FINAL PROJECT REPORT

WECC WIND GENERATOR DEVELOPMENT

Appendix IV
WIND POWER PLANT DATA COLLECTION

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National Renewable Energy Laboratory

A CIEE Report

Acknowledgments

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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.
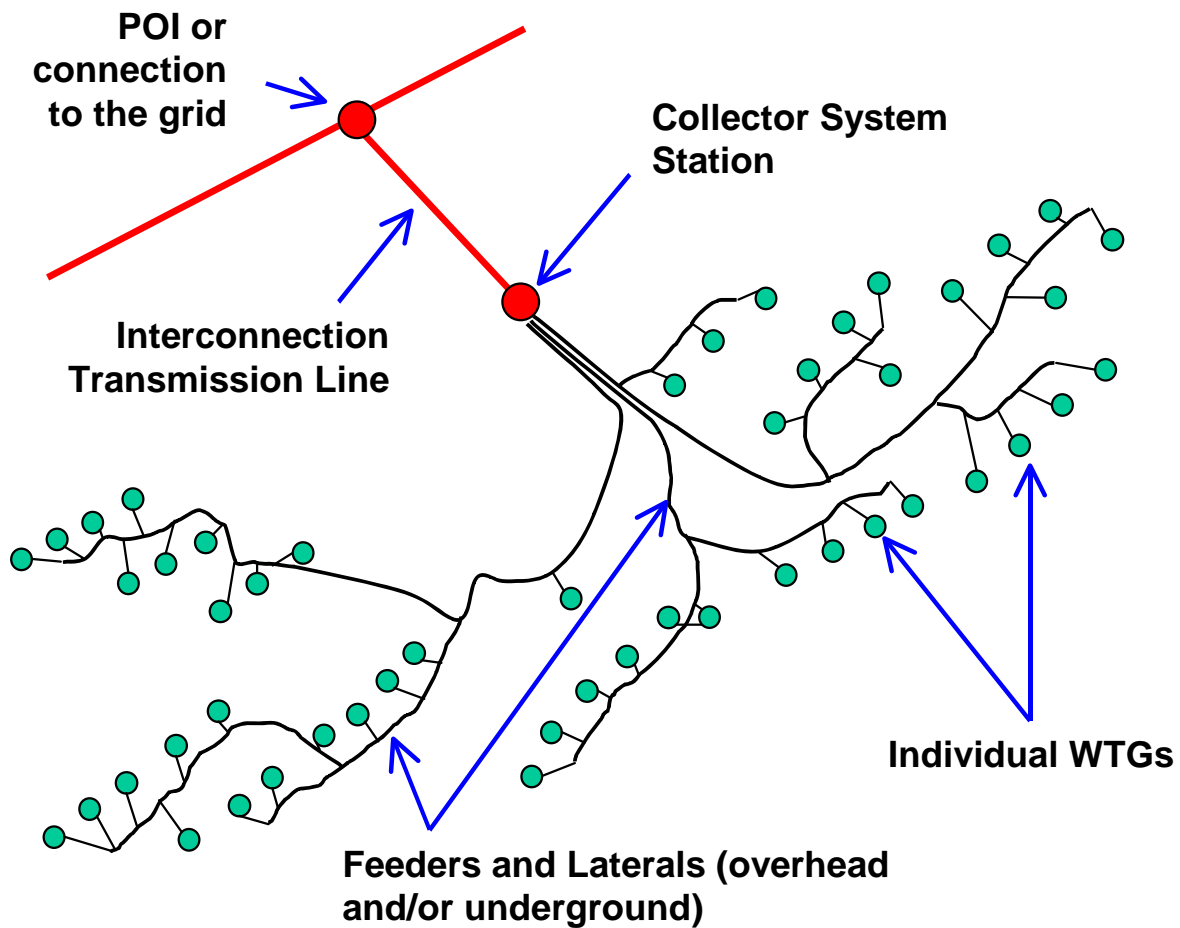
Figure 1. Physical diagram of a typical WPP
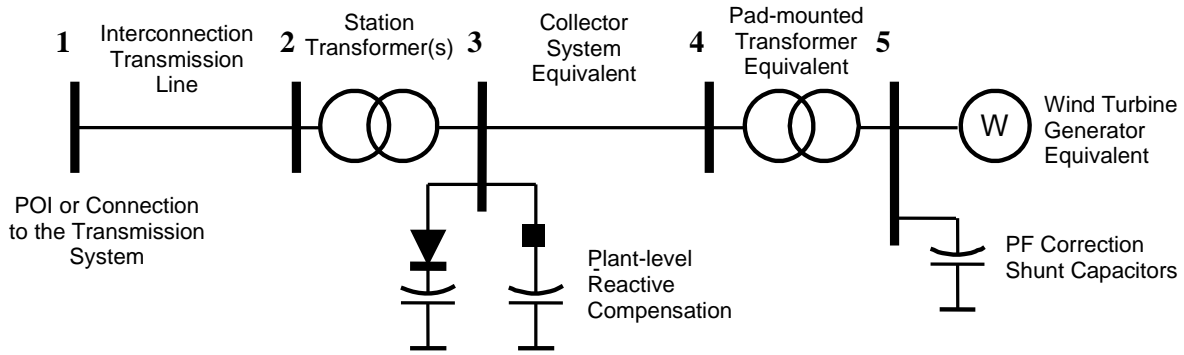
Figure 2. Single turbine representation for a WPP
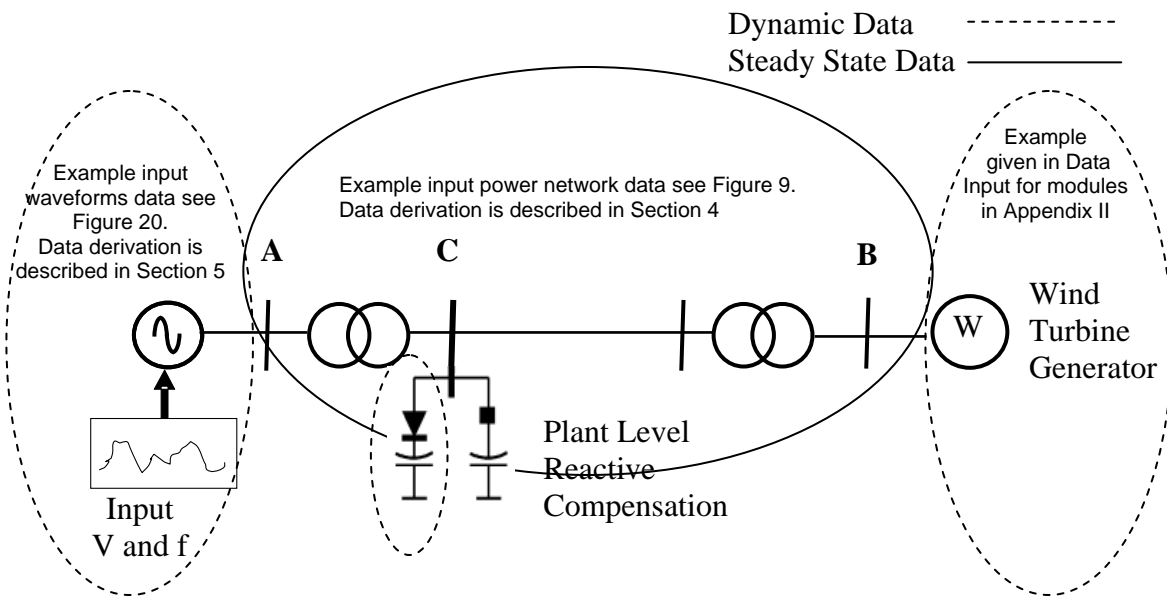
Figure 3 – Steady state and dynamic data groupings.

