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Preprint

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To be presented at the European Wind Energy Conference
Athens, Greece
February 27 – March 2, 2006

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COMPARING SINGLE AND MULTIPLE TURBINE REPRESENTATIONS IN A WIND FARM SIMULATION

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Abstract—Utility system operators and engineers want a better understanding of the impacts of large wind farms on grid stability before they are interconnected to the grid. Utilities need wind electrical models and methods of analysis that will help them analyze potential problems of grid stability. Without the necessary tools and knowledge of the behavior of large wind farms, utilities are reluctant to integrate more wind power into the grid.

This work compares single turbine representation versus multiple turbine representation in a wind farm simulation. While single turbine representation presents a simpler model, it has some disadvantages compared to multiple turbine representation. One disadvantage is that a single turbine representation does not capture the composite behavior of the wind farm, another, is that the single turbine represents the worst-case scenario when a fault occurs in the wind farm where the farm either stays connected to the grid or becomes completely disconnected from the grid. In this work, we tried to identify the advantages and disadvantages of the two system representations when simulating dynamic response of a wind farm exposed to a fault condition. We want to determine the impact of diversity in a wind farm, such as different impedances in the line feeders connected to each turbine, on the turbine behavior during fault. This paper emphasizes the dynamic behavior of the power system.

Index Terms—wind turbine, wind farm, wind energy, aggregation, power system, variable-speed generation, renewable energy, low voltage ride through.

I. INTRODUCTION

Modern wind turbines are ready for large-scale deployment and play an important role in the utility grid. Despite early stagnation, wind power has grown very fast and has become competitive with other types of generation. The knowledge base accumulated during many years of development is an asset as the technology moves forward. With low penetration of wind power, the utility was not affected by the presence of the wind farm. The loss of generation from a small wind farm was not considered a threat to the security of the overall power system. However, the size of wind farms is increasing, and so is the presence of wind energy in the power grid. More wind farms are being erected in more states—in part because the lead-time to build a wind farm is relatively short compared to conventional power plants.

In the past five years, wind energy has been considered one of the fastest growing technology sectors and has been adopted globally to fill the need of electrical energy demands. As the number of wind farms continues to grow and the level of penetration increases, utility planners need to find a method that they can use to predict the behavior of a wind farm.

As the size and rating of the modern wind farm keeps increasing, the number of turbines within the wind farm can be as high 200 turbines or more. It is not practical to simulate the entire wind farm by representing all individual turbines in the simulation. To simplify, it is common to represent the entire wind farm by groups of turbines or a single turbine. The question is, how much can we simplify without compromising the validity of the model and which configuration is best for simulating a wind farm.

In this paper, we used a large generic wind farm with many turbines for our simulation. Based on the available electrical network data, we used steady-state analysis to derive the equivalent circuit of the wind farm. The equivalence of the collector systems in the wind farm can be represented as single line impedance or it can be represented as several line impedances. Once we defined the single turbine representation, we could simulate various conditions and compare the single turbine representation to the multiple turbine representation. To limit the scope of this paper, only variable-speed wind turbines were considered.

Although stability studies have been conducted since the early development of wind energy, there are still several important questions to be answered. Will a wind farm survive a fault on the grid? How far should the fault be from the wind farm to minimize the number of turbines disconnected from the grid? How do we assess the potential drop-off of a wind farm from the power grid?

We describe the general concept of planning and operation of a wind farm in section II. In section III, we discuss single turbine and multiple turbine representations. In section IV, we simulate several aspects of wind farm diversity to understand the impact of the turbine and power system network under normal operation or under fault conditions. Finally, we summarize our conclusion in Section V.

II. PLANNING AND OPERATION OF A WIND FARM

A. Steady-State Analysis

In planning the power system for a wind farm, there are several studies performed such as an interconnection feasibility study, an interconnection system impact study, and an interconnection facilities study. The system impact study, which is related to this paper, is generally performed to investigate the impact of the new wind farm on the surrounding power systems.

The various studies listed above include steady-state (load-flow) and dynamic (transient and fault) analysis. The study is used to investigate the impact of the proposed wind farm on the reliability of the power system network. From this study, we can assess if the power system connected to the wind farm is adequate or if any upgrades are needed to ensure the reliability of the system with the connection of the new wind farm.

In the steady-state analysis, load-flow simulations are performed with the wind farm set to generate rated output power to observe the impact on the loading capability of the transmission, distribution lines, the corresponding transformers, and the switchgear components. This aspect is normally concerned with the thermal impact of the rated generation of the wind farm. The reactive power adequacy is also assessed to determine if the grid is sufficiently ready to accept this particular wind farm or if additional reactive power compensation is necessary. The reactive power assessment can predict the voltage behavior of the grid under various conditions. A commonly used method to check the voltage stability is the PV and QV curves, where the output of the wind farm is increased from medium to high output above rated until the voltage collapses. This practice measures the stability margins of the wind farm operation.

