0.93470    1.05154    0.99994    0.000    0.000    0.000
           0.93496    1.05196    0.99986    0.000    0.000    0.000
```

```
 0.99268    0.74470    1.01356    0.000     0.000     0.000
 0.99294    0.74520    1.01443    0.000     0.000     0.000
 1.00490    0.86179    1.04088    0.000     0.000     0.000
 1.00516    0.86629    1.04064    0.000     0.000     0.000
 1.04624    1.05347    0.99955    0.000     0.000     0.000
 1.04650    1.05279    0.99980    0.000     0.000     0.000
 1.05820    1.05244    1.00034    0.000     0.000     0.000
 1.05846    1.05276    1.00018    0.000     0.000     0.000
 1.05872    1.05307    1.00002    0.000     0.000     0.000
 1.08082    1.02686    0.99981    0.000     0.000     0.000
 1.08108    1.02642    0.99997    0.000     0.000     0.000
 1.10136    1.03401    1.00016    0.000     0.000     0.000
 1.10162    1.03428    1.00007    0.000     0.000     0.000
 1.16558    1.03032    0.99901    0.000     0.000     0.000
 1.16584    1.03022    0.99906    0.000     0.000     0.000
 1.19236    1.03437    1.00020    0.000     0.000     0.000
 1.19262    1.03450    1.00015    0.000     0.000     0.000
 1.19314    1.03477    1.00005    0.000     0.000     0.000

                                .
                                .
                                .

 4.00400    1.03367    0.99961    0.000     0.000     0.000
 4.00426    1.03367    0.99961    0.000     0.000     0.000
10.0000    1.0000     1.0000     0.0000    0.0000    0.0000
                               end
```

FINAL PROJECT REPORT

WECC WIND GENERATOR DEVELOPMENT

Appendix V
MODEL VALIDATION OF WIND TURBINE GENERATOR

Prepared for CIEE By:

National Renewable Energy Laboratory

University of California

ciee

A CIEE Report

Acknowledgments

This work is part of a larger project called WECC Wind Generator Modeling. The support of the U.S. Department of Energy, the Western Electric Coordinating Council, and the California Energy Commission's PIER Program are gratefully acknowledged.

The author expresses his gratitude to the members WECC WGMG and MVWG, General Electric, and Siemens PTI who have been instrumental in providing technical support and reviews, and, in particular to Dr. Abraham Ellis of Sandia National Laboratory, who works with us on this project as the Chair of WECC-WGMG, and continuously provides technical guidance during the development of this project.

Table of Contents

List of Figures

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
    - Section 1 is devoted to the introduction and project scope.
- Section 2 – Background
    - This section provides historical background and the requirement for a generic dynamic model of a wind turbine generator.
- Section 3 – Wind Turbine Dynamic Model
    - 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
    - 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
    - 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
    - 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
    - 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.

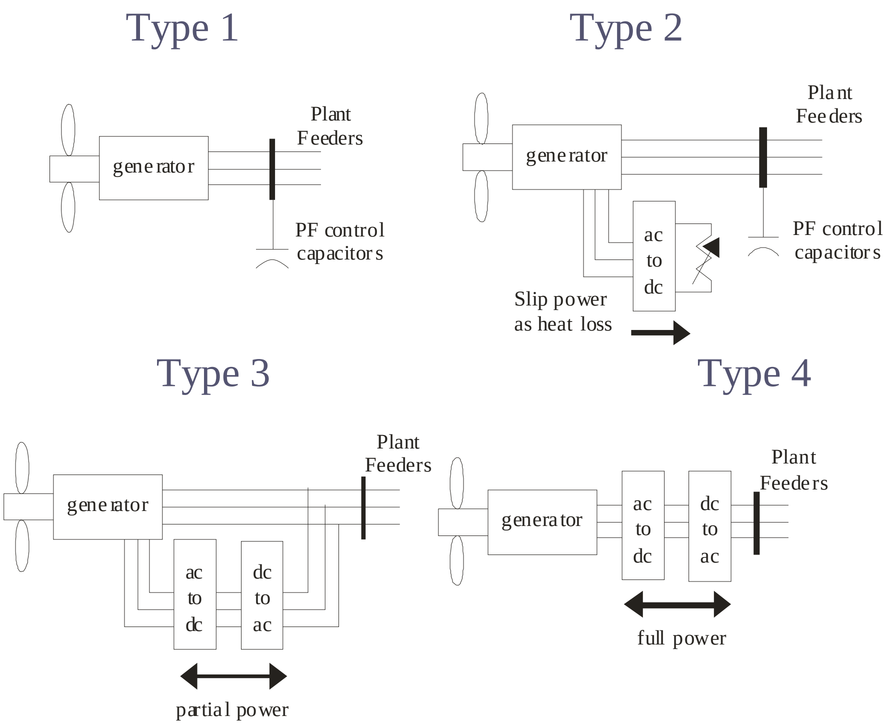


Figure 1. Four types of wind turbine generator models

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.

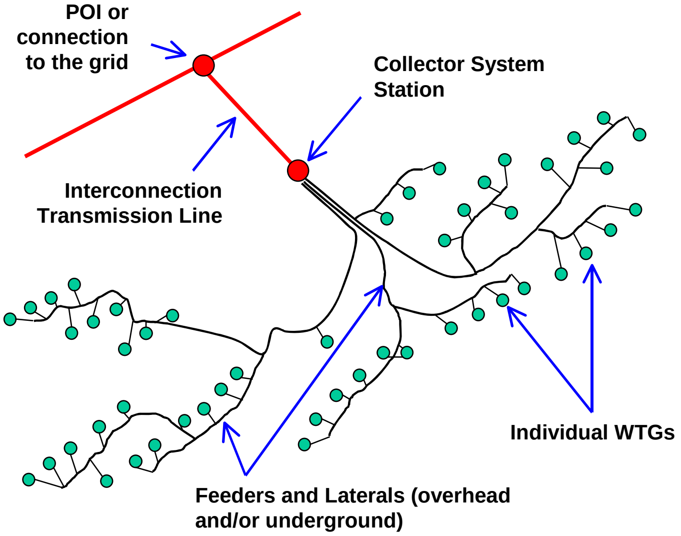


Figure 2. Physical diagram of a typical wind power plant.

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)

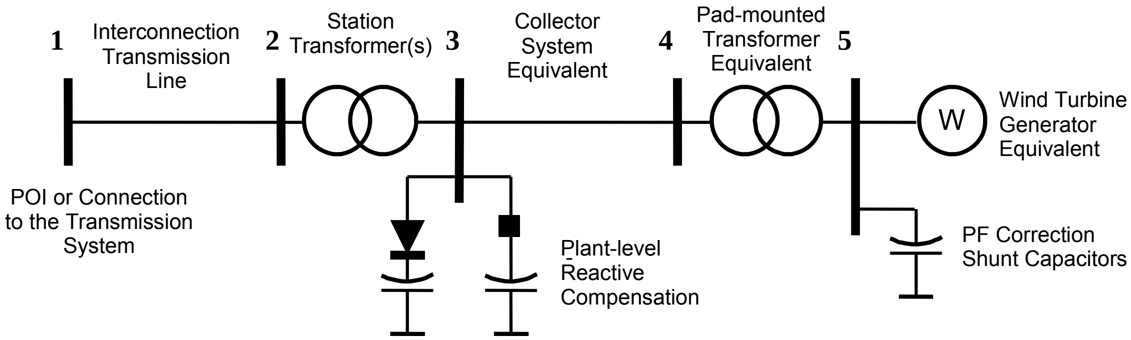


Figure 3. Single-machine equivalent power flow representation for a WPP.

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>}
  - Example:
    wt3g 5 "BUS5" 0.575 "1 " : #9 mva=33.3 /
  - 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>]
  - Example:
    wt3e 5 "BUS5" 0.575 "1 " 3 "BUS3" 34.5 "1 " 1 : #9 mwcap=33.3 /
  - 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.

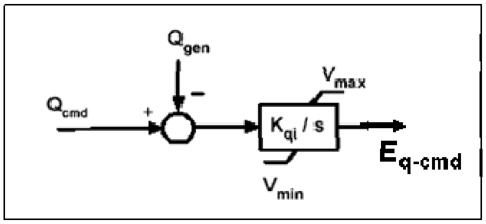
For type 3 and type 4:

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

- WT3E: Converter Control Model

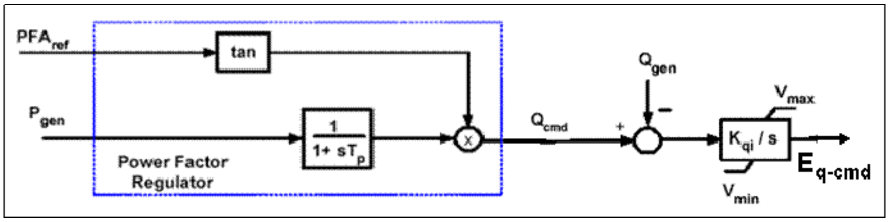
  The following flags have influence in reactive power controllability.