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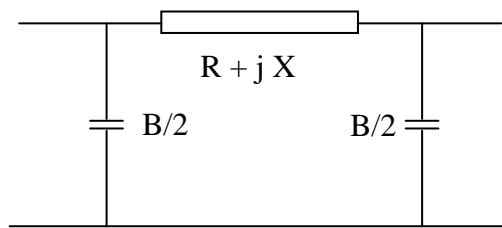
Figure 4. Representation of the collector system line impedance in a WPP

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.
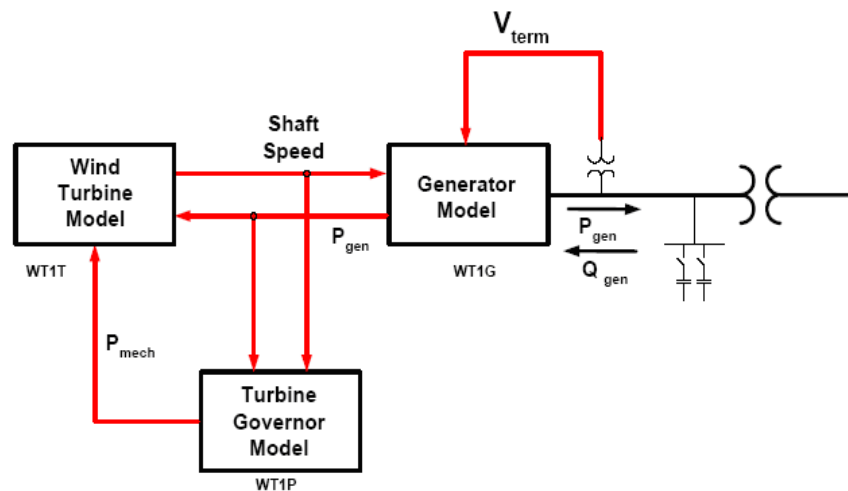
Figure 5 – Type 1 WTG dynamic connectivity.

