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Authors
Muljadi, Eduard
Ellis, Abraham

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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

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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.

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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 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.

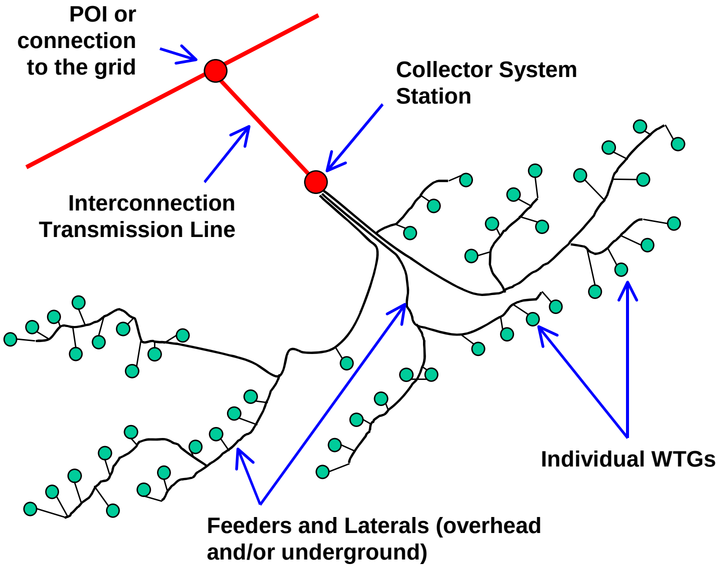


Figure 1. Physical diagram of a typical WPP

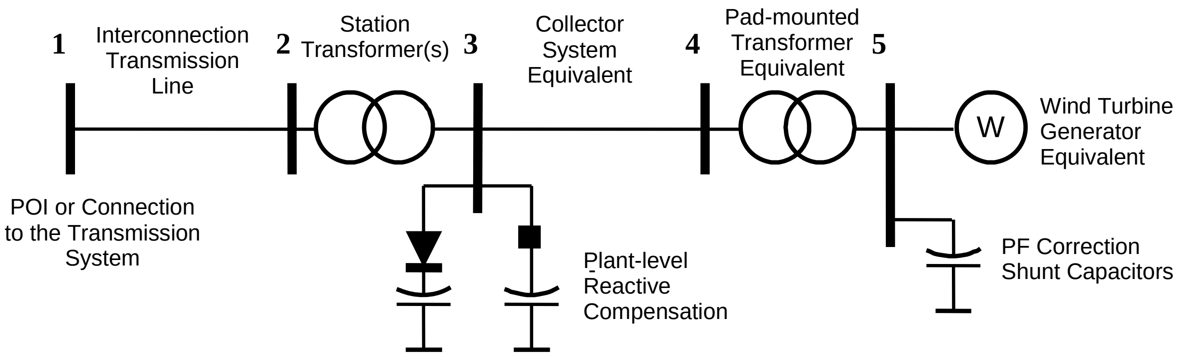
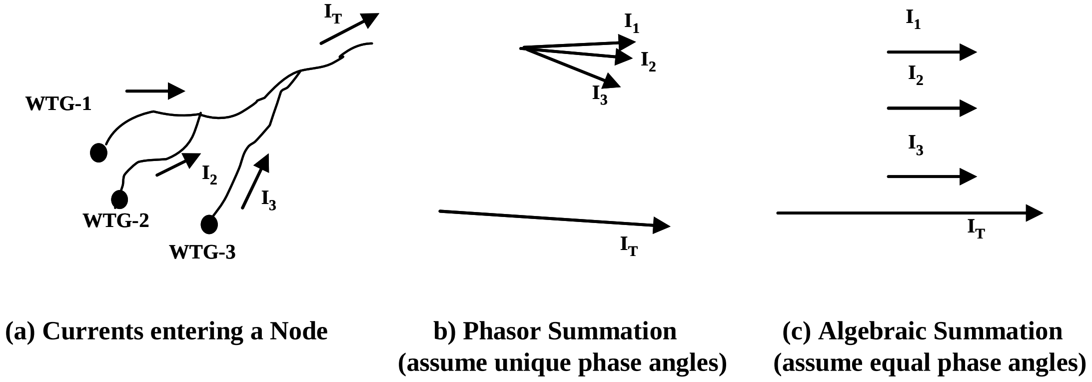