  varflg and vltflg



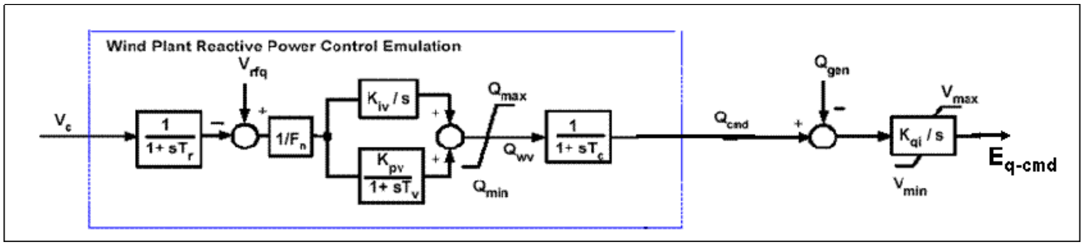
Reactive power control:
- **Q_{cmd} = Q_{ref} = $Q_{gen\_load\_flow}$**
- **varflg = 0; vltflg = 0**
- **voltage is not controlled**

[a] Reactive Power Control



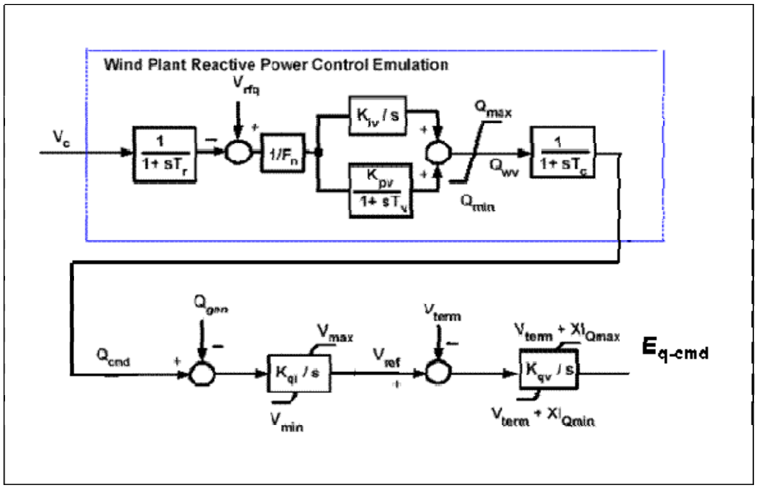
Power factor control:
- **varflg = -1; vltflg = 0**
- **voltage is not controlled**
- **PFA_{ref} is defined at initial load flow solution based on P_{gen}, Q_{gen}**

[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



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:

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

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.

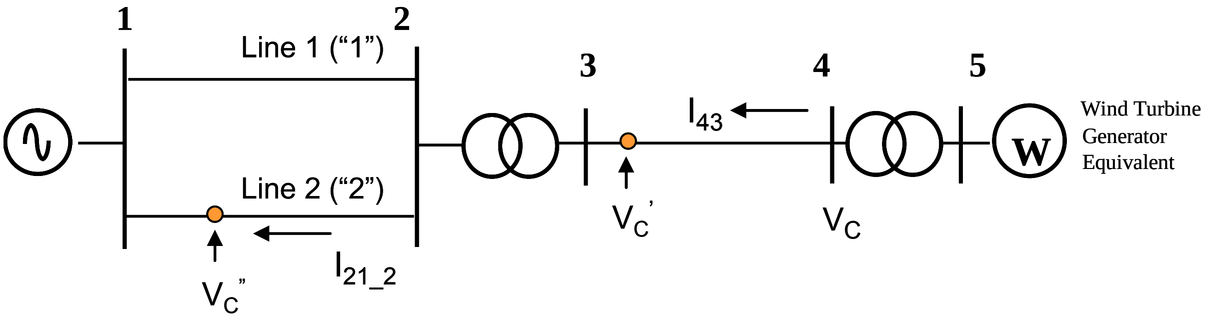


Figure 5. Simplified single line diagram describing voltage control at a remote node

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. $\mathbf{V_C' = V_4 - jX_C\, I_{43} \quad X_C \leq X_{43}}$

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. $\mathbf{V_C'' = V_2 - jX_C\, I_{21} \quad X_C \leq X_{21}}$

- **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.

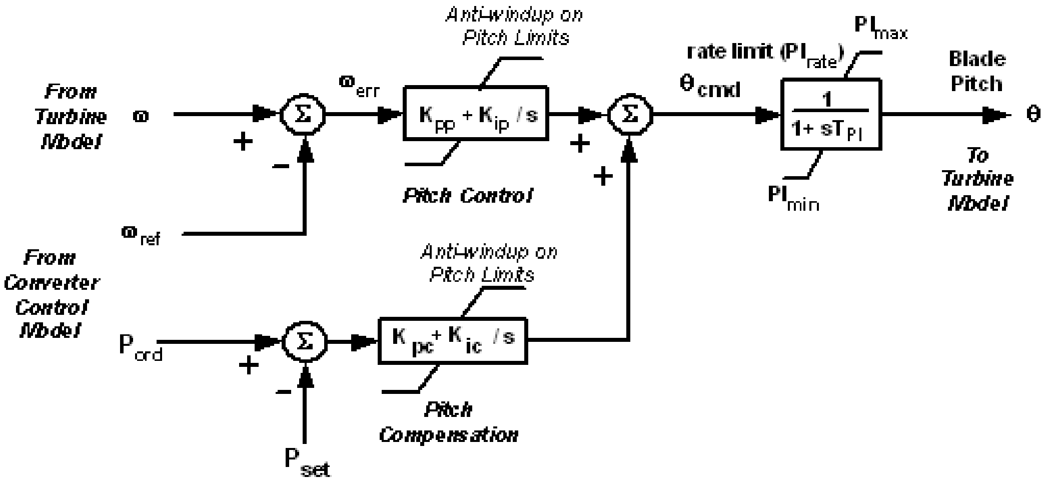


Figure 6. Type 3 WTG pitch control

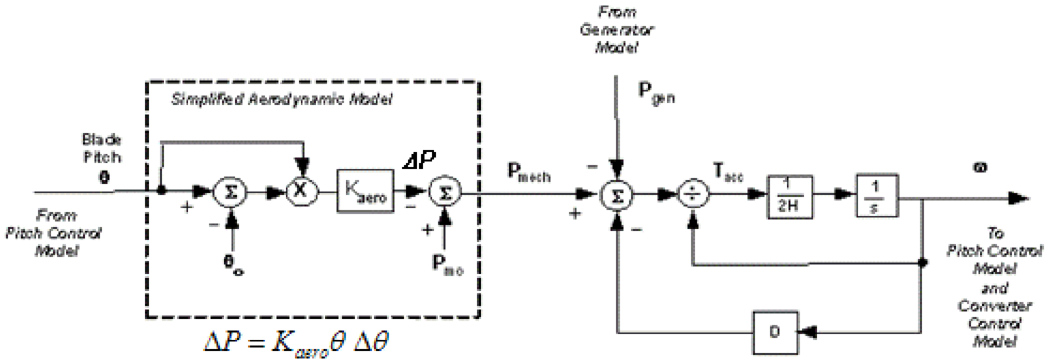


Figure 7. Type 3 WTG turbine model with one-mass model

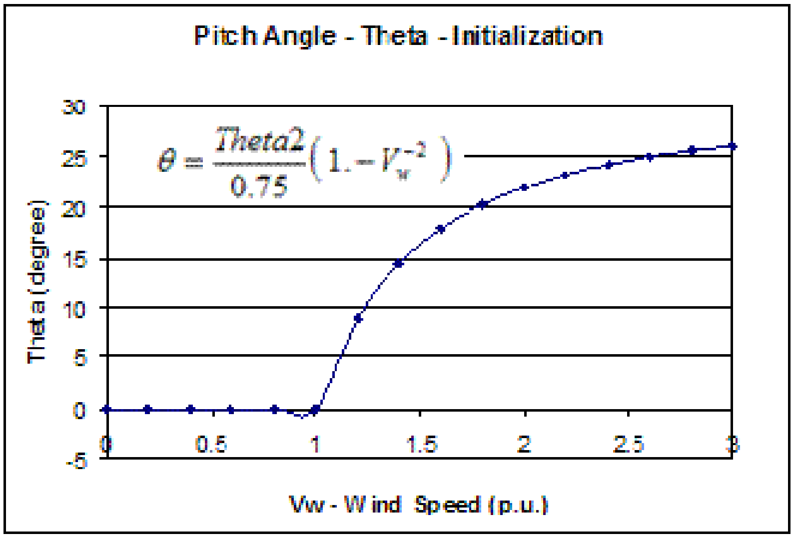


Figure 8. Pitch angle versus wind speed initialization

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 ($\simeq$ 1.12 p.u.) and Vw should be set to Vw < 1.0p.u. , and the blade pitch is adjusted to its optimum ($\theta = 0$ 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 ($\theta = 0$ 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.