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.
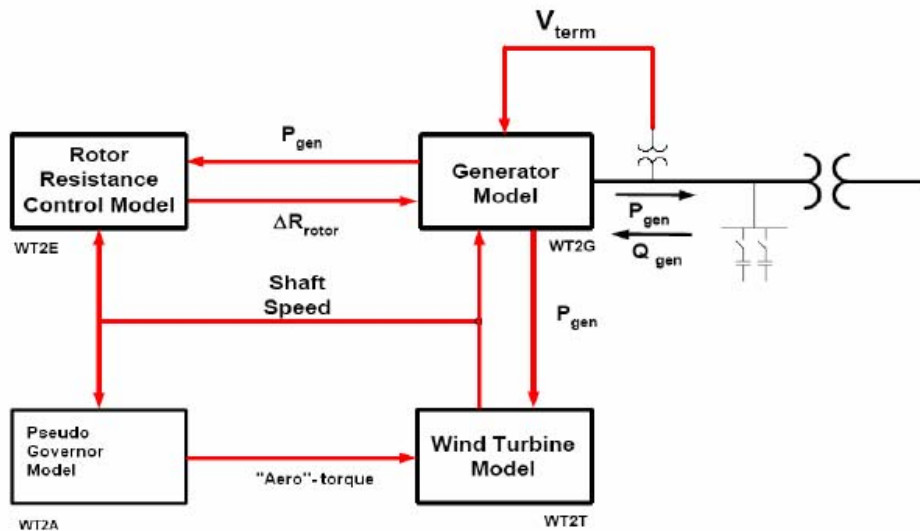
Figure 6 – Type 2 WTG dynamic connectivity

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.
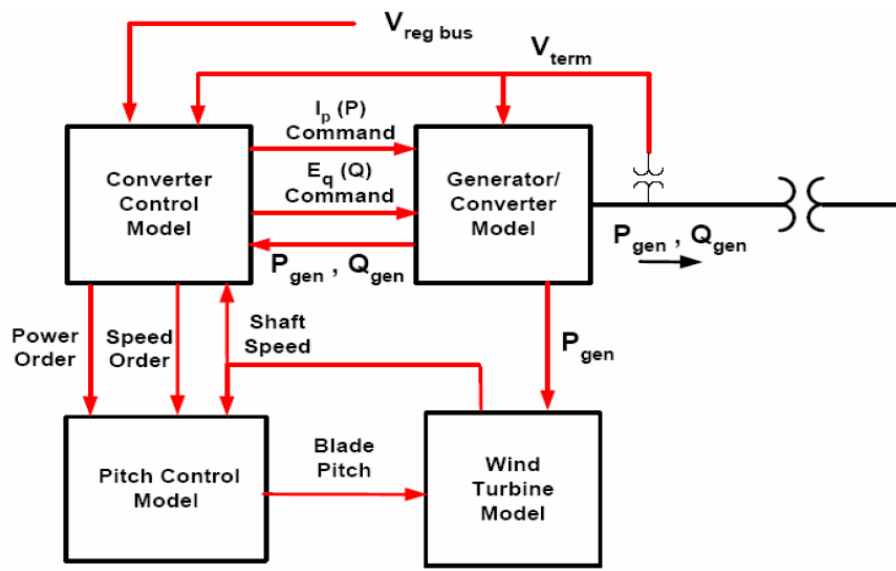
Figure 7 – Type 3 WTG dynamic connectivity

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.
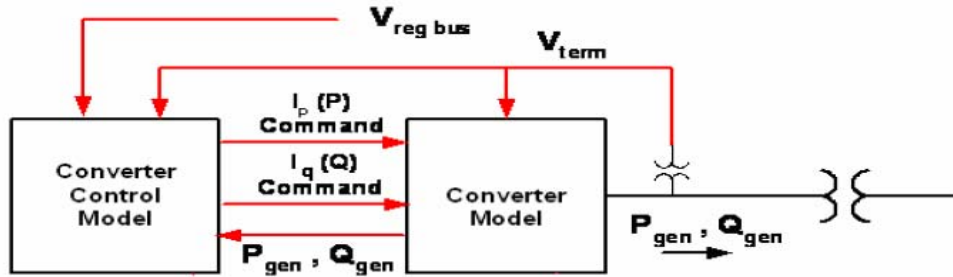
Figure 8 – Type 4 WTG dynamic connectivity