Figure 2. Single turbine representation for a WPP

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

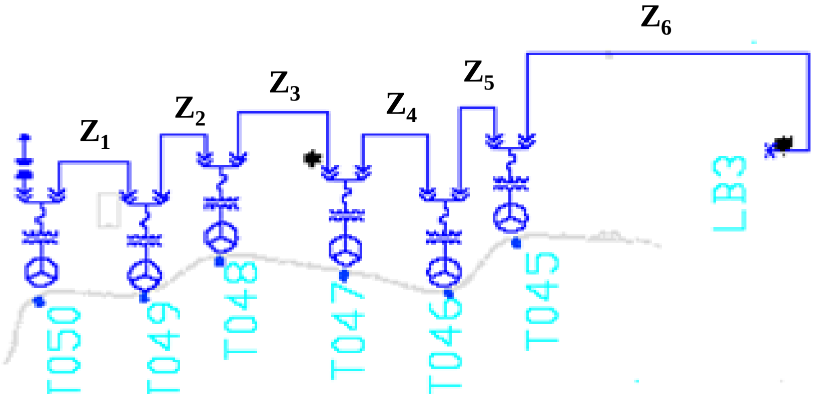
$$Z_2 = \Delta\mathbf{V_{Z2}} = (\mathbf{I_1}+\mathbf{I_2})\,\mathbf{Z_2} = 2\,\mathbf{I}\,\mathbf{Z_2}$$

.

.

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:

$$\mathbf{S}_{\mathbf{Loss\_Z1}} = \Delta\mathbf{V}_{\mathbf{Z1}}\ \mathbf{I_1^*} = \mathbf{I_1 I_1^*}\ \mathbf{Z_1} = I^2\ \mathbf{Z_1}$$

$$\mathbf{S}_{\mathbf{Loss\_Z2}} = \Delta\mathbf{V}_{\mathbf{Z2}}\ \mathbf{I_2^*} = (\ \mathbf{I_1}+\mathbf{I_2})\ (\mathbf{I_1}+\mathbf{I_2})^*\ \mathbf{Z_2} = 2^2\ I^2\ \mathbf{Z_2}$$

.

.

$$\mathbf{S}_{\mathbf{Loss\_Z6}} = \Delta\mathbf{V}_{\mathbf{Z6}}\ \mathbf{I_6^*} = \Delta\mathbf{V}_{\mathbf{Z6}}\ (\ \mathbf{I_1} + \mathbf{I_2} + \mathbf{I_3} + \mathbf{I_4} + \mathbf{I_5} + \mathbf{I_6})^* = 6^2\ I^2\ \mathbf{Z_6}$$

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

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

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

where

I = output current of a single turbine

m = index

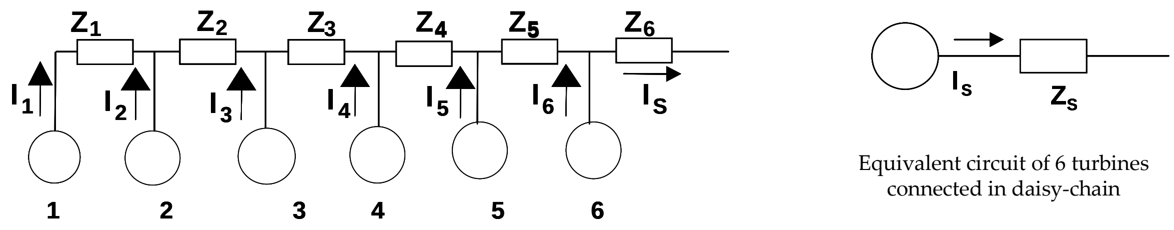
n = number of turbines in a daisy-chain string