Steady-state analysis is also used to determine the new level of short circuit after the additional of the wind farm to the power grid. It determines if the size of the existing circuit breakers and other auxiliary equipment in the surrounding power system will be affected by the addition of the wind farm. If the wind farm does have an impact, what sort of modifications or upgrades must be made to the existing switchgear and power system protection, and what, if any, changes need to be made in the settings due to the addition of wind farm? These simulations were run under normal conditions and under a different set of contingencies (contingency analysis) to ensure the reliability of the power systems under different scenarios.

B. Dynamic Analysis

Dynamic analysis is performed using dynamic modeling in a time domain. The dynamics are created by the inputs exciting the wind turbine due to various events during normal, disturbance, or fault conditions.

Under normal conditions, there are a few things that can be measured and analyzed. For example, the harmonics generated by each turbine, the harmonics at the point of common coupling, the flicker, the voltage fluctuations under varying wind, and the frequency variations under different ramp-up or ramp-down conditions. Other types of operations worth observing include the impact of capacitor switching on the wind turbines operation, the start-up behavior of the wind turbines, and unbalanced voltage operations of the wind turbines. We can analyze and simulate the characteristics of a wind turbine under normal conditions using dynamic models. The time of observation for this type of analysis normally varies between a few seconds to minutes.

The analysis is important for finding out how the power system behaves when a fault occurs within the vicinity of the wind farm, and what happens to the power system when the wind farm is affected by faults that occur in the transmission network. It is also important for gauging the behavior of the wind farm under fault conditions.

Under fault conditions, it is important to understand the transient stability of the power system to predict the post-fault condition. It is necessary to simulate the faults to see if the power systems remain stable after the fault is removed from the systems. Some faults are self-clearing (i.e., lines temporarily touching vegetation due to wind) and the network topology does not change after the fault is cleared. However, more severe faults may disconnect some lines and the network and the topology of the network changes after the fault. Some generators might get disconnected thus changing the spinning reserve allocation, or an island might be formed that includes the wind farm, several generators, and some loads. Although a system might be robust and stiff before the fault, it may become weaker in the post fault condition. Once the fault is cleared, any oscillations that may occur should be damped appropriately. Various contingencies should be simulated and the proper remedial action scheme (RAS) should be taken to ensure optimal operation of the wind farm and the power systems in the pre-fault and post-fault conditions. The time frame for this simulation normally varies from a few cycles to seconds.

III. SINGLE AND MULTIPLE TURBINE REPRESENTATION

A. Single Turbine Representation

Within the scope of a single turbine, like many other power plants, a wind turbine is modeled with its individual major components included. Thus, different turbine types have to be modeled differently. Similarly, the control block diagram and control algorithm are modified as the new edition is manufactured.

A typical module consists of the following blocks:
- Aerodynamic
- Pitch mechanism
- Wind input
- Shaft dynamic
- Relay protections
- Generator and power electronics
- Control algorithm.

The components that govern the behavior of a wind turbine are represented above. These components are normally built in modules to allow sharing of modules for different turbines with minimum modifications.

Aerodynamic characterizes the aerodynamic behavior of a wind turbine. In this module, information about the turbine blade, the air density, the performance coefficient curve, and tip speed ratio are given as input or calculated in the module to compute the aerodynamic power at any wind speed. The pitch mechanism is included for a pitch-able turbine to represent the pitching activities when the wind turbine operates in the power regulation or speed regulation.

The wind input is accessible through external file. Ideally,

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it is available in a time series with varying wind speed versus time. This time domain input wind speed can be useful to examine the power and voltage fluctuations due wind turbulence or wind gusts. The shaft dynamic is available to simulate a single inertia or two inertias with stiffness and damping specified. The shaft dynamic model can tell us about the mechanical damping during disturbance.

The relay protection aspects of the wind turbine should reflect the capability of the wind turbine as well as the local regulations. If the local regulation requires that the turbine should always be connected to the grid under a certain voltage profile (low voltage ride through, LVRT), we need to test the turbine for this capability. The characteristics of the relay should be programmed based on the wind turbine manufacturers standard.

B. Multiple Turbine Representation

Within the scope of wind farm, the behavior of the wind farm embodies the collective behavior of all the turbines within the wind farm. To represent a more realistic model of the wind farms, the diversity in the wind farms and aggregate impact are included in the models. Typical aspects of diversity in a wind farm include the following:

- Spatial distribution
- Line impedance
- Different settings of relay protections
- Different types of wind turbines
- Different settings and control set-points
- Different control strategies
- Different types of reactive power compensation.

Although this list could be extended, if most of the listed items are taken into account, the modeled wind farm should be acceptably realistic.

The spatial distribution has an impact on the total output of the wind farm because the modern large wind farm is normally spread across a very large area. The wind speeds driving each individual turbine will not be identical. Thus, the response of individual turbines will be different at any instant of time. In addition, because the wind turbines are geographically dispersed, the line impedance of the feeders and the voltage drops across the feeders will not be the same at each turbine. The impact of voltage drop differences among the turbines leads to the difference in voltage at the terminals of each turbine. Voltage relay protection is based on terminal voltage to protect the wind turbine generator against over voltage or under voltage. Thus, the difference in terminal voltage may result in different set-off times. This fact is a positive contribution. For example, if a wind farm is connected to a weak grid, and the reactive power compensation is not properly designed or controlled, only a portion of the turbines will be disconnected from the grid during a fault event. Thus, the wind farm does not lose 100% of the generation and it is still contributing to the power grid.