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

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.
      - $Q_{max} = P_{max}*\tan(\mathrm{acos}(0.95)$;
      - $Q_{min} = - P_{max}*\tan(\mathrm{acos}(0.95))$
      - 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.
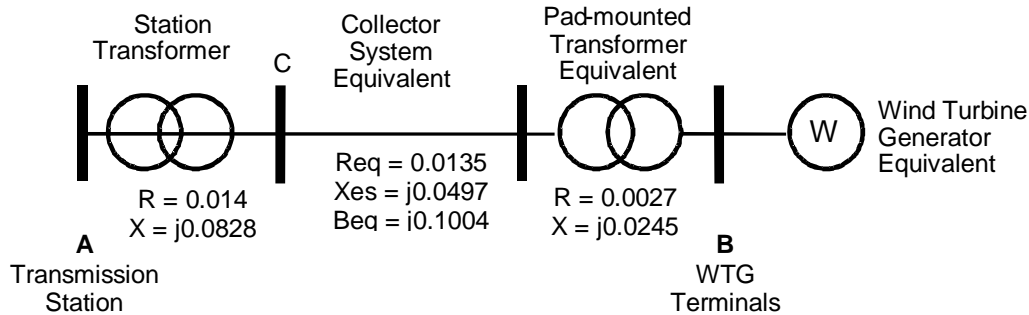
Figure 9 – Single-machine equivalent impedance of NMEC WPP

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

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- 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.
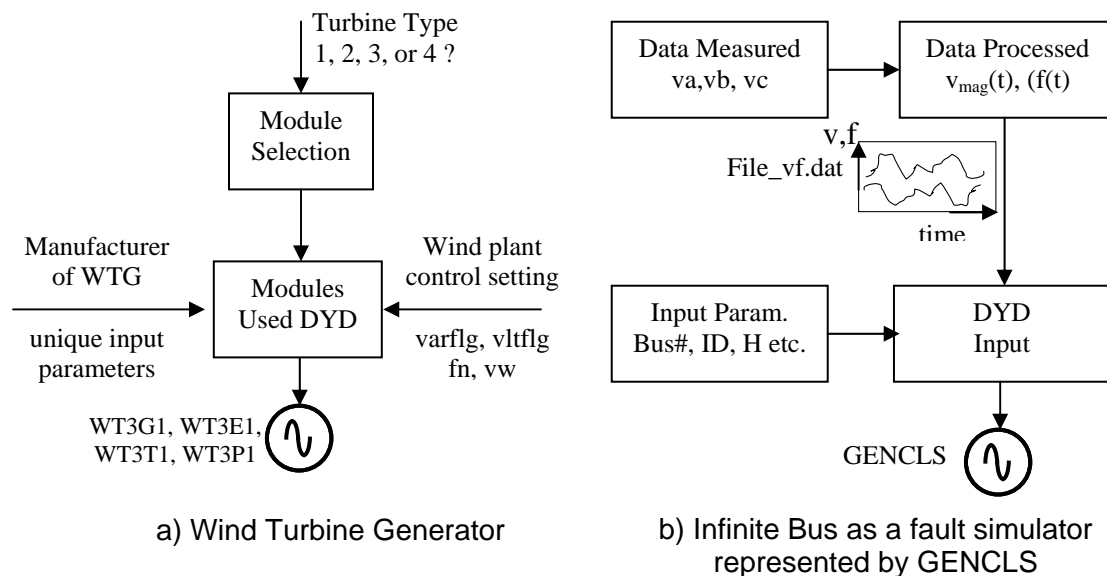

a) Wind Turbine Generator

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 $\theta = 0^\circ$.