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

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

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

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

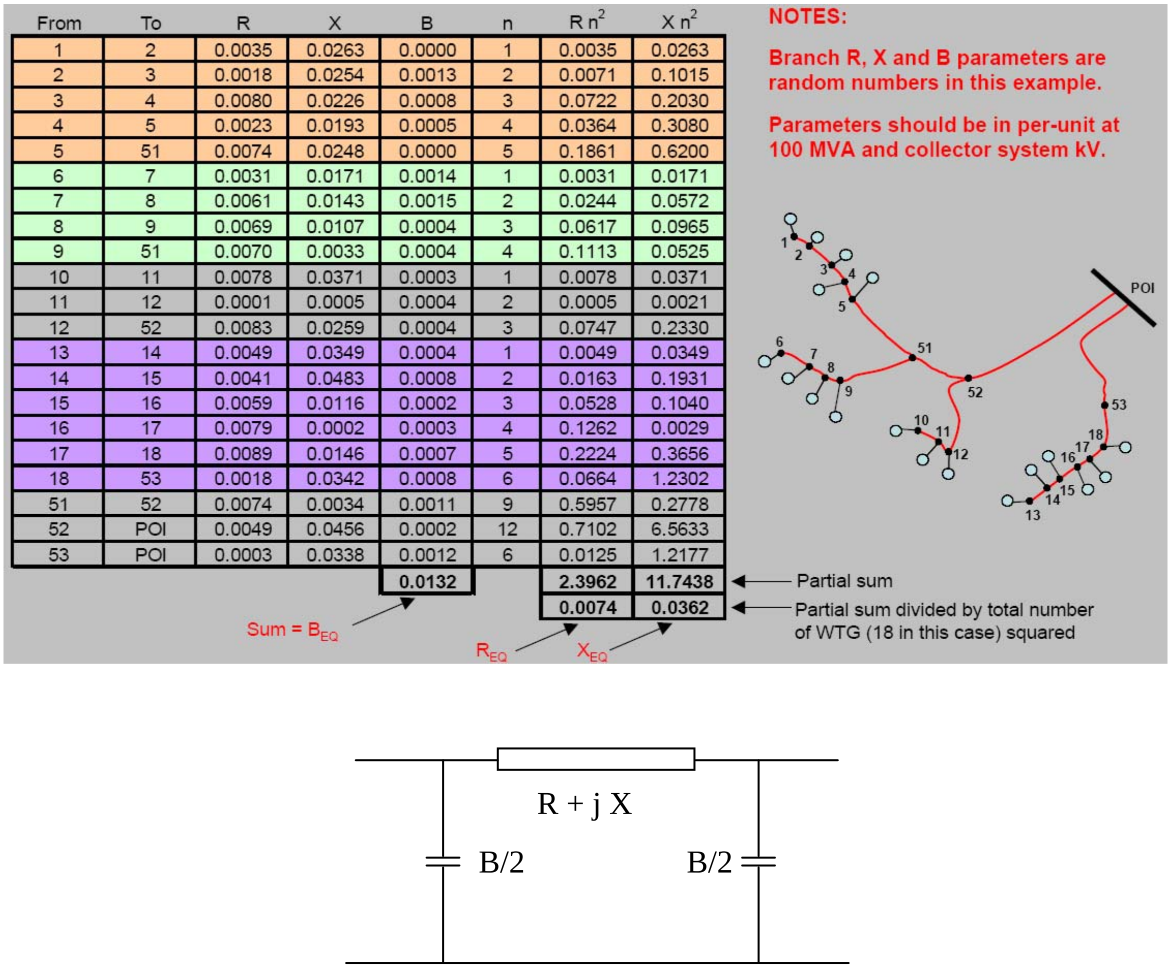
Z_m = the impedance of a branch

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 n²	X n²
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

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.

Partial sum

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

Sum = B_{EQ}

R_{EQ}

X_{EQ}

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.

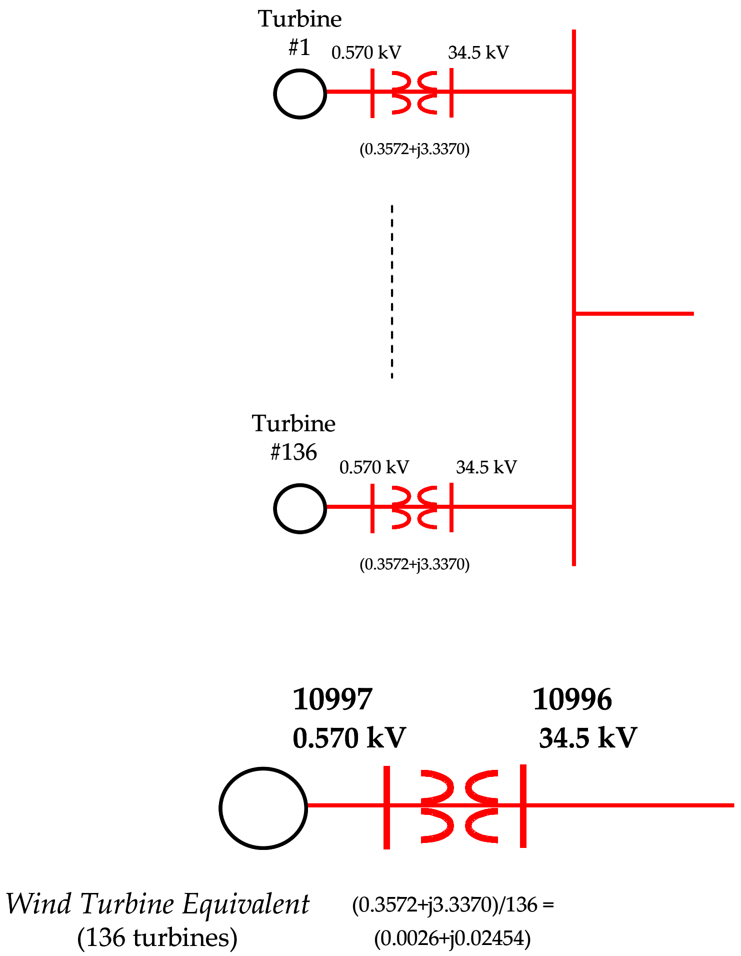


Figure 7. Representing the pad mounted transformer equivalent impedance

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.