In a very large area or even on the same wind farm, there may be several types of wind turbines installed (for example, in the Tehachapi, California, and McCamey, Texas, areas there are many wind farms connected to the same power grid

located within the same area). The differences can be in the year of make, the model, the size, or the manufacturer. Different types of turbines are normally built differently, and therefore, the control mechanisms or control algorithms are different. Because the controllers mostly consist of microprocessors or microcontrollers, two identical turbines, can be easily set to operate differently (for example, two identical turbines located within proximity can be set to start at slightly different cut in wind speeds or have different time delays to avoid start-up at the same time). Similarly, two identical wind turbines can be operated at different control algorithms. This difference signifies the signature of different turbines or different wind farms.

The reactive power compensation can be implemented at the turbine level to compensate an individual turbine. Most of the turbines are manufactured this way. Some wind farm operators add additional reactive compensation at the point of interconnection (POI) to improve the power quality of the interface at the POI.

### C. Wind Farm Representation

1) Load-Flow Simulation

How do we represent a wind farm in a power system steady-state simulation? For a steady-state analysis, the simulation is performed by using load-flow analysis. The wind farm is represented as a "single" conventional generator with output based on the characteristics of the wind farm. In performing the PV and QV analysis, we need to have the PQ characteristic of the wind farm, which can be derived from the generator parameters and the reactive power compensation characteristic at the wind farm. A better way to represent a PQ characteristic, however, is from the field measurement. Having said that, it is necessary to reevaluate this characteristic (repeat the measurement) when there are any changes in the size and the strategy of reactive power compensation.

2) Dynamic Simulation

How do we represent a wind farm in a power system dynamic simulation? For the worst-case scenario in a fault analysis, a single turbine representation may be sufficient. However, a more realistic representation will include the unique characteristics of the wind farm. This does not mean that we have to represent every single turbine installed in the wind farm. For example, consider a wind farm that covers a very large area and consists of 200 turbines of 2 different types of turbines (fixed speed and variable speed), and the variable-speed turbine is deployed with two different control strategies (constant voltage and constant power factor). Figure 1 shows the representation of the wind farm based on the unique description provided.

The example diagram presented in Figure 1 represents five different groups of turbines with distinctive characteristics as follows:

- Geographical dispersion causing line impedance difference:
  - Group 1: 40 WTGs fixed speed through line A (low impedance)
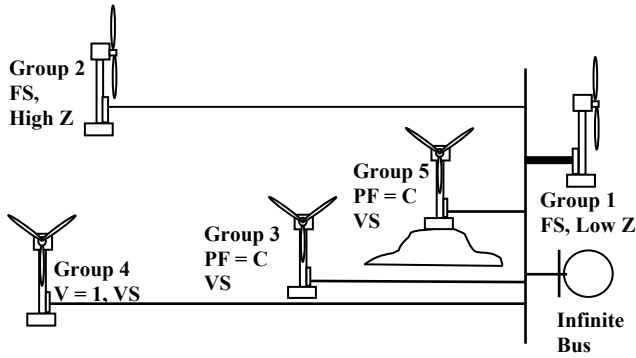
Figure 1. Methods of grouping wind turbines based on the unique characteristics of each group.

- Group 2: 30 WTGs fixed speed through line B (high impedance)
- Different types of turbines and different control algorithms:
  - Group 3: 38 WTGs variable speed with constant power factor control.
  - Group 4: 62 WTGs variable speed with voltage control.
- Different wind resource characteristics:
  - Group 5: 30 WTGs variable speed with constant power factor control (same type as group 3) but the wind turbine is located on a hill with the wind resource is significantly better than group 3, thus group 5 turbines experience a higher average wind speed than group3.

The above diagram and the description presented is only an illustration of how the wind farm can be represented by unique characteristics of the groups of turbines. Note that the purpose of separating these groups is to represent the unique signature of each group. Thus, the size of each group in megawatts must be significant enough to cause different responses at the POI for different excitations and events.

IV. VARIOUS COMPARISONS OF SIMULATION RESULTS

In this section, various comparisons will be presented. The impact of line impedance, the impact of reactive power compensation, and the impact of wind speed diversity will be presented to illustrate the points and assumptions made in the previous sections. In an attempt to clearly show the impact of the differences, the parameter used might be scaled up or down.

A. Operation Under Normal Conditions

In this section, normal conditions will be simulated to show the response of single turbine representation or multiple turbine representation. Let us first consider the impact of geographical diversity using the wind speed difference among the wind turbines. We will compare the power fluctuations and voltage fluctuations at the point of interconnection as a result of blades passing through the tower thus creating output power pulsations. We will compare the output power and

voltage at the point of interconnection for a wind farm represented by a single turbine and a wind farm represented by multiple wind turbines. To illustrate the point, we chose a fixed-speed wind turbine because the tower shadow impact is very pronounced in a fixed-speed wind turbine generation. In this particular example, we assume that there are 200 fixed-speed turbines divided into 16 groups separated with a certain distance between consecutive groups. A time series wind speed stored in a file is used to drive the wind turbines. To simulate the wind speed on each group, it is assumed that the groups of wind turbines are lined up along the direction of the prevailing wind speed. The wind speed driving each group of turbines is taken from the same file, except that each group is driven by wind speed with a certain time delay to simulate the distance between each group. The time delay of the wind speed arriving at the location of each group is computed from the distance divided by the average wind speed. This method represents a very rudimentary approach and introduces a frozen turbulence. This concept introduces the phase shift in wind speed, simulating the geographical diversity within a very large wind farm.