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].
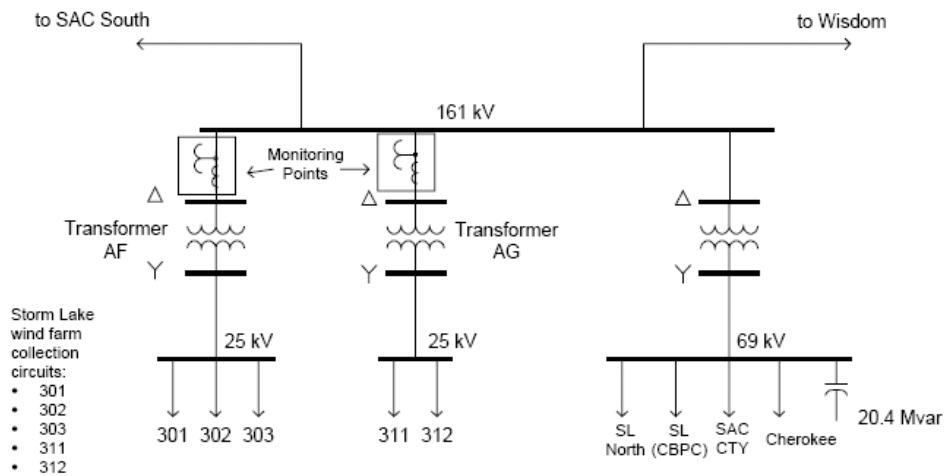
Figure 11 – Example of one-line diagram of the substation connected to collector systems.
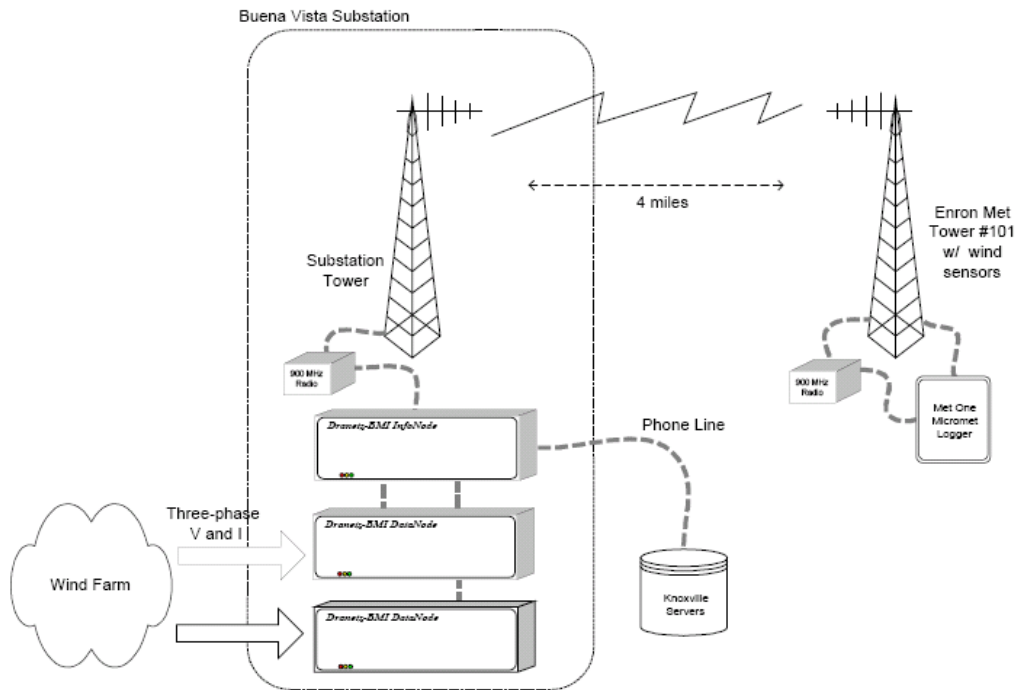
Figure 12 – An example of the data flow of monitoring equipment in a WPP.

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.
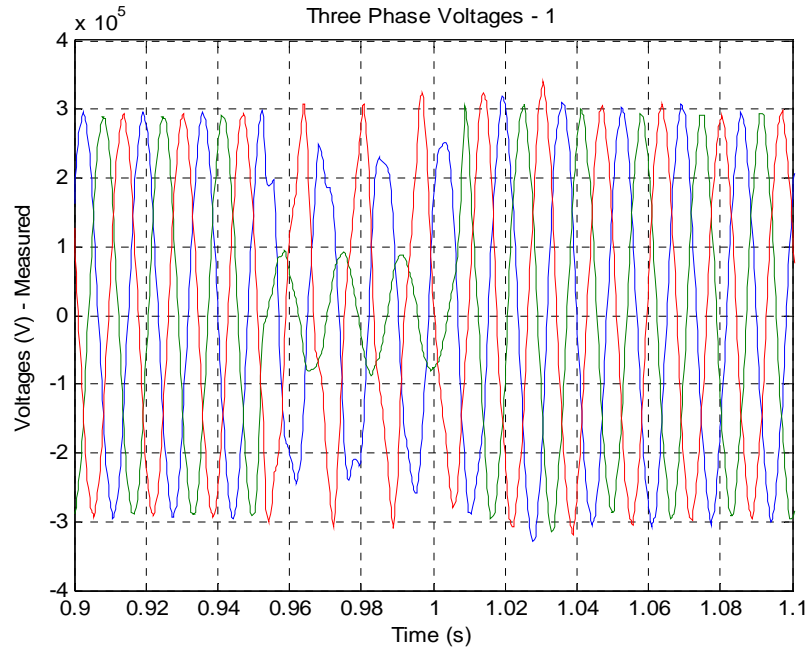
Figure 13 – The per phase voltages van, vbn , and vcn as recorded
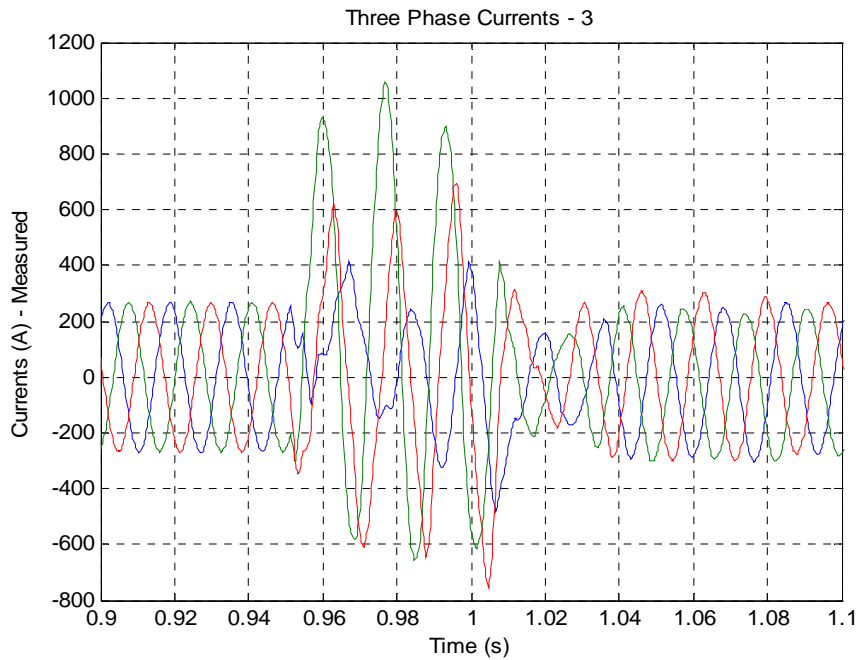
Figure 14   The line currents ia, ib , and ic as recorded