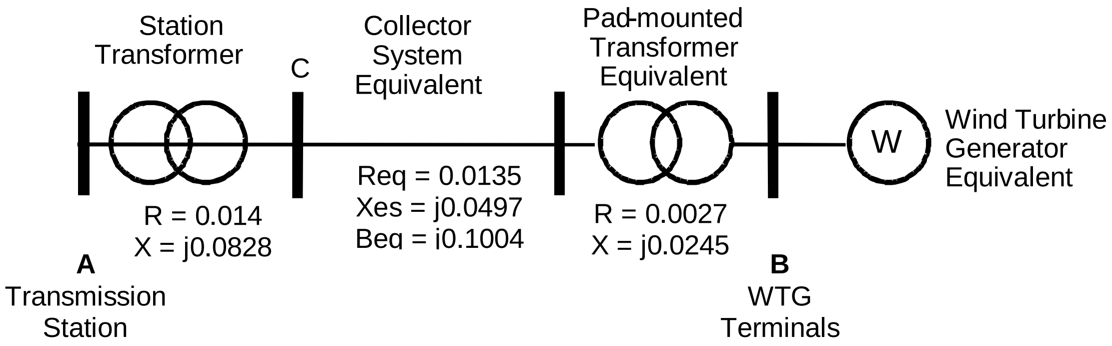


Figure 8. Single-machine equivalent impedance of NMEC wind power plant

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.

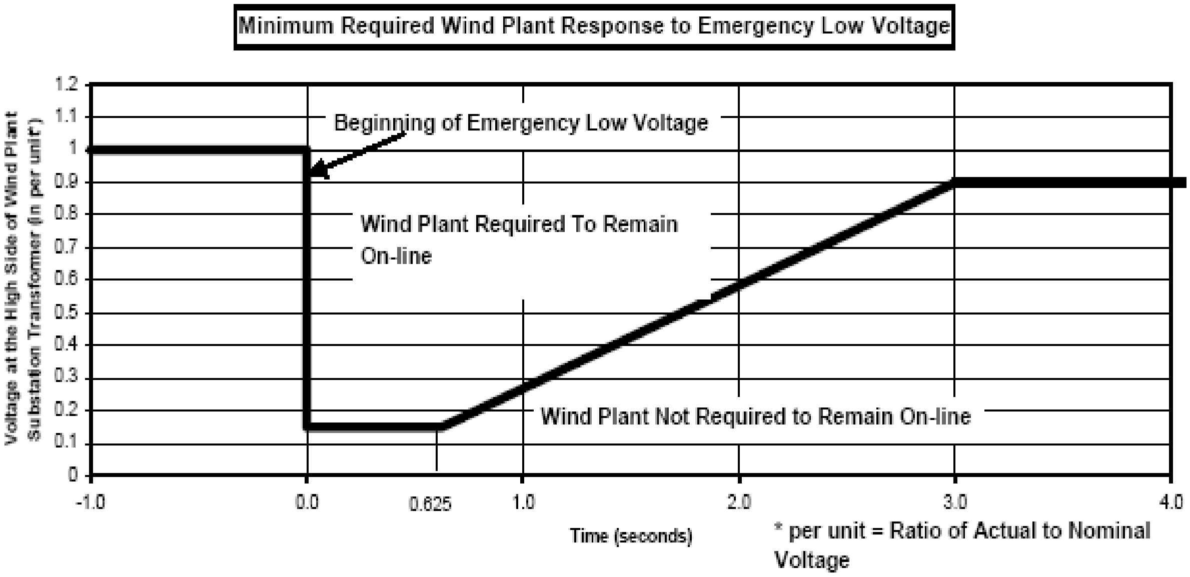


Figure 9. Test voltage profile (ref. from FERC NOPR, Jan. 24, 2005)

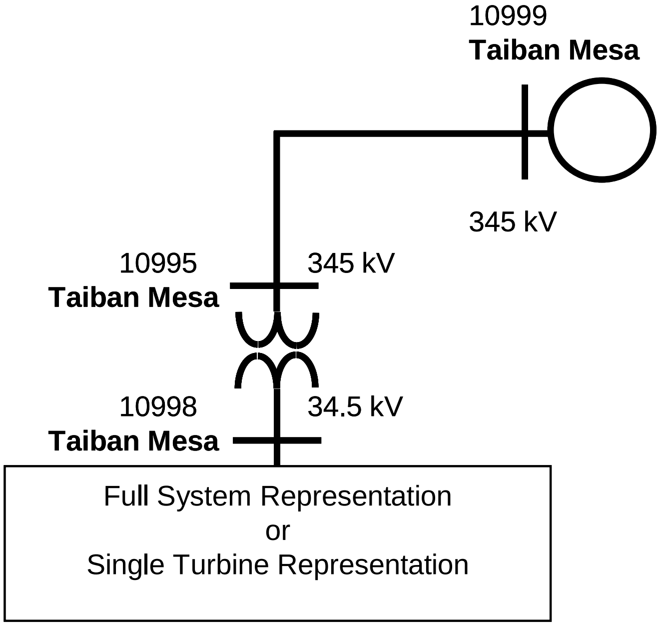


Figure 10. Single line diagram of the WPP for two types of collector system configurations