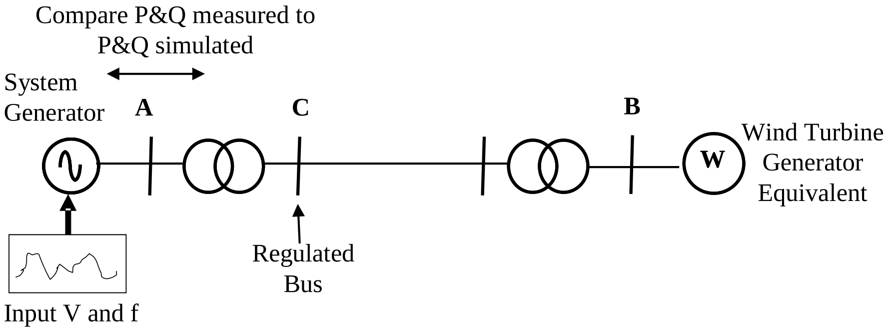


Figure 9. Simplified single-line diagram of the WPP network

5.2. Data for the Simulation

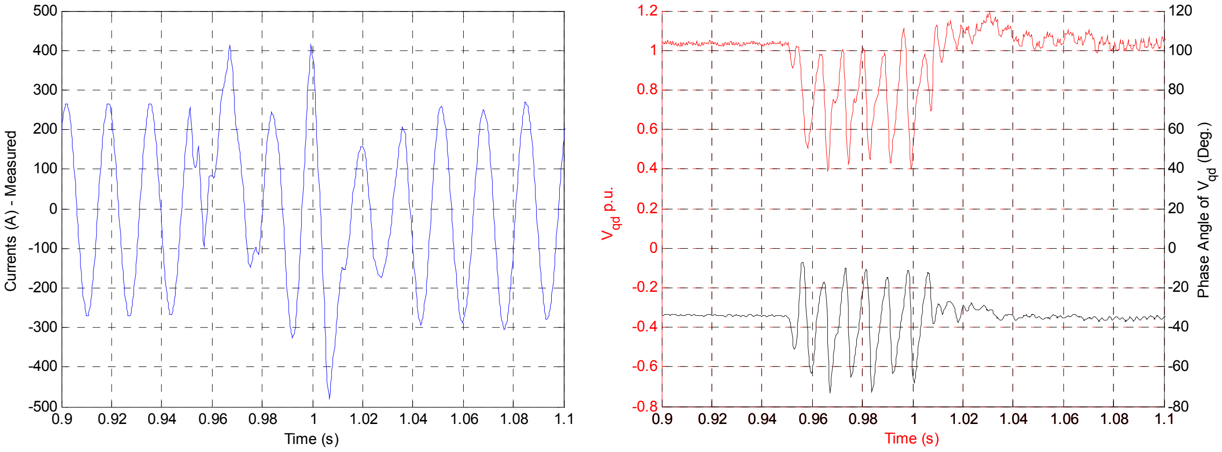
To perform the validation, it is important that we simulate the system to be as accurate as possible. The simulation should represent the actual WPP and the actual events we tried to simulate. There are several types of data required.

- 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]

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

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

[2]

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

[3]

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

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

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].

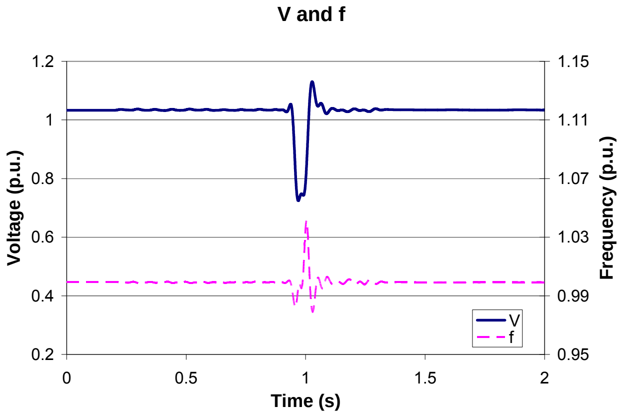
The frequency change at each step can be derived from the phase angle changes in each time step by using equation 4:

$$\Delta f\,(t) = \Delta\theta_{qde} / \,(2\pi\;\Delta t) \qquad [4]$$

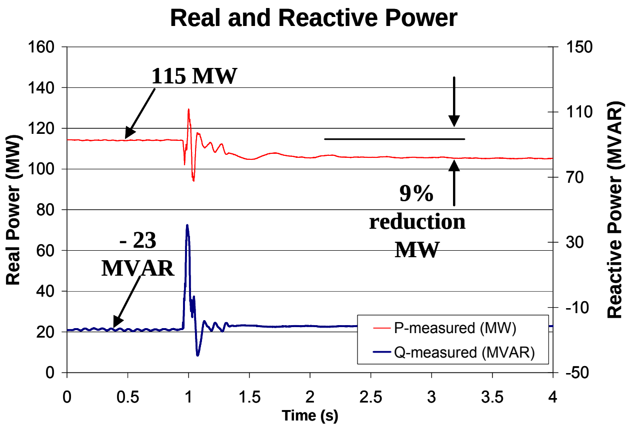
Instantaneous real and reactive power can be computed from the measured voltages and currents with the following equations:

$$\begin{aligned} p &= \frac{3}{2}\left(v_{qe} i_{qe} + v_{de} i_{de}\right) \\ q &= \frac{3}{2}\left(v_{qe} i_{de} - v_{de} i_{qe}\right) \end{aligned} \qquad [5]$$

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.

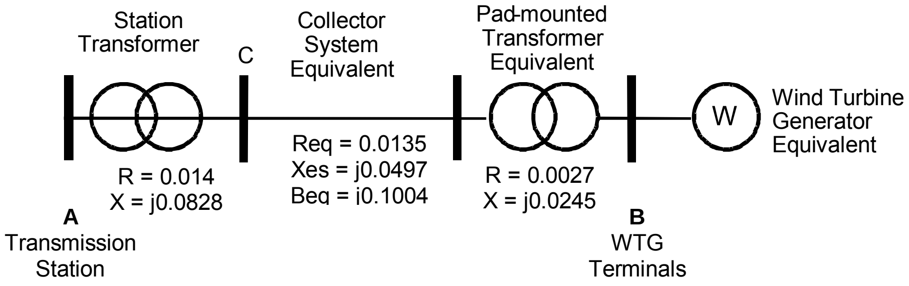


Figure 12. Single-machine equivalent representation for reference WPP

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].

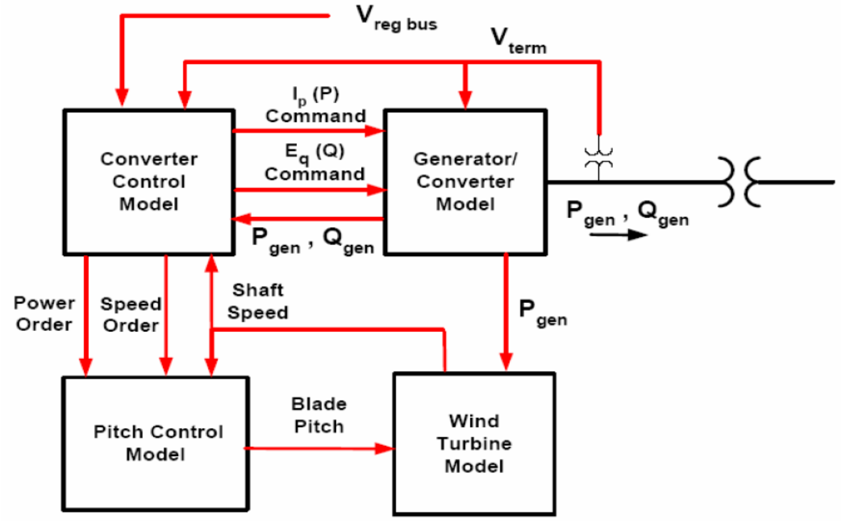


Figure 13. Block diagram of WECC generic DFIG model

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.

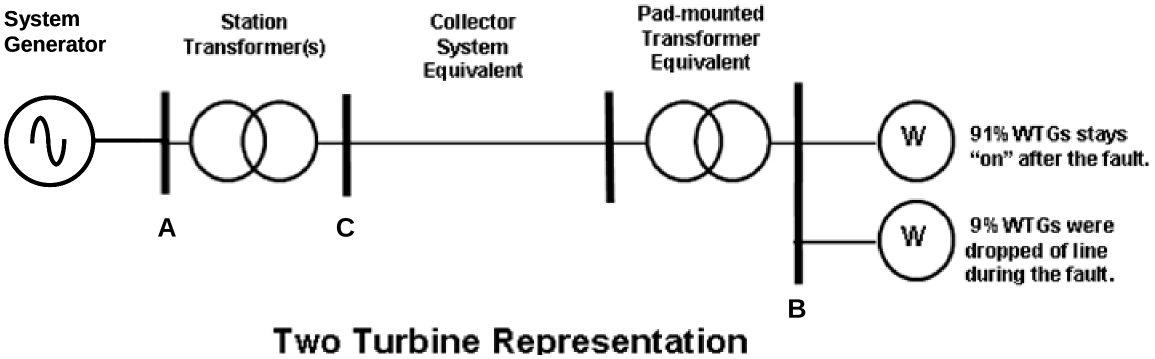


Figure 14. The WPP is represented by a two turbine representation

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.