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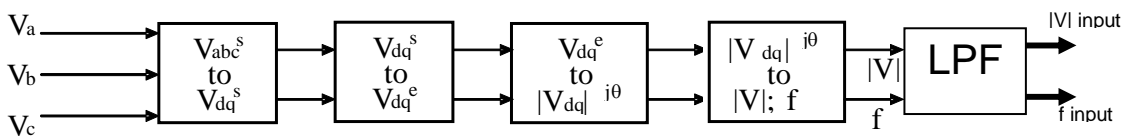
Figure 15 – Block diagrams indicating the flow process to convert the monitored voltage into the input data for GENCLS module

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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:

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

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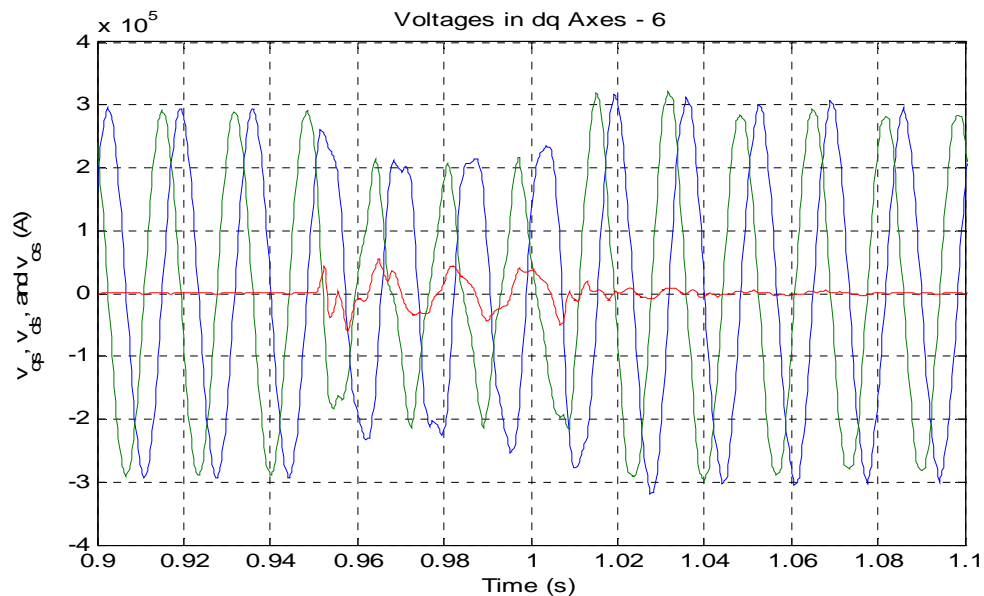
Figure 16 – The voltages expressed in the dq axis in a stationary reference frame