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

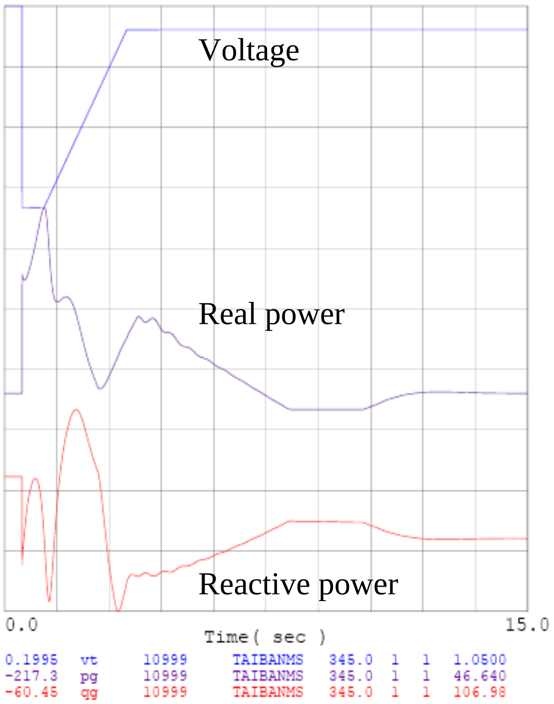


Figure 11. Voltage, real power and reactive power response to the fault at the Taiban Mesa 345-kV substation

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.

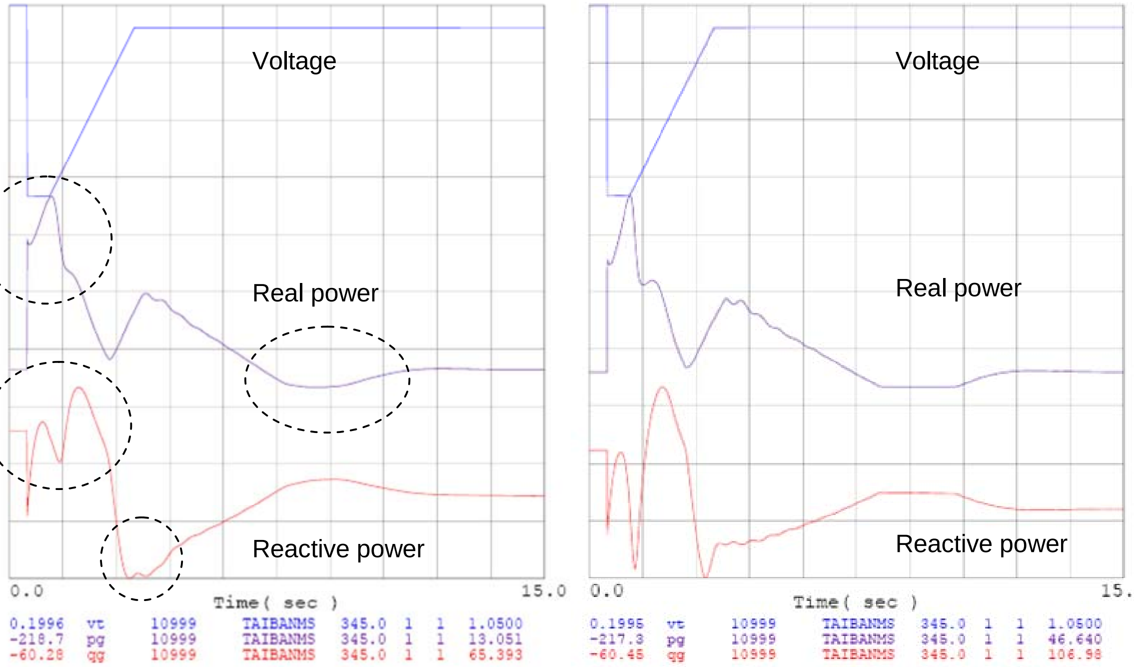
The dynamic model of each generator consists of the wind turbine prime mover model, generator-power converter model, and the relay protection model, all of which must each be represented in the dynamic file. Thus, for the entire 136 turbines, these models must be repeated and represented creating many 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.