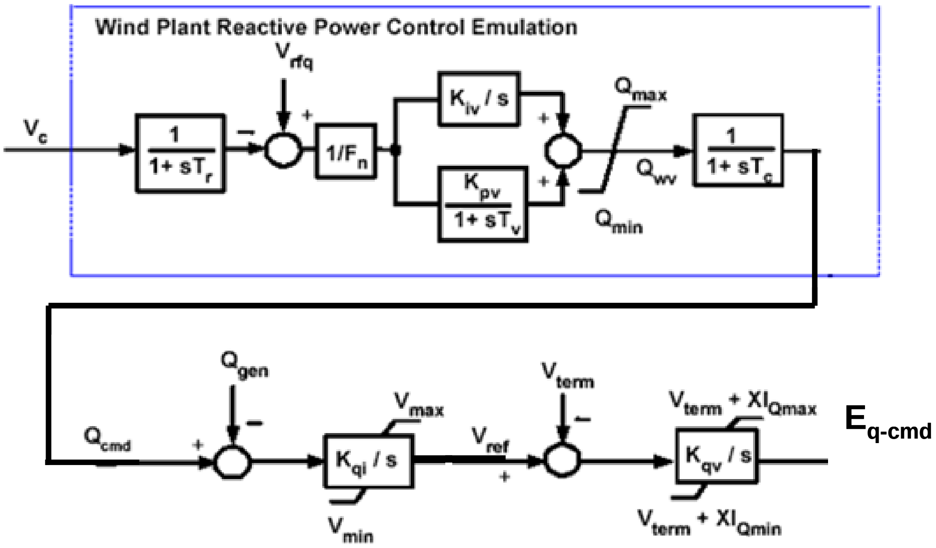


Figure 15. The control block diagram for the system being validated

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.

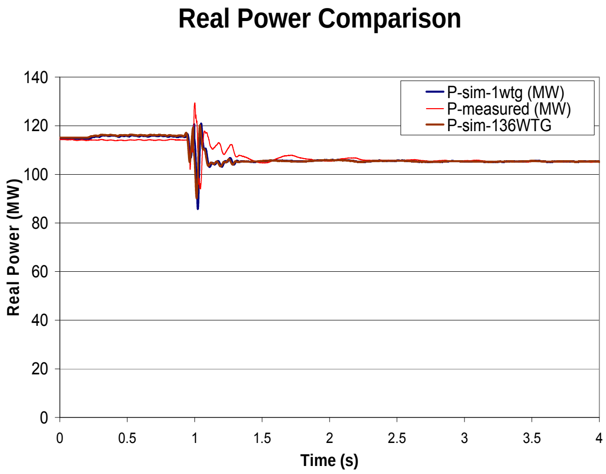


Figure 16. Real Power Comparison

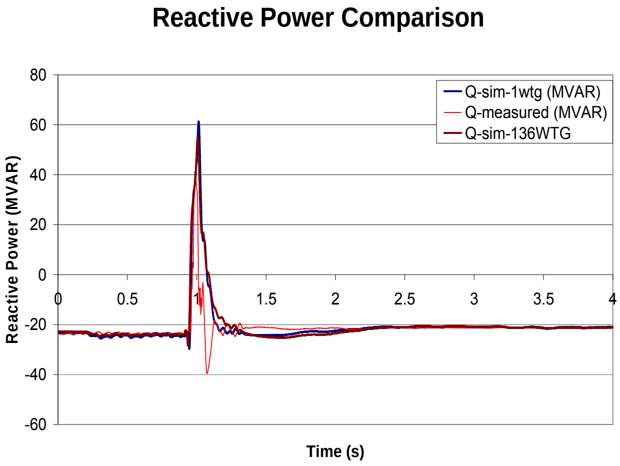


Figure 17. Reactive Power Comparison

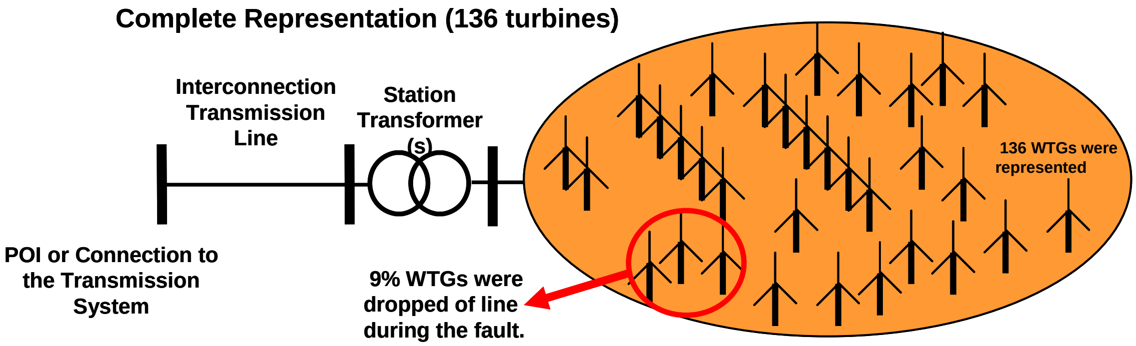


Figure 18. Simplified diagram of full system representation of the WPP

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.

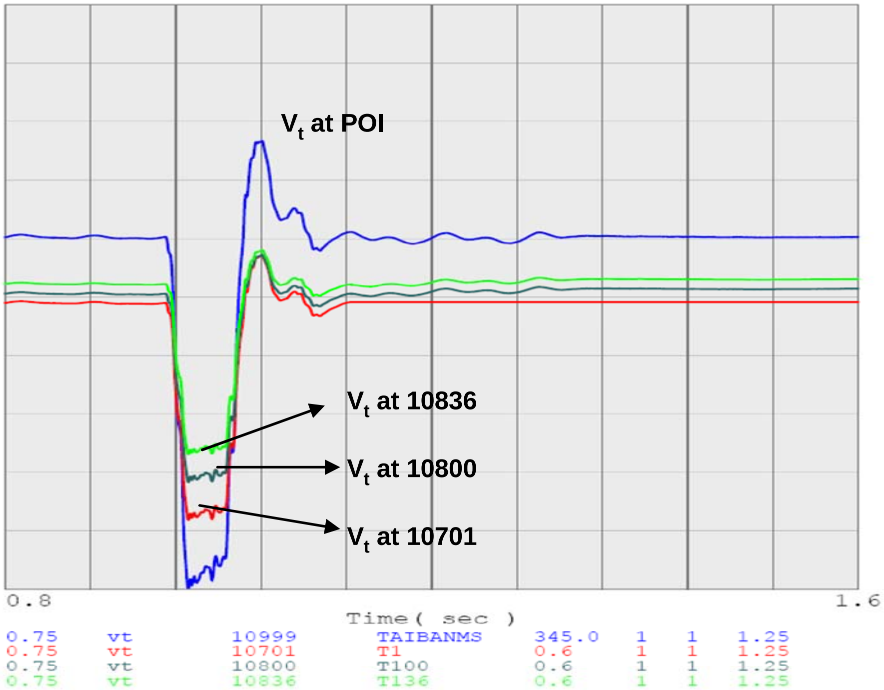


Figure 19. Terminal voltage of different WTGs and the voltage at the POI

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.

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[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.

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[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

FINAL PROJECT REPORT

WECC WIND GENERATOR DEVELOPMENT

Appendix VI
WECC WIND POWER PLANT
POWER FLOW MODELING GUIDE

Prepared for CIEE By:

National Renewable Energy Laboratory

University of California
ciee

A CIEE Report

Western Electricity Coordinating Council
Modeling and Validation Work Group

WECC Wind Power Plant Power Flow Modeling Guide

Prepared by
WECC Wind Generator Modeling Group

May 2008

1. Introduction

This document contains technical recommendations for power flow representation of wind power plants (WPP) in the Western Electricity Coordinating Council (WECC), and was written by the WECC Wind Generation Modeling Group (WGMG). WGMG is also advancing the state of the art on WPP generic dynamic model implementation, and plans to produce dynamic representation guidelines for use in WECC. Those guidelines will be issued as a separate document.