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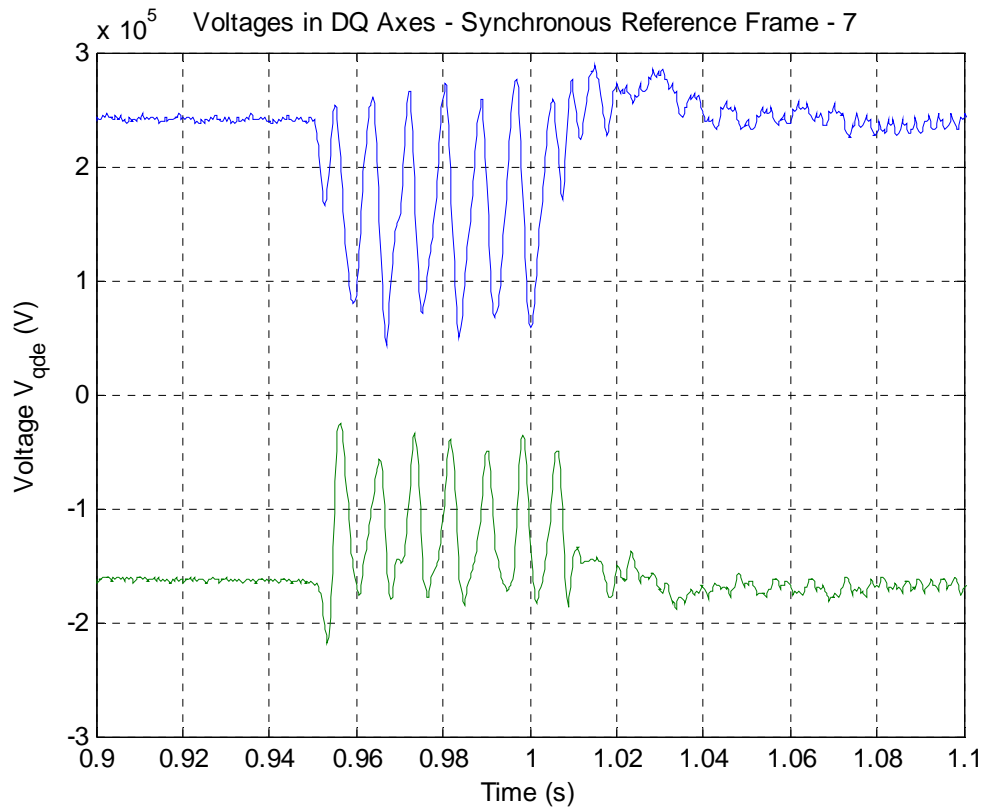
Figure 17 – The voltages expressed in the dq axis in a synchronous reference frame

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:

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

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

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.
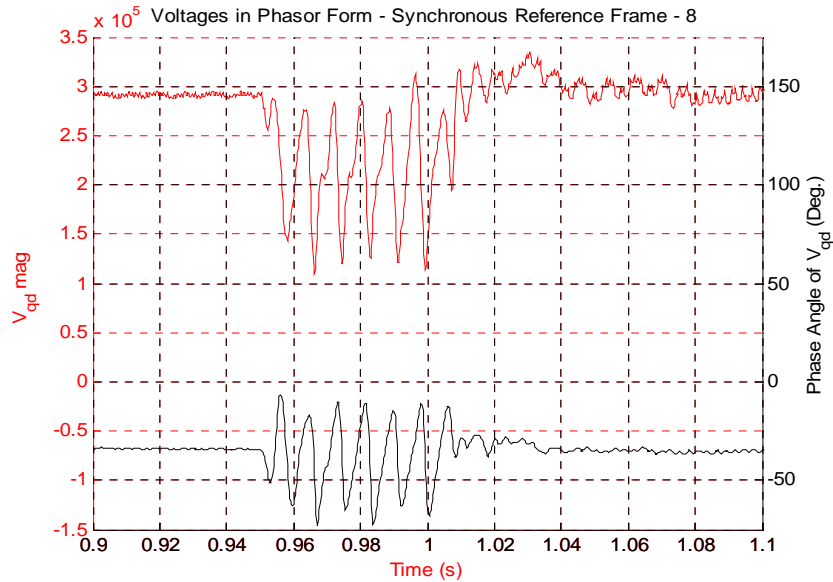
Figure 18 – The voltage expressed in its magnitude and phase angle
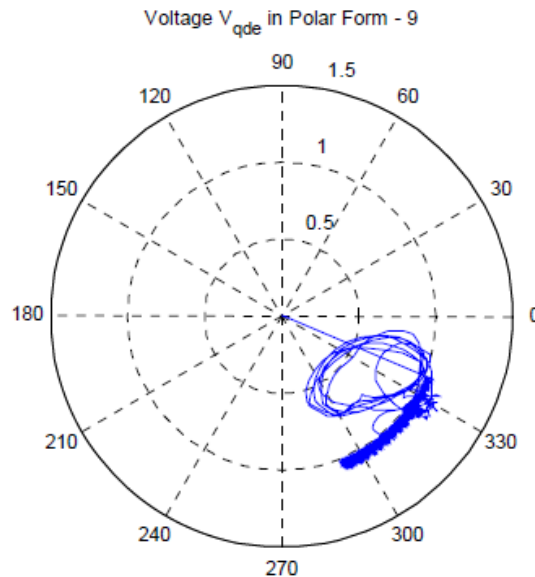
Figure 19 – The trajectory of voltage expressed in its polar form as time progressed from 0 to 4 seconds