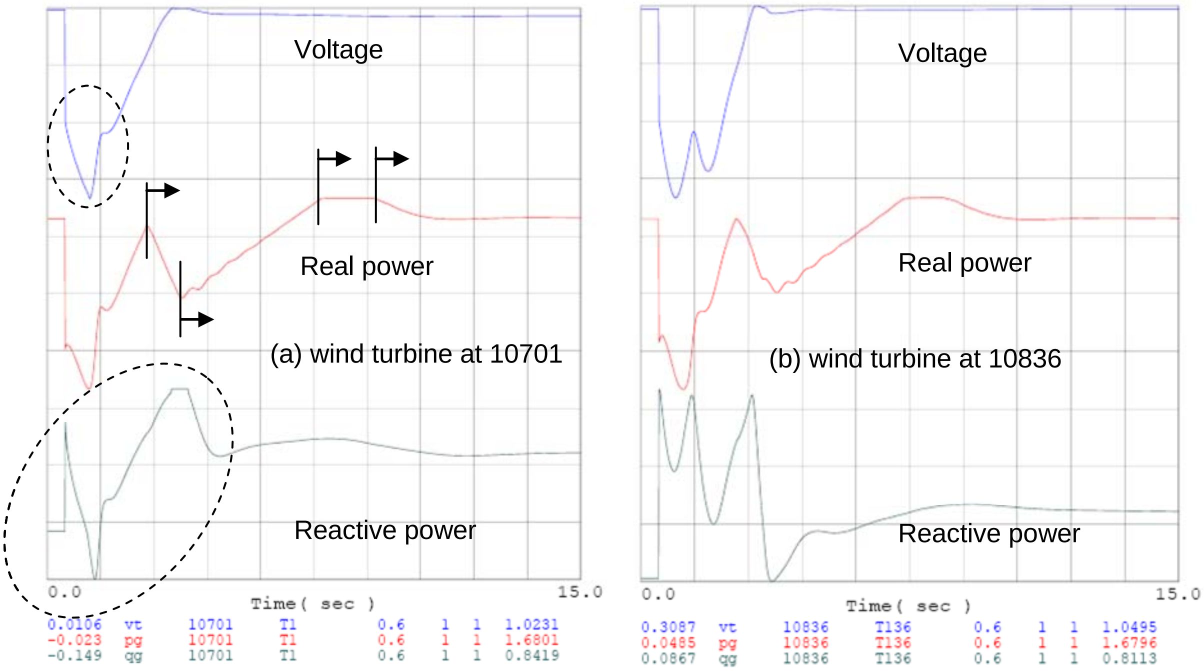


Figure 14. Voltage, real power, and reactive power at two different turbines

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.

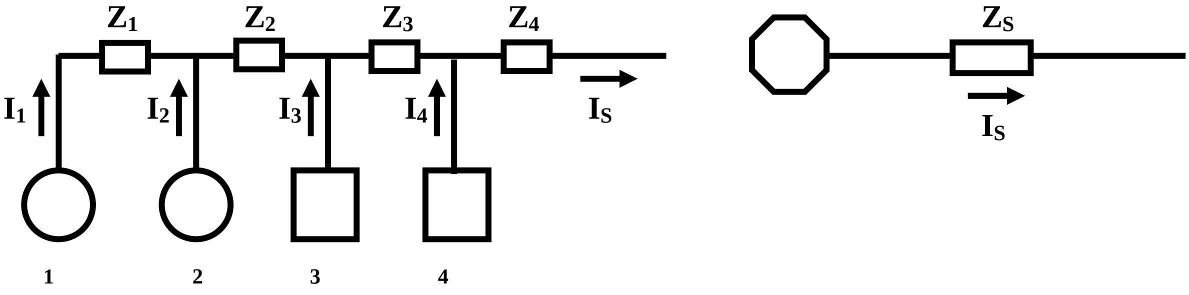
When this problem arises, analysis of WPPs must take into account that the WPP can no longer be represented by a single generator. Obviously, the representation must be based on several considerations.

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 Z_i. The power loss in each line segment can be written as:

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

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

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

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

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

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:

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

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).