2. Brief Background

2.1 Wind Power Plant Topology

A wind power plant (WPP) consists of many individual wind turbine generators (WTGs) tied to a medium voltage collector system, and connected to the transmission system at the interconnection point. Modern utility-scale WTGs have nameplate rating ranging from 1 MW to 4 MW. Terminal voltage is about 600 V. A step-up transformer, generally a pad-mounted unit, connects each WTG to a medium-voltage collector system operating at 12 kV to 34.5 kV. The collector system consists of one or several feeders connected together at a collector system station. One or more station transformers at the collector system station are used to achieve transmission system voltage. Unless the collector system station is adjacent to the interconnection point, an interconnection transmission line is needed. Reactive compensation in the form of mechanically switched capacitors and continuously variable devices such as STATCOMs or Static Var Systems (SVS) may be installed at the collector system station. Depending on the type of WTG, shunt reactive compensation at the WTG terminals may be installed for power factor correction. The amount and nature of reactive compensation is driven by interconnection requirements and collector system design considerations, including voltage regulation and losses. Figure 1 shows a typical WPP topology.

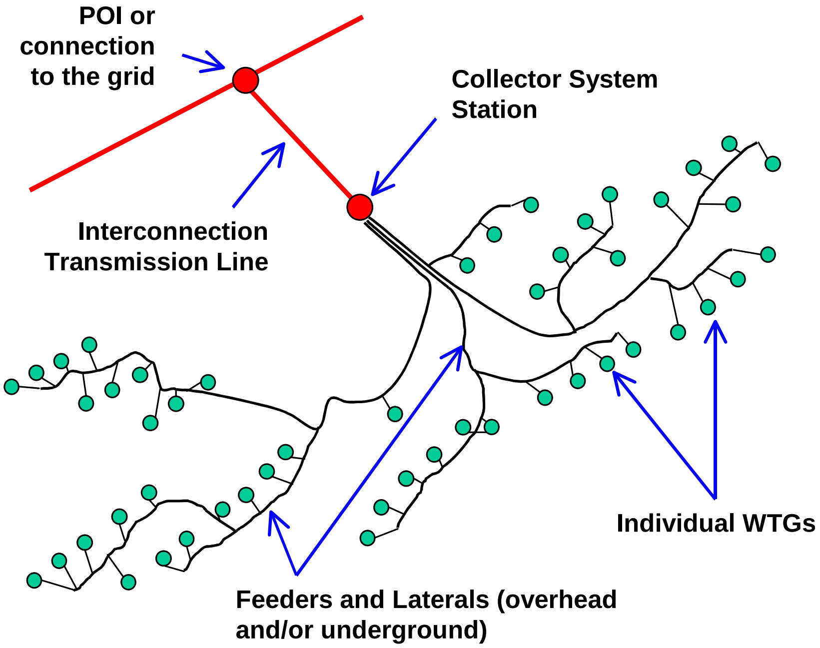

Figure 1. Wind Power Plant Topology

2.2 Types of Wind Turbine Generators

Early vintage WTGs were simple cage induction generators prone to tripping during grid disturbances. Until recently, tripping was considered preferable from the transmission system point of view, considering the small capacity of WPPs and their tendency to increase reactive power consumption and delay voltage recovery following electrical fault events. However, WPPs are becoming increasingly prominent in terms of size, especially in certain areas of the system. Also, they are located in sparsely populated windy areas, where the transmission system tends to be weak. Today, WPPs are expected to tolerate grid disturbances and contribute to overall power system reliability. In response to evolving wind generator interconnection standards, WTGs have improved rapidly with respect to steady-state and dynamic performance. WTG manufacturers have introduced numerous variations of electrical and mechanical controls as well as drive train and generator configuration. Most of modern WPPs have the ability to provide reactive power support to the system by using reactive capability built into the WTGs, or through external reactive compensation systems.

Despite the large variety of utility-scale WTGs available in the market, each can be classified into one of four basic types, based on the grid interface[1], as listed below:

- Type 1 – Cage rotor induction generators
- Type 2 – Induction generators with variable rotor resistance
- Type 3 – Doubly-fed asynchronous generators with rotor-side converter
- Type 4 – Full-power converter interface

The distinctive topological characteristics of each type are shown in Figure 2.

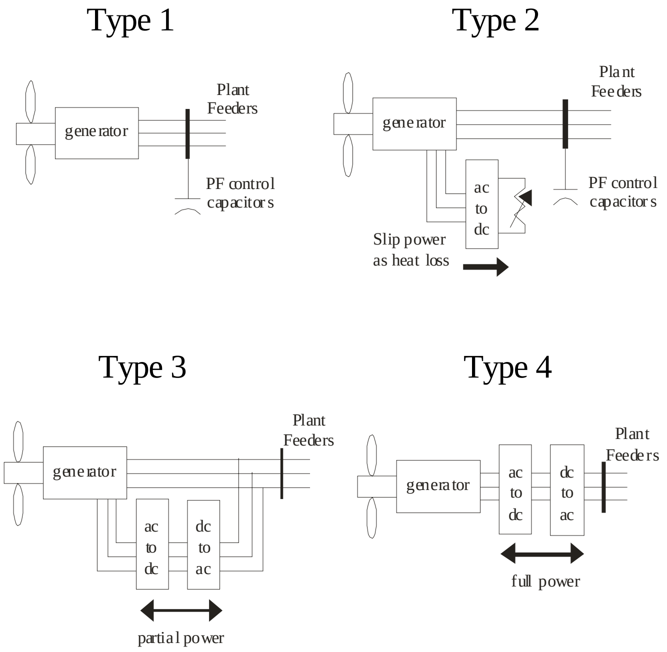

Figure 2 – Classification of WTGs Based on Generator Topology and Grid Interface

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[1] Dynamic performance for each type of WTG is different. WGMG is working on WECC standard models for each.

3. Single-Machine Equivalent Representation

The WGMG recommends the use of the single-machine equivalent representation shown in Figure 3 to model WPPs in WECC base cases. Based on industry experience, this representation is also considered adequate for positive-sequence transient stability simulations.

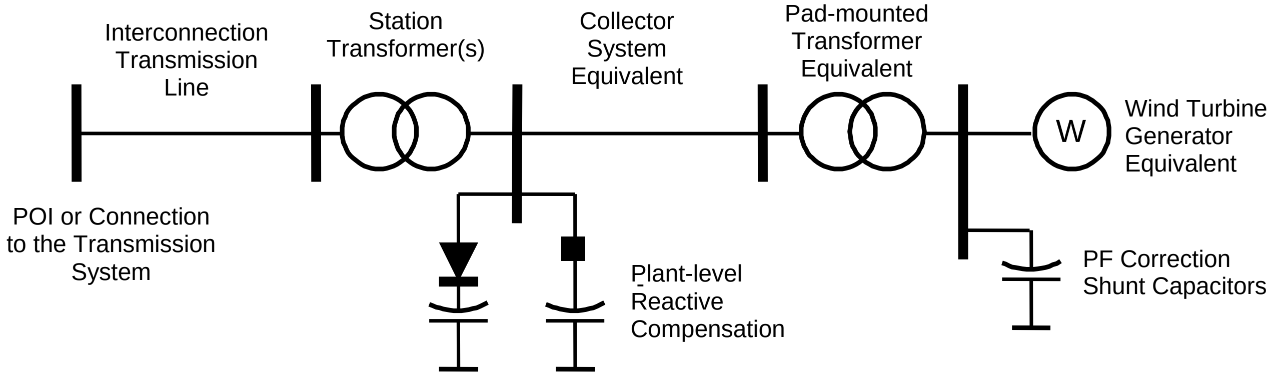

Figure 3: Single-Machine Equivalent Power Flow Representation

The interconnection transmission line, station transformer(s) and plant-level reactive compensation should be represented explicitly, according to established industry practice. Equivalent representations are needed for the collector system station and WTGs.

- The equivalent generator and associated power factor correction capacitors represents the total generating capacity and reactive compensation of all the WTGs in the WPP.
- The equivalent generator step-up transformer (pad-mounted transformer) represents the aggregate effect of all WTG step-up transformers
- The equivalent collector system branch represents the aggregate effect of the WPP collector system, and should approximate real power losses and voltage drop out to the "average" WTG in the WPP.

Established power flow modeling principles should be applied to WPP representation, although there are some differences that require especial attention. Single-machine equivalent model parameters can be derived from preliminary data. Appendix A contains a sample data request form that covers all the powerflow data needs. Preliminary data should be replaced with as-built data when such data becomes available, certainly shortly after commissioning. Powerflow model data should be validated from time to time by comparing the model to actual data, consistent with WECC and NERC requirements and methodologies. However, as of the date this guide was written, specific WPP testing and model validation guidelines have not been adopted for use in WECC.

With the proper model parameters, this model should approximate WPP powerflow characteristics at the interconnection point, collector system real and reactive losses and voltage profile at the terminals of the "average WTG" in the WPP. There are some limitations, however. Due to collector system effects, terminal voltage of individual WTGs could vary widely. WTGs that are closest to the interconnection point may experience significantly different terminal voltage compared to WTGs that are electrically farthest from the interconnection point. In actual operation, terminal voltage of some

WTGs may reach control or protection limits, resulting in different terminal behavior, or tripping. During the design stage, or in special circumstances, it may be reasonable to use a more detailed representation of the collector system. However this type of detail usually is not relevant for large-scale simulations.