As shown in Figure 2, in a single turbine representation, the power fluctuation is merely an amplification of power fluctuation of a single turbine. While in the multi turbine representation, the wind farm's total output power with the natural filtering allows for power fluctuation cancellations due to unequal phase shift among the turbines. Note that the instantaneous wind speed dictates the operating slips of individual turbines and thus, dictates the nature of the tower shadow as it appears at its output. Both real and reactive power varies accordingly, and the impact on the POI voltage
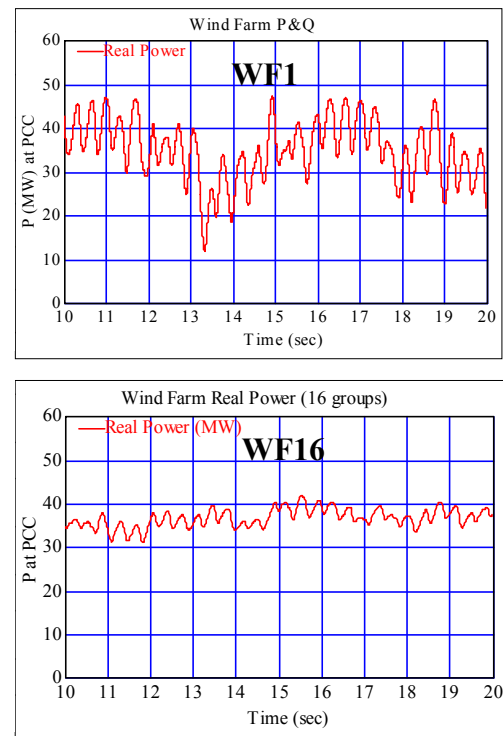

Figure 2. Power variations caused by tower shadow effect
a) single turbine representation (WF1)
**b) multiple turbines representation (WF16)**

can be shown in Figure 3. In the longer time frame, such as shown in Figure 3, the fluctuation in real and reactive power is caused by the combination of the wind speed average, wind turbulence, and tower shadow effect. From Figure 3, it is obvious that the voltage fluctuation in a multiple turbine representation is significantly reduced due to cancellation effects among the turbines.

The power quality that results from using 16 groups of turbines will also show a better representation of an actual wind farm. Figure 4 shows the significant reduction of the flicker level as the number of groups representing the wind farm increases from one group to sixteen groups of turbines. Obviously, there are limits above which increasing the number of groups of turbines will no longer provide a better picture of the reality. For example, from Figure 4 we can see that there is a significant reduction in flicker level if the wind farm is represented as one group of turbines or four groups of turbines
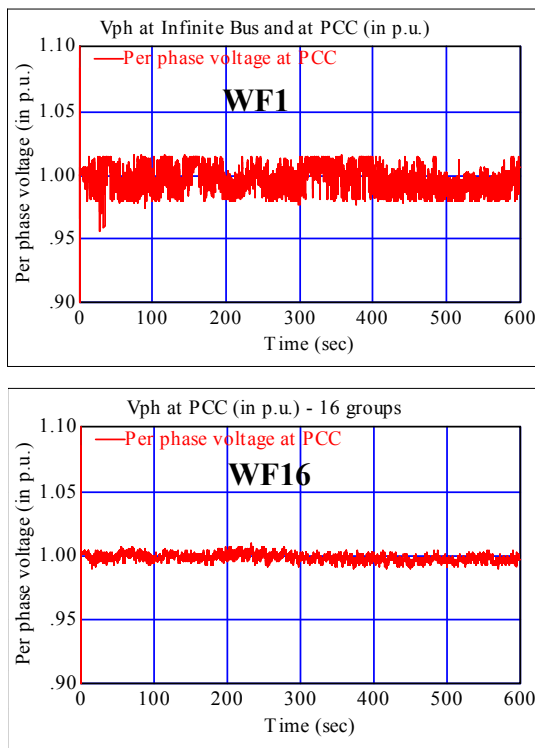
Figure 3. Voltage variations at POI
a) single turbine representation (WF1)
b) multiple turbines representation (WF16)
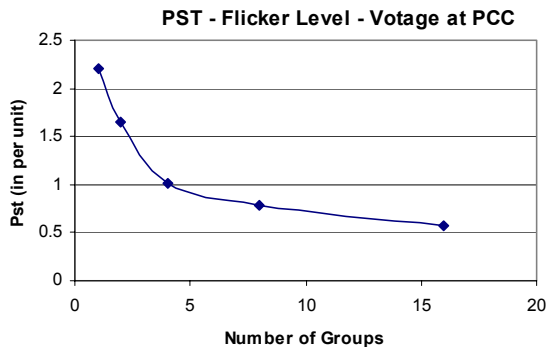
Figure 4. Flicker level of the voltage at the POI as a function of the number of the groups in the wind farm.