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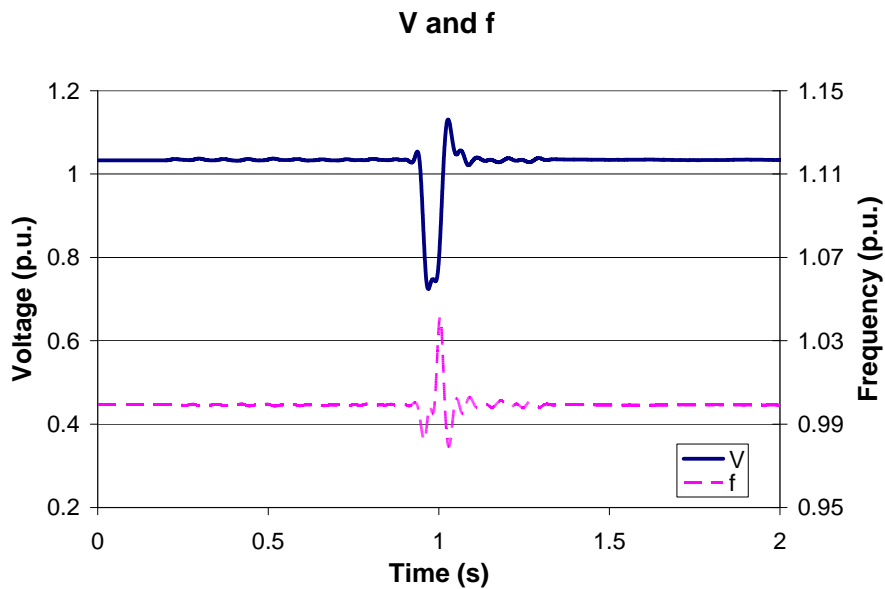
Figure 20 – Input data to GENCLS to perform the dynamic simulation

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

References

[1]   "20% Wind Energy by 2030 - Increasing Wind Energy's Contribution to U.S. Electricity Supply." U.S. Department of Energy, May 2008. DOE/GO-102008-2567, http://www1.eere.energy.gov/windandhydro/pdfs/41869.pdf

[2]   Zavadil, R.M.; Smith, J.C. "Status of Wind-Related U.S. National and Regional Grid Code Activities," Power Engineering Society General Meeting, June 12-16, 2005, pp. 2892-2895.

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

[4]   N. W. Miller, J. J. Sanchez-Gasca, W. W. Price, R. W. Delmerico, "Dynamic modeling of GE 1.5 and 3.6 MW wind turbine-generators for stability simulations," Power Engineering Society General Meeting, 2003, IEEE , vol.3, no., pp. 1977-1983 Vol. 3, 13-17 July 2003.

[5]   E. Muljadi, S. Pasupulati, A. Ellis, D. Kosterov, "Method of equivalencing for a large wind power plant with multiple turbine representation," Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, vol., no., pp.1-9, 20-24 July 2008.

[6]   E. Muljadi, A. Ellis," Validation of Wind Power Plant Dynamic Models", invited panel discussion at the IEEE Power Engineering Society, General Meeting, Pittsburgh, PA, July 20-24, 2008.

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

[8]   H. Romanowitz, et al "Effective Use of Distributed VARs from Grid Friendly Wind Power Generation" presented at the Wind Power 2005 Conference, Denver, Colorado, May 15-18, 2005

[9]   PSSE User's Manual, version 31.1.0, Siemens Power Technologies International, January 12, 2009.

[10]   "Mechanics of Running PSLF Dynamics", PSLF short course notes, General Electric International Inc., January 2005

[11]   Power System Stability and Control by Prabha Kundur, MgGraw Hill Inc., 1994

[12]   J.W. Smith, "DOE/NREL Wind Farm Monitoring: Annual Report, July 2000-July 2001", http://www.nrel.gov/docs/fy02osti/31188.pdf

[13]   P. C. Krause, Analysis of Electric Machinery, McGraw Hill Co. NY, 1986.

[14]   PSLF User's Manual, version 17.0_01, General Electric International Inc., September 08, 2008

[15]   E.Muljadi, "Model Validation of Wind Turbine Generator", Report CEC-500-2009, California Energy Commission, 2009

[16]   E.Muljadi, "Wind Power Plant Equivalencing", Report CEC-500-2009, California Energy Commission, 2009

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