The following guidelines should be considered to model each of the components of the WPP single-machine equivalent representation.

3.1 Interconnection Transmission Line

Standard data includes line voltage, line length, and line parameters (R, X and B). In some cases, the interconnection transmission line may be operated at a voltage level lower than the system voltage at the interconnection point, but higher than the collector system voltage. This requires an additional transformation stage and perhaps more shunt compensation to make up for higher reactive losses. Economics may favor this approach depending on a number of factors.

3.2 WPP Station Transformer

A WPP contains one or several station transformers at the collector system station. Station transformers should always be modeled explicitly. They represent the majority of the impedance between the interconnection point and the terminals of the equivalent WTG. Standard data includes transformer terminal voltage, MVA ratings (ONAN/FA/FA), percent impedance on the transformer’s self-cooled (ONAN) MVA base, and X/R ratio. Positive-sequence impedance for these types of transformers is in the range of 7 to 10%, with X/R ratio in the range of 40 to 50.

3.3 Plant Level Reactive Compensation

Many WPPs have reactive compensation installed at collector system station, consisting of mechanically switched capacitors, continuously acting reactive power devices (such STATCOM or SVS). The plant-level reactive power compensation system can be controlled to meet one of three possible steady-state control objectives:

- **Closed-loop voltage control** - Maintain voltage schedule within the reactive power capability of the WPP, over a certain range of real power output. Controlling voltage at the interconnection point is likely to cause large reactive power swings for small voltage changes if the WPP is connected to a strong transmission system. Reactive droop compensation can be used to improve reactive power stability without compromising voltage control benefits. A small voltage hysteresis may be allowed in some situations. For instance, the requirement may be to regulate voltage at the interconnection point within 1% or 2% of schedule when WPP output exceeds 20% of rated capacity.

- **Power factor control** - Maintain power factor at the interconnection point close to a specified level. For instance, the requirement may be to maintain power factor between 0.98 lead and unity at the interconnection point.

- **Reactive power control** - Maintain reactive power flow within some specified limits. For instance, the requirement may be to limit reactive power flow at the interconnection point to 5 or 10 Mvar, in either direction.

Some WTGs have the capability to participate in steady-state voltage control and meet a portion or all the interconnection requirements. However, this capability is not always implemented in the field (see Section 3.6).

To properly model plant level reactive compensation, it is very important to establish what reactive control mode has been implemented, as well as the type of WTGs and compensation devices that are used. The following should be kept in mind to properly model reactive compensation devices:

- Discrete shunt capacitors should be modeled as constant impedance devices in power flow, to capture voltage-squared effects.
- Continuously variable reactive power devices such as STATCOMs should be modeled as a reactive power generator in power flow. Reactive limits should be set to the continuous rating of the device, consistent with power flow time frame. Some STATCOM manufacturers allow a transient overload capability in the 2 to 3 second time frame. This can be taken into account in dynamic simulations. However, the temporary overload capability should not be used in power flow.
- Ideally, SVCs should be represented as "svd" (static Var devices) with the appropriate number and size of steps. However, standard positive-sequence simulation programs require that this type of devices be represented as generators in power flow before conducting dynamic simulations. Therefore, it is recommended that SVCs be represented as generators in power flow to avoid having to convert a potentially large number of svd to generators in order to conduct dynamic simulations. Until this modeling issue is resolved, it is recommended that SVCs be represented as generators in power flow.

3.4 Equivalent Collector System

WPP collector systems consist of relatively long medium voltage feeders and laterals. Factors considered in feeder design include cost, real power losses, and voltage performance. A typical design goal is to keep average real power losses below 2%. At full output, real power losses can be higher, in the 3% to 5% range. Land use agreements usually favor the use of underground feeders despite the higher cost. For that reason, equivalent collector system X/R ratio tends to be low and line susceptance is high compared to typical overhead circuits. The equivalent collector system impedance also tends to be small compared to the station transformer impedance, but is not insignificant.

A simple method developed by NREL[2] can be used to derive equivalent impedance (Z_{eq}) and equivalent susceptance (B_{eq}) from conductor schedule as follows:

$$Z_{eq} = R_{eq} + jX_{eq} = \frac{\sum_{i=1}^{I} Z_i n_i^2}{N^2},$$

$$B_{eq} = \sum_{i=1}^{I} B_i \,,$$

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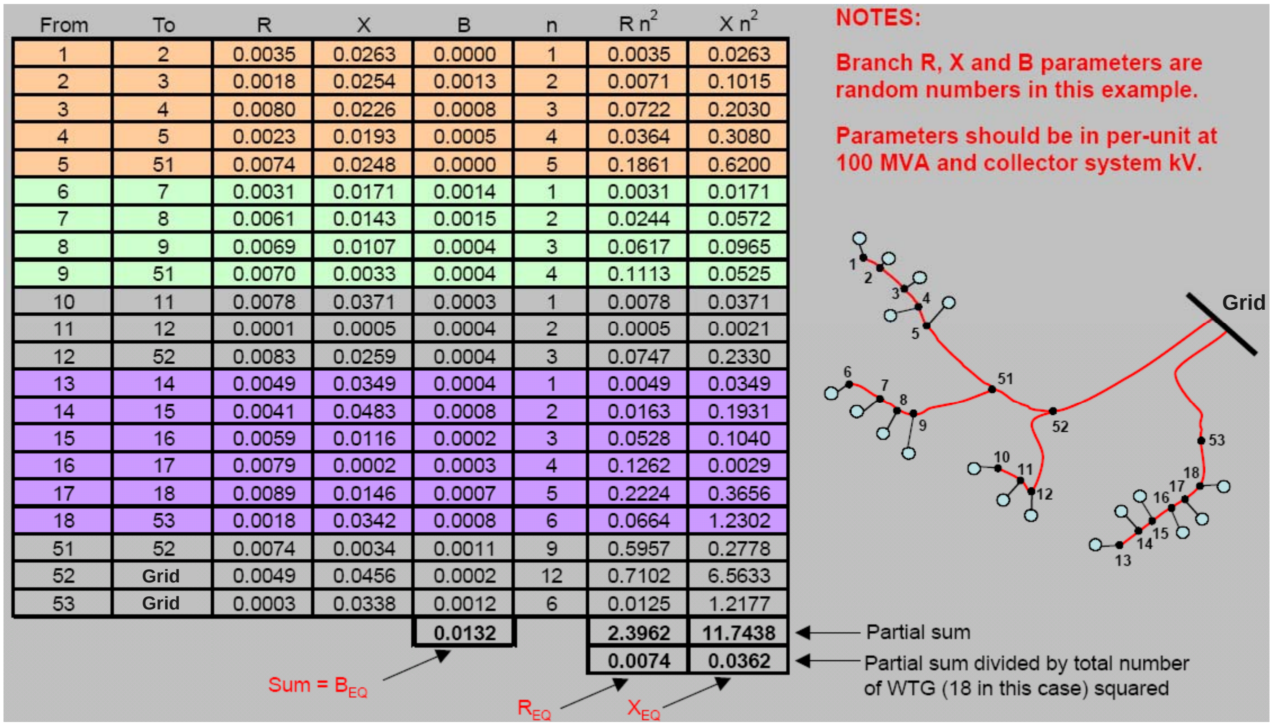
[2] E. Muljadi, A. Ellis, et al, "Equivalencing the Collector System of a Large Wind Power Plant", IEEE Power Engineering Society Annual Conference, Montreal, Quebec, June 12-16, 2006.

where I is total number of branches in the collector system, Z_i and n_i are the impedance ($R_i + jX_i$) for i^{th} branch, and N is the total number of WTGs in the WPP. As stated before, the equivalent impedance computed in this manner approximates real and reactive losses seen by the "average WTG" in the WPP. This calculation can be easily implemented in a spreadsheet. Figure 4 shows a simple example with I = 21, N = 18.



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	Grid	0.0049	0.0456	0.0002	12	0.7102	6.5633
53	Grid	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 4 – Computation of Collector System Equivalent Parameters

Larger WPPs have lower Z_{eq} and higher B_{eq} considering that additional circuits are needed to handle larger currents. However, this relationship does not always hold. Table 1 shows some examples of actual equivalent collector system parameters for several WPP of different nameplate capacity and different collector system configuration. Per unit parameters are on a 100 MVA and collector system kV base.

Table 1 – Sample Equivalent Collector System Parameters

Plant size	Collector voltage	Feeder	R (pu)	X (pu)	B (pu)
100 MW	34.5 kV	All underground	0.017	0.014	0.030
100 MW	34.5 kV	33% overhead (carrying 100% of WTG)	0.018	0.079	0.030
110 MW	34.5 kV	All underground	0.012	0.011	0.036
200 MW	34.5 kV	Some overhead	0.007	0.025	0.055
200 MW	34.5 kV	25% overhead (carrying 50% of WTG)	0.010	0.039	0.099
300 MW	34.5 kV	Some overhead	0.005	0.020	0.085
300 MW	34.5 kV	Some overhead	0.006	0.026	0.150

Note: per unit parameters are on a 100 MVA base and collector system kV base.