(2.2 per unit to 1 per unit). However, Figure 4 also shows that the difference between an eight groups turbine representation and a sixteen groups turbine representation is not very significant (0.75 per unit to 0.5 per unit).

B. Operation Under Fault Condition

Many types of faults may occur in a wind farm power system. In this paper, a three-phase symmetrical fault will be investigated because this fault generates the highest fault current and is considered to be the worst-case scenario. This type of analysis is necessary to properly size switchgear to protect the power system.

In this section, we perform a dynamic analysis using models of wind turbines downloaded from the Siemens Power Technologies Inc. Web site. We use a variable–speed, GE 1.5-MW turbine with its voltage control capability set to control its own bus. The software used is Power Systems Simulations for Engineers (PSS/E). Each wind farm can be configured to input wind speed, the number of turbines, and system protection (voltage and frequency relays). To include diversity in the analysis, a large wind farm may be split into several collector buses to represent a unique group of turbines from different perspectives (e.g., types of turbine, controller setting, length of line feeders, spatial diversity of wind speed within the wind farm). The method faults one specific bus at a time, then observes the response on the entire wind farm. For a faulted bus, the fault is designed to last 9 cycles and is then cleared.

1) Stiff grid versus weak grid:

To simulate a condition of stiff grid and weak grid, the following single line diagram is used. As shown in Figure 5, five buses represent the infinite bus 1, the high voltage side of the main substation bus 2, the medium voltage side of the main substation bus 3, the medium voltage side of the group turbines bus 4, and the low voltage of the group turbines bus 5. The rectangular block represents a group of turbines with n_1 indicating the number of turbines represented by the group. There are two line impedances Z_{LINE} and Z_{COL}. The Z_{LINE} represents the Thevenin impedance from the main substation to the infinite bus. The short circuit capability of the substation is determined by Z_{LINE}. The Z_{COL} represents the collector equivalence of the line impedance. Using this we will simulate a fault condition that occurs at point A for both stiff grid simulation and weak grid simulation. For this condition, we set the wind speed at 13 m/sec, thus, the wind turbine generates rated power before and after the fault. The number of wind turbines n_1=67 is chosen to provide approximately 100 MW of wind generation to the power grid. The wind turbine is a 1.5-MW variable-speed wind turbine
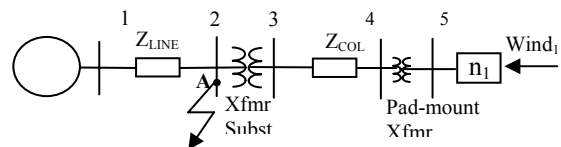
Figure 5. A typical single line diagram of a wind farm power system with a single turbine
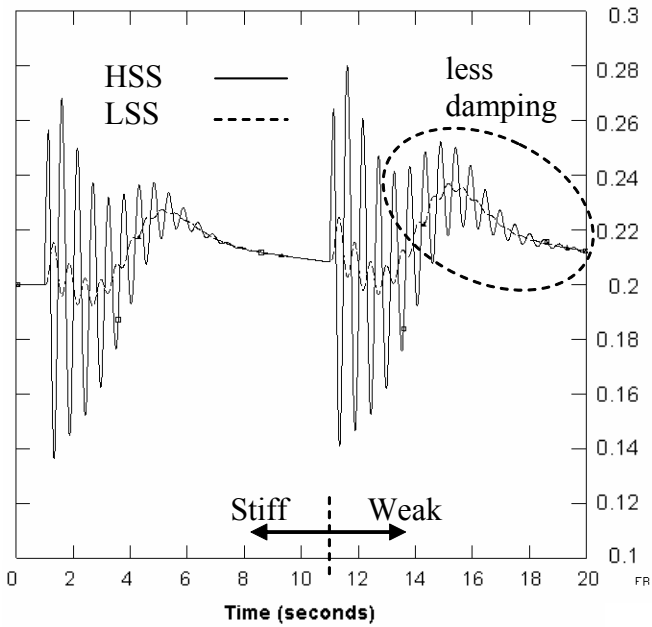
Figure 6. Rotor speed at the low-speed shaft (LSS) and high-speed shaft (HSS).
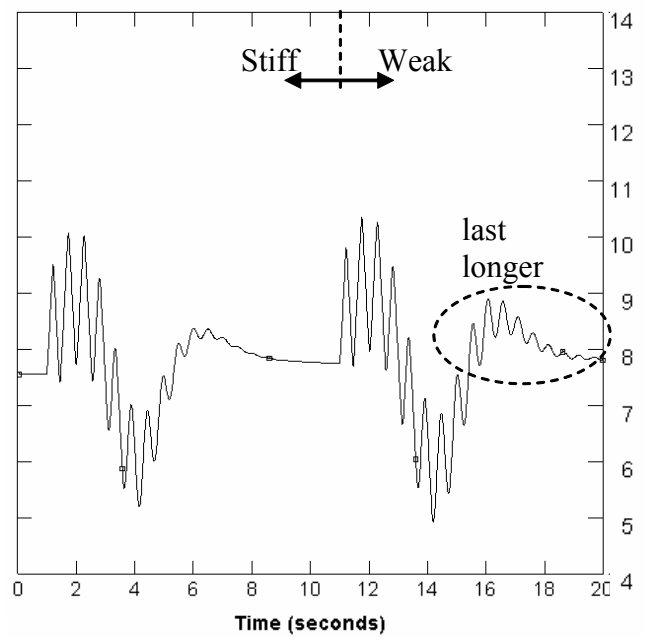
Figure 7. Pitch angle in degrees.