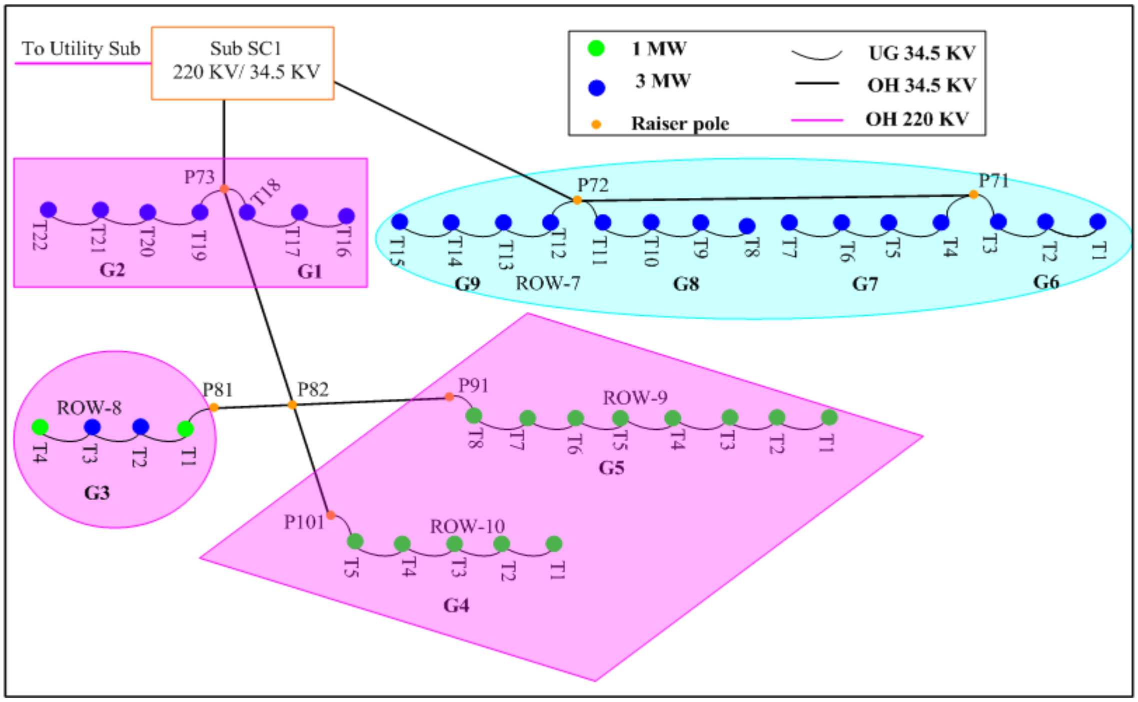


Figure 16. Groups of turbines within a wind power plant

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

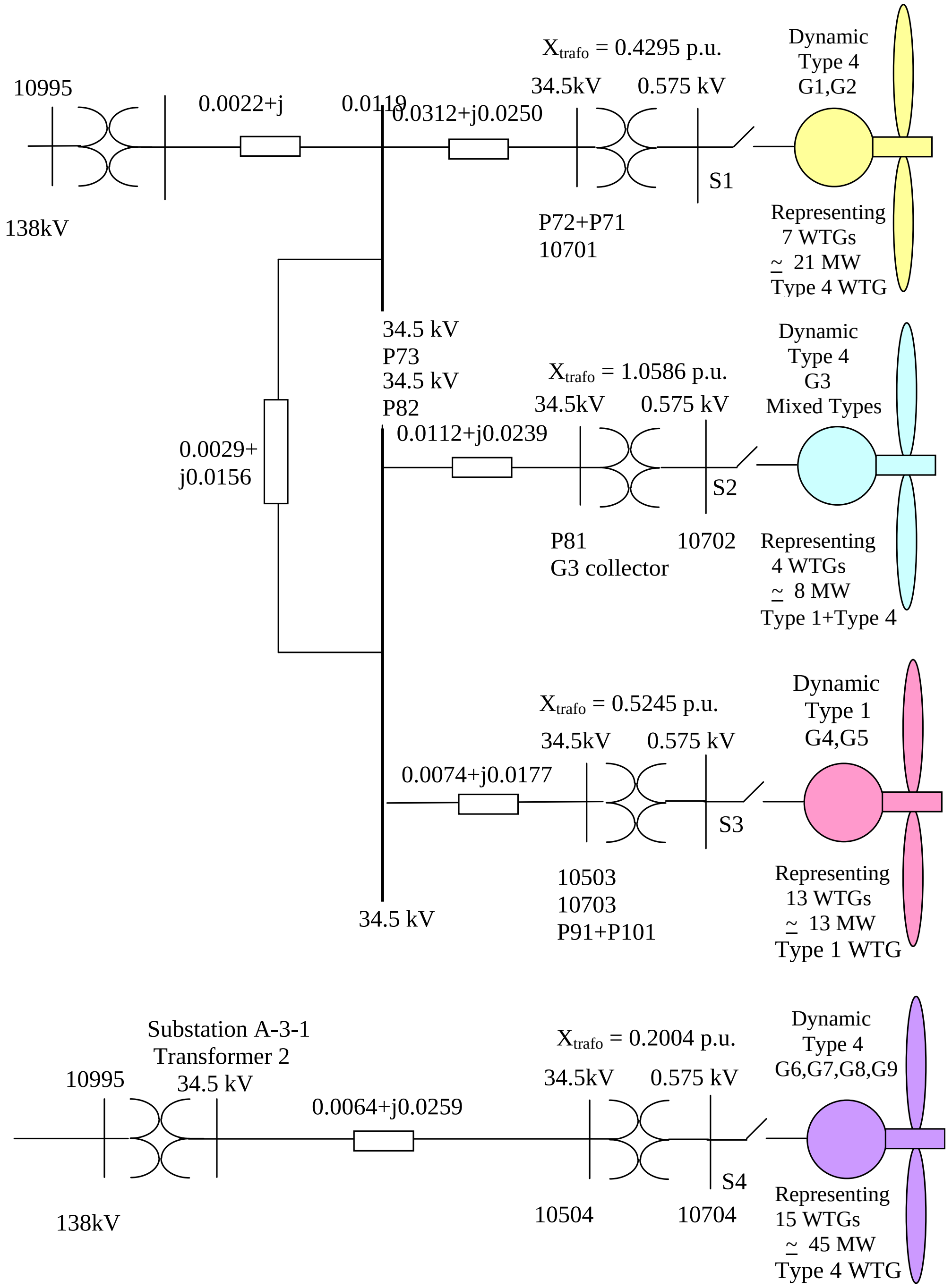


Figure 17. A WPP equivalent with a four-turbine representation

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.

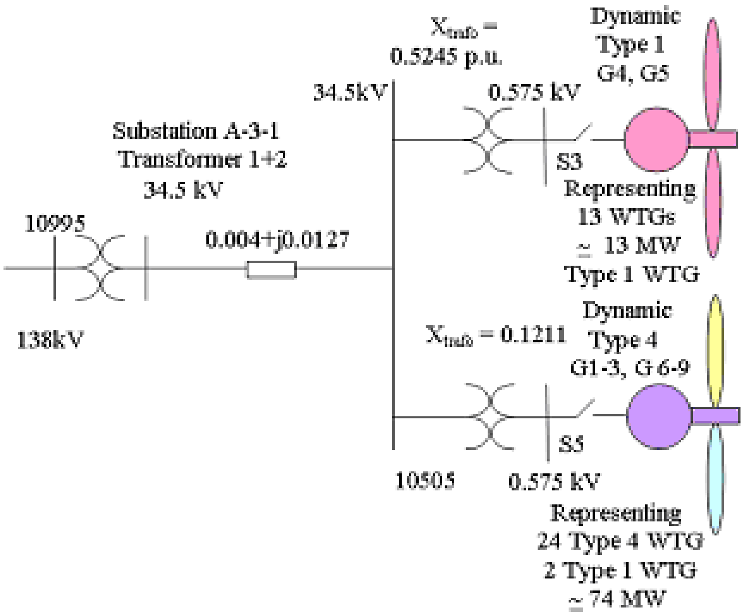


Figure 18. A simplified WPP equivalent with a two-turbine representation

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.

References

[1] Zavadil, R.; Miller, N.; Ellis, A.; Muljadi, E. “Making Connections,” Power and Energy Magazine, IEEE, Vol. 3, Issue 6, Nov.-Dec. 2005, pp. 26-37.

[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] 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.

[4] Miller, N.W.; Sanchez-Gasca, J.J.; Price, W.W.; Delmerico, R.W. “Dynamic Modeling of GE 1.5 and 3.6 MW Wind Turbine-Generators for Stability Simulations,” Power Engineering Society General Meeting, IEEE, Vol. 3, July 13-17, 2003, pp. 1977-1983.

[5] Muljadi, E.; Butterfield, C.P.; Ellis, A; Mechenbier, J.; Hocheimer, J.; Young, R.; Miller, N.; Delmerico, R.; Zavadil, R.; Smith, J.C.; ”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.

[6] 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.

[7] Tande, J.O.G., et al, “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., November 22-25, 2004.

[8] M. Behnke, et al “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.

[9] 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.

[10] “WECC Wind Power Plant Power Flow Modeling Guide”, prepared by WECC Wind Generator Modeling Group, November 2007

[11] James F. Manwell, Jon G. McGowan, Anthony L. Rogers, “Wind Energy Explained,” Wiley, 2002, ISBN 0 471 49972 2

[12] Thomas Ackermann (editor), “Wind Power in Power Systems”, Wiley; 1st edition (March 25, 2005) , ISBN-10: 0470855088

[13] Turan Gonen, Electric Power Distribution System Engineering, 2nd edition, CRC Press, 2008, ISBN 1-4200-6200.

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