3.5 Equivalent WTG Step Up or Pad-Mounted Transformer

WTG pad-mounted transformers are typically two-winding air-cooled transformers. The per-unit equivalent impedance (Z_{Teq}) and the equivalent MVA rating (MVA_{Teq}) for the N identical WTG step-up transformers, each of which has impedance Z_T on its own MVA base (MVA_T), are computed as follows:

$$Z_{Teq} = Z_T$$
$$MVA_{Teq} = N \times MVA_T$$

Step-up transformers associated with modern utility-scale WTGs (1 to 3 MVA) have impedance of approximately 6% on the transformer MVA base, with X/R ratio of about 8.

3.6 Equivalent WTG Representation

For power flow simulations, the equivalent WTG should be represented as a standard generator. Real power level and reactive power capability must be specified according to the guidelines below.

3.6.1 Active Output Level

Generator interconnection studies are typically conducted with the WPP at full output. At the discretion of the transmission planner, WPPs in the study area that are included in the base case can be assumed to be at full output, or at some other output level, depending on the purpose of the study. The following should be taken into account:

- For regional transmission planning studies, it is recommended that the power level be established based on the average output level during the time frame of interest, unless specific high or low wind output scenarios are of interest. This approach allows for consideration of realistic load and resources balance over the study area. Average output during a certain time frame varies depending on the location of the WPP. For example, in the US desert southwest, WPP output tends to be low (5% to 15% of nameplate capacity) during the during peak summer load hours due in part to temperature-related wind turbulence. Average output increases during the evening hours (off peak load periods), as turbulence decreases. Average output is significantly higher during the spring and winter and fall. In locations near the coast, wind resource may be driven by other factors such land-water temperature differential, resulting in very different seasonal output patterns.

- Due to the steepness of WTG power curve or output versus wind speed characteristic (see Figure 5), an individual WPP is likely to be at either low output (< 20% of nameplate capacity) or high output (> 80% of nameplate capacity) at any given time. Figure 6 shows an example of power output distribution for an individual WPP in the Pacific Northwest. This pattern tends to hold even for the aggregate output of wind farms that are in close proximity. Based on these observations may be reasonable to represent a WPP or group of WPPs installed in a certain region either off-line or at maximum power output. Again, the choice is dependent on the purpose of the study.

Additional investigation and operational experience is underway to reconcile the above observations and provide guidance for dispatching wind generation in WECC base cases.

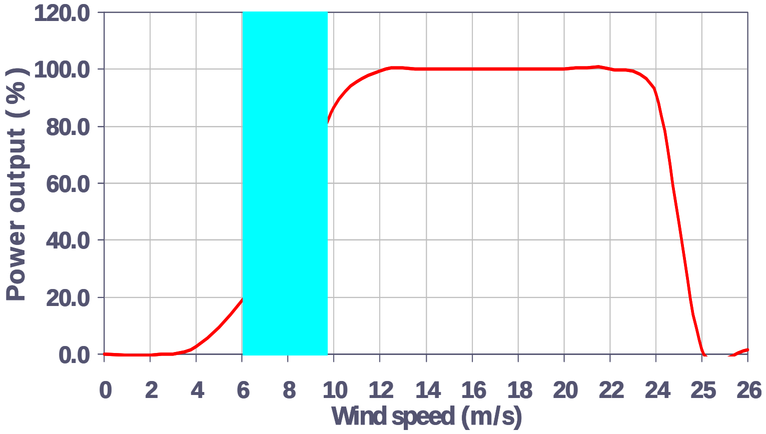


Figure 5 – Typical wind power curve (output versus wind speed)

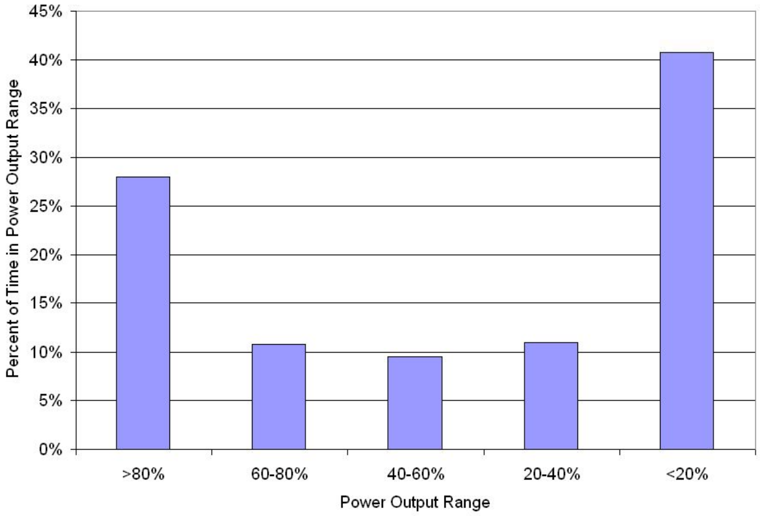


Figure 6 – Output distribution for a wind power plant in the Pacific Northwest

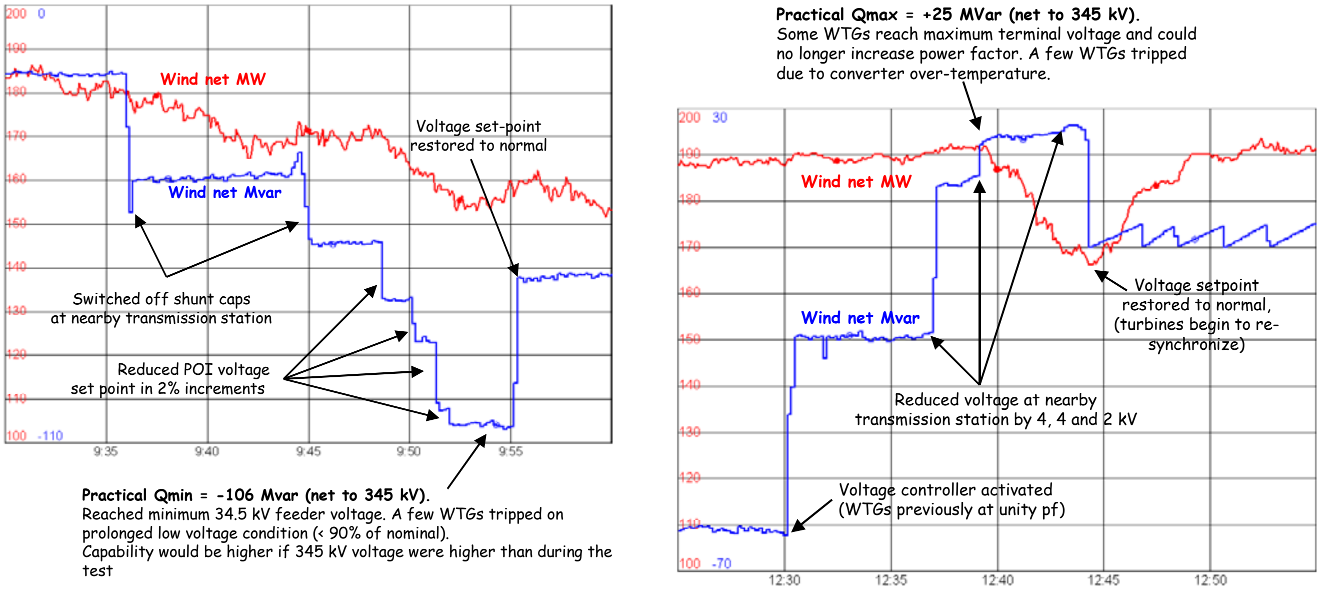
3.6.2 Reactive Power Capability and Power Factor Correction Capacitors

WTG reactive power capability is related to the type of WTG, as defined in Section 2.2, and the manner in which they are operated. The following guidelines apply:

- Type 1 and 2 WTGs are induction machines. In the range of 50% to 100% power level, uncompensated power factor typically ranges from 0.85 to 0.90 under-excited (consuming reactive power). Several stages of capacitors banks at the WTG terminals are normally applied to raise the power factor to approximately unity. In power flow, power factor correction capacitors should be modeled as fixed shunt devices, considering that that WPP power output is held constant in power flow studies. In the power flow model, reactive power consumption can be assumed to be ½ of the power output. A capacitor should be shown at the WTG terminals to compensate power factor to unity at nominal voltage. For example, for a 100 MW WPP at full output, both Q_{min} and Q_{max} would be set to -50 Mvar, and add a 50 Mvar shunt capacitor at the WTG terminals. Plant level reactive compensation may still be installed to meet interconnection requirements.