and it is set to control the voltage at bus 4 (medium voltage side of the pad mount transformer.

a) Stiff grid (from t= 0 seconds to t = 11 seconds):

The short circuit ratio for this particular system will be 10. In this simulation, the line impedance Z_{LINE} is set up to be two parallel lines (line$_1$=0.125 p.u. in parallel with line$_2$ = 0.5 p.u.) and the total impedance is about 0.1 p.u. Initially, the system operates normally for one second. When a fault condition occurs at point A, at t=1sec, the fault is self-cleared after 9 cycles. In this scenario it is assumed that none of the circuit breaker is opened.

b) Weak grid (from t=11 seconds to t = 20 seconds):

The same grid is exposed to the same fault at t=11 seconds, but, this time, line$_1$ is removed from the line at the end of the fault (9 cycles), thus in the post fault condition, the grid becomes a weak grid with line$_2$ remains connected. The total impedance of 0.5 p.u. or short circuit ratio of 2.0 from the main substation.

c) Discussion:

In this subsection, the stiffness of the grid condition is examined. Let us first consider the mechanical aspect of the wind turbine model. In this particular model, the mechanical shaft is modeled with its stiffness and damping characteristics included. The inertia of the turbine rotor including the blades and the generator are used as inputs. In Figure 6, the rotor speeds at the low-speed shaft and at the high-speed shaft are shown in per unit values on the same Figure. The number on the vertical axis indicates the slip above the synchronous speed of the generator. Note that the rated speed of the doubly-fed induction generator is about 20% above its synchronous speed. At this wind speed (13 m/sec), the wind turbine operates in region 3 (rated speed). In this region, the rotor speed is controlled by the pitch mechanism to stay at its rated speed even when the wind speed increases or fluctuates

above its rated value.

It is shown that when the grid is stiff, the wind turbine responded very well and the oscillation was damped out rather quickly. The LSS and the HSS seem to be out of phase as expected. The rotor speed HSS being connected to the lower inertia of the generator has a larger swing. The weaker grid seems to provide less electrical damping, and the oscillation lasts a little bit longer.

Below the rated speed, the rotor speed (HSS) is used as a signal to command of the power converter so that the turbine will generate output power proportional to the cube function of the rotor speed. This region corresponds to region 2 (low to medium wind speed). At rated speed and above, it is used to control the pitch angle of the pitch mechanism to limit the aerodynamic power, thus, to ensuring that the rotor speed stays at or below rated speed to avoid a run-away condition.

Figure 7 shows the variation of the pitch angle as the pitch controller works to keep the rotor speed below its rated speed. It shows that, for a weak grid, the pitch angle variation lasts longer. This time delay is due to the fact that, for a weaker grid, the rotor speed oscillation lingers longer.

In Figure 8, the real power and reactive power are presented on the same graph. Because the commanded power to the power converter is based on the rotor speed (filtered), the electrical output power reflects the rotor speed variation. The filtered rotor speed shows a smoother variation in output power than the actual rotor speed. The reactive power is based on the voltage controller. The reactive power is modulated to maintain the voltage at the wind turbine site to be constant all the time (within the limit of current rating of the power converter). The reactive power shown in Figure 8 is a reflection of the effort of the wind turbine generator to keep the terminal voltage at the wind turbine terminals constant. Note that there is an elevation of the reactive power
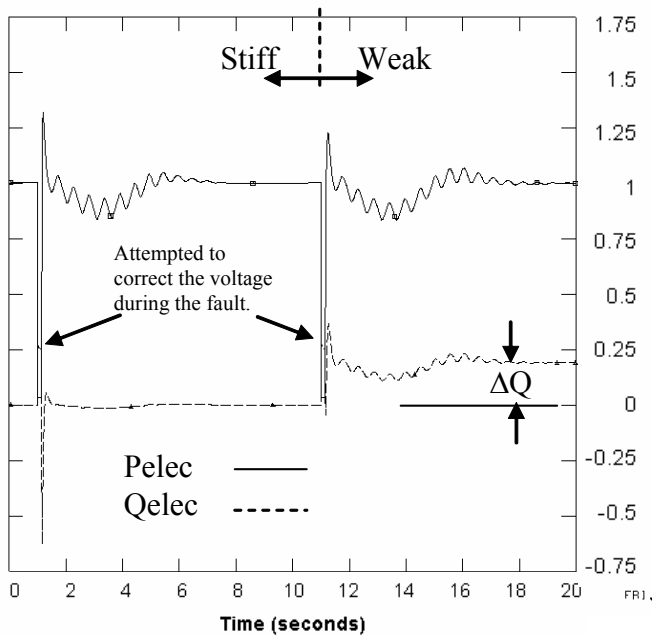
Figure 8. Electrical output real power (Pelec) and reactive power (Qelec) in p.u.

generated by the wind turbine when the grid is weaker (t > 11sec). This is due to the fact that there is more voltage drop across the weaker line impedance that must be compensated for by the wind turbine. It also shows that, during the fault, the power converter attempted to restore the voltage at the turbine terminals up to its current capability.