- Type 3 and Type 4 WTGs normally do not have power factor correction capacitors installed at the machine terminals. These WTGs are capable of adjusting power factor to a desired value within the rating of the generator and converter. They are also capable of voltage control at the interconnection point. When this functionality is implemented, the individual WTGs respond to a reactive power or power factor commands from an external plant-level controller. It should be kept in mind that, for commercial and other reasons, WTG-assisted steady-state voltage control functionality is not implemented or enabled in many WPPs with Type 3 or Type 4 WTGs. External reactive power compensation is often required to meet interconnection requirements, as discussed in Section 3.3. If these WTGs do not participate in voltage control, the equivalent generator should be assigned a fixed power factor, typically unity. (i.e., Q_{min} and Q_{max} would be set to 0). If the WTGs do participate in voltage control, then the equivalent generator should be assigned a reactive capability approximately equal to the aggregate WTG reactive power range. The WTG reactive power range is a function of power output. For example, consider a 100 MW WPP that employs Type 4 WTGs with specified power factor range +/-0.95 at full output. In this example, Q_{min} should be set to -33 Mvar and Q_{max} should be set to +33 Mvar. At an output level below rated, the reactive limits should be adjusted according to the WTG capability curve.

Due to collector system effects, some WTGs in the WPP will actually reach terminal voltage limits before reaching the nameplate reactive power limits. The net effect is that actual reactive power capability could be significantly less than the nameplate. The reactive power capability can be determined by field test or careful observation of WPP performance during abnormally high or low system voltage. For example, Figure 7 shows the results of field tests to determine the practical reactive limits of a 200 MW WPP. All measurements were made at the interconnection point. Taking into account the effect of transformer and collector system impedances, the reactive power limits of the equivalent WTG can be established. Currently, there are no industry standard guidelines for testing WPP steady-state reactive limits.



Practical Qmin = -106 Mvar (net to 345 kV).
Reached minimum 34.5 kV feeder voltage. A few WTGs tripped on prolonged low voltage condition (< 90% of nominal).
Capability would be higher if 345 kV voltage were higher than during the test

Practical Qmax = +25 MVar (net to 345 kV).
Some WTGs reach maximum terminal voltage and could no longer increase power factor. A few WTGs tripped due to converter over-temperature.

(a) Maximum under-excited WPP output *(b) Maximum over-excited WPP output*

Figure 7 – Determination of Practical Reactive Power Limits by Field Test

4. Modeling during post transient and power flows

Modeling of WPP generator and reactive compensation components should be consistent with WECC pos-transient methodology. Control devices that can complete switching or operation within 3 minutes (e.g., SVCs, STATCOMS and shunts under automatic control) should not be blocked. Devices that require operator action should be blocked. The equivalent WPP generator should have the Load Flag set to “1” to reflect the fact that the output should not change during a governor power flow.

APPENDIX A
SAMPLE DATA REQUEST FOR WIND POWER PLANTS

1. One-line Diagram. This should be similar to Figure 1 below.

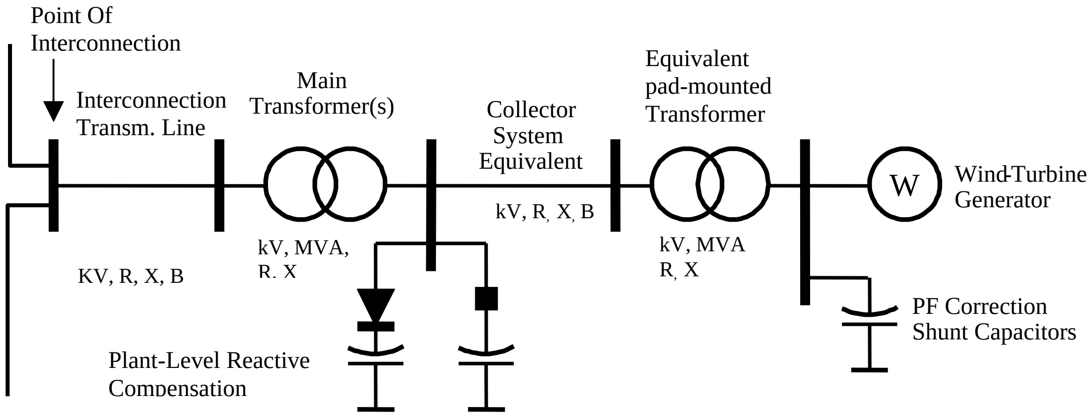


Figure A-1. Single-machine representation one-line diagram

2. Interconnection Transmission Line.

- Line voltage = ______ kV
- R = ________ ohm or _______ pu on 100 MVA and line kV base (positive sequence)
- X = ________ ohm or _______ pu on 100 MVA and line kV base (positive sequence)
- B = ________ uF or _______ pu on 100 MVA and line kV base

3. Station Transformer. (NOTE: If there are multiple transformers, data for each transformer should be provided)

- Rating (ONAN/FA/FA): ______/_____/_____ MVA
- Nominal Voltage for each winding (Low /High /Tertiary): _______/_______/_______ kV
- Winding Connections: ________/________/________ (Delta, Wye, Wye grounded)
- Available taps: _____________ (indicated fixed or ULTC), operating Tap: _______
- Positive sequence Z: _____%, ____X/R on transformer self-cooled (ONAN) MVA
- Zero sequence Z: _____%, ____X/R on transformer self-cooled (ONAN) MVA

4. Collector System Equivalent Model. This can be found by applying the equivalencing methodology described in Section 3.4; otherwise, typical values can be used.

- Collector system voltage = ________ kV
- R = _________ ohm or _______ pu on 100 MVA and collector kV base
- X = _________ ohm or _______ pu on 100 MVA and collector kV base
- B = _________ mF or _______ pu on 100 MVA and collector kV base
- Attach a one-line diagram of the collector layout.

It is also acceptable to provide a complete collector system description similar to Figure 4 of the Power Flow Modeling Guide.

5. Wind-turbine Generator (WTG) Pad-Mounted Transformer. Note: These are typically two-winding air-cooled transformers. If the proposed project contains different types or sizes of pad-mounted transformers, please provide data for each type.

- Rating: ______ MVA
- Nominal voltage for each winding (Low /High): _______/_______kV
- Winding Connections: _______/_______ (Delta, Wye, Wye grounded)
- Available taps: __________ (please indicated fixed or ULTC), Operating Tap:_______
- Positive sequence impedance (Z1) _____%, ____X/R on transformer self-cooled MVA
- Zero sequence impedance (Z0) _____%, ____X/R on transformer self-cooled MVA

6. WTG Powerflow Data. Proposed projects may include one or more WTG Types (See NOTE 1 below). Please provide the following information for each:

- Number of WTGs: _______
- Nameplate rating (each WTG): ________ MW
- WTG Manufacturer and Model: ________________
- WTG Type: __________

For Type 1 or Type 2 WTGs:

- Uncompensated power factor at full load: _______
- Power factor correction capacitors at full load: ______Mvar
- Number of shunt stages and size ___________
- Please attach capability curve describing reactive power or power factor range from 0 to full output, including the effect of shunt compensation.

For Type 3 and Type 3 WTGs:

- Maximum under-excited power factor at full load: _______
- Maximum under-excited power factor at full load: _______
- Control mode: _______________ (voltage control, fixed power factor) (See Note 7.2)
- Please attach capability curve describing reactive power or power factor range from 0 to full output.

NOTE 7.1: WTG Type can be one of the following:

- Type 1 – Squirrel-cage induction generator
- Type 2 – Wound rotor induction machine with variable rotor resistance
- Type 3 – Doubly-fed asynchronous generator
- Type 4 – Full converter interface

NOTE 7.2: Type 1 and Type 2 WTGs typically operate on **fixed power factor** mode for a wide range of output level, aided by turbine-side power factor correction capacitors (shunt compensation). With a suitable plant-level controller, Type 3 and Type 4 WTGs may be capable of dynamically varying power factor to contribute to **voltage control** mode operation, if required by the utility. However, this feature is not always available due to commercial and other reasons. The data requested must reflect the WTG capability that can be used in practice. Please consult with the manufacturer when in doubt. The interconnection study will determine the voltage control requirements for the project. Plant-level reactive compensation requirements are engineered to meet specific requirements. WTG reactive capability data described above could significantly impact study results and plant-level reactive compensation requirements.

7. Wind Farm Reactive Power Compensation. Provide the following information for wind farm-level reactive compensation, if applicable:

- Individual shunt capacitor and size of each: ______X_______ MVA
- Dynamic reactive control device, (SVC, STATCOM): _______________________
- Control range ___________________________ Mvar (lead and lag)
- Control mode (line drop, voltage droop, voltage control): _______________________
- Regulation point _______________________
- Describe the overall reactive power control strategy: ____

8. Wind-turbine Generator (WTG) Dynamic Data. Model and parameter data required for transient stability analysis is specific to each WTG make and model. The dynamic models must be in an approved WECC format, or in a PSSE or PSLF format that is acceptable to the transmission provider. We strongly suggest that the manufacturers provide this information.

- Library model name: ______________
- Model type (standard library or user-written): ___________
- Model access (proprietary or non-proprietary): ___________
- Attach full model description and parameter data