Figure 9 shows the bus voltages at bus 2 (location of the fault) and at bus 5 (terminals of wind turbine). As can be expected, under normal conditions, the terminal output voltage is kept at its preset value. During the fault, the voltage at bus 2 drops to zero, and the voltage at the terminal voltage is higher than zero, indicating that there is sufficient impedance between the fault and the terminal of the wind turbine ($Z_S = Z_{XFMR\_SUB} + Z_{COL} + Z_{XFMR\_WTG}$). The fault current ($I_F$) from the
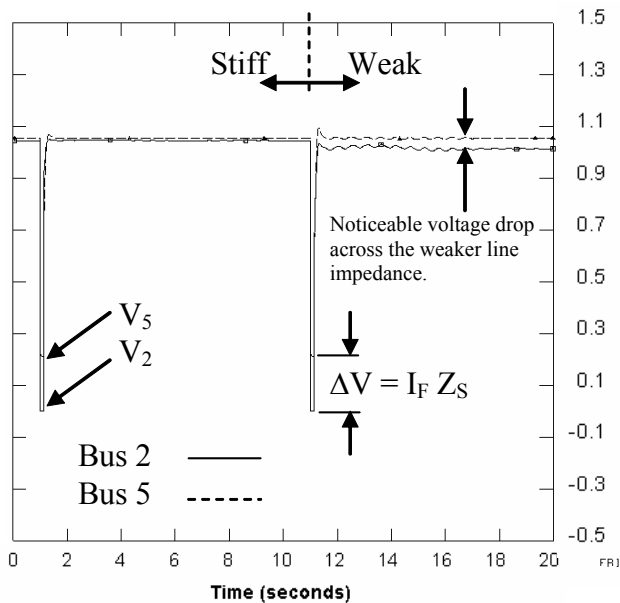
wind turbine generates sufficient voltage drop (ΔV) between the fault and the terminal of the wind turbine as appear as the voltage at the terminals during the fault.

2) Different wind speed conditions:

To simulate a condition of a very large wind farm, the simple power system network is subjected to different wind conditions. The purpose of this exercise is to show, at different wind levels, what characteristic of the wind turbine is important. The short circuit level of the line impedance Z_{LINE} is chosen to be 10. The wind farm is assumed to generate about 100 MW.

There are several tests to be included in this section, as listed below:

a. Wind speed is below rated (enough to generate 50% of rated output power of individual turbine). The wind speed is set to 8.5 m/sec. At this wind speed each turbine generates only 0.75 MW instead of 1.5 MW. To generate 100 MW total output, the number of turbines in the wind farm is doubled to 134 turbines.

b. Wind speed is just reaching its rated value. The wind speed chosen is 13 m/sec. The blade pitch angle is very small at about 4 degrees during normal conditions. The number of wind turbines is 67 and the total output of the wind farm is 100 MW.

c. Wind speed is above rated (about 125% rated value or 16.25 m/sec. With this wind speed, the output of the wind farm is at rated, but the blade pitch angle is large. The number of wind turbine is 67 and the total output of the wind farm is 100 MW.

The above three cases were run, one at a time, and the output of each case are compared to the others. The system is operated normally for the first second, then, a three-phase fault is introduced at bus 2. The length of the fault is 9 cycles. The fault is self-cleared, thus, there are no changes in the short circuit level before and after the fault.

Figure 9. Bus voltages (in p.u.) at bus 2 and bus 5.
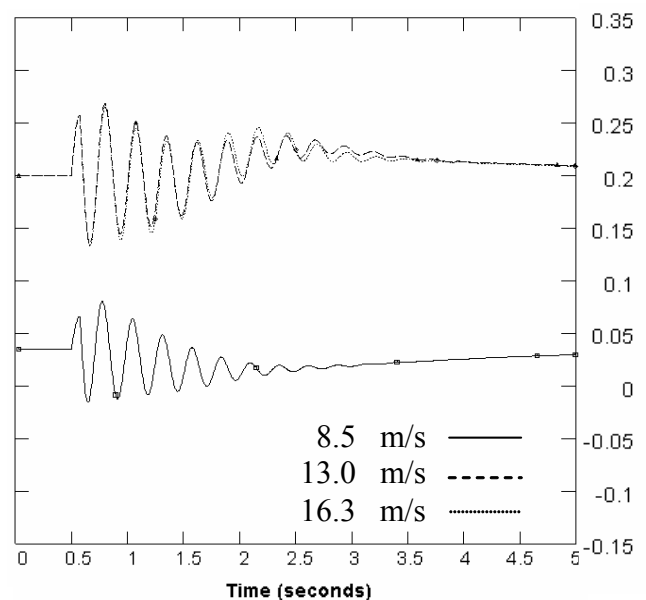
Figure 10. Rotor speed (in p.u. wrt synch. speed)

As shown in Figure 10, for the two higher wind speeds (13 m/s and 16.3 m/s), the rotor speeds of the turbines indicate that they have reached rated rotor speed. At this level, the pitch controller adjusts its pitch angle to keep the turbine rotor speed at its rated. Thus, the turbine blade angle is positioned not to capture maximum aerodynamic power, but it is positioned to avoid a run-away condition.

For a lower wind speed (8.5 m/s), the rotor speed is below its rated speed and the pitch controller is basically at its optimum angle to capture the most optimum aerodynamic power.

The responses of the turbines to the fault, shown by the rotor speeds, are different at different levels of wind speed. The turbines driven by higher wind speeds, having more aerodynamic power available to them, need a longer time to settle down, back to the pre-fault steady state condition. There is not a big difference in response shown by the rotor speeds between the turbine driven by 13 m/s and the 16.3 m/s wind speeds. The lower wind speed (8.5 m/s) shows smaller amplitude of oscillation and the time to return to pre-fault condition is a lot faster.

Figure 11 shows the variation of pitch angles in response to the fault for different wind speed conditions. The pre-fault pitch angle, as can be expected, varies for different initial wind speeds. The higher wind speed has the highest initial pitch angle. Below rated wind speed, the pitch angle, positioned at a slightly negative pitch angle, corresponds to the optimum pitch angle for this wind turbine. The response to the transient fault also differs for different wind speeds. The pitch controller is driven by rotor speed error as well as a small contribution from the power error. The two inputs and the gain of the controller parameters determine the behavior of the pitch angle at any condition.

Figure 12 shows the variation of the mechanical (aerodynamic) torque, which is based on the wind speed input and the performance coefficient Cp (which is affected by the
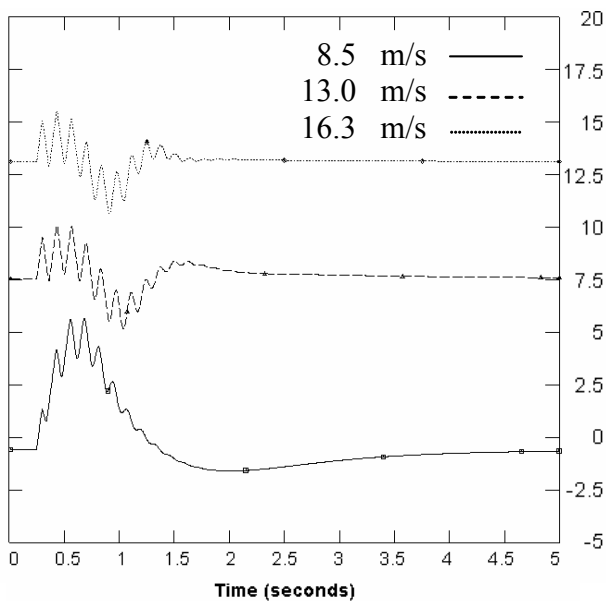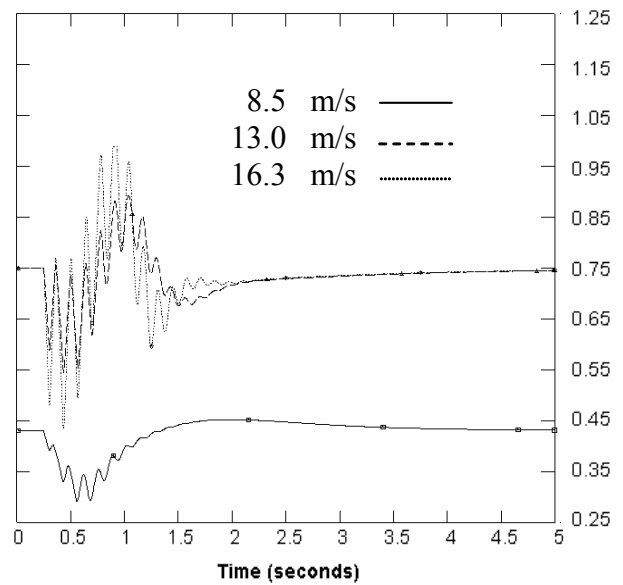

Figure 12. Aerodynamic torque (in p.u.).

rotor speed, wind speed, and pitch angle). The mechanical (aerodynamic) torques is shown to have very different signatures at different wind speeds. At high wind speed, the aerodynamic torque shows a very active variation considering that the wind speed average is high. The 16.3 m/s wind speed is about 25% higher than 13 m/s. Theoretically, at constant Cp, it can generate about twice the aerodynamic power as the 13 m/s wind speed. Thus, although under normal conditions the aerodynamic power of the two wind speeds is equal, during transient conditions, very active large swings can be observed at 16.3 m/s wind speed.

The aerodynamic torque of the turbine at lower wind speed (8.5 m/s) is very mild and it is damped out very nicely in short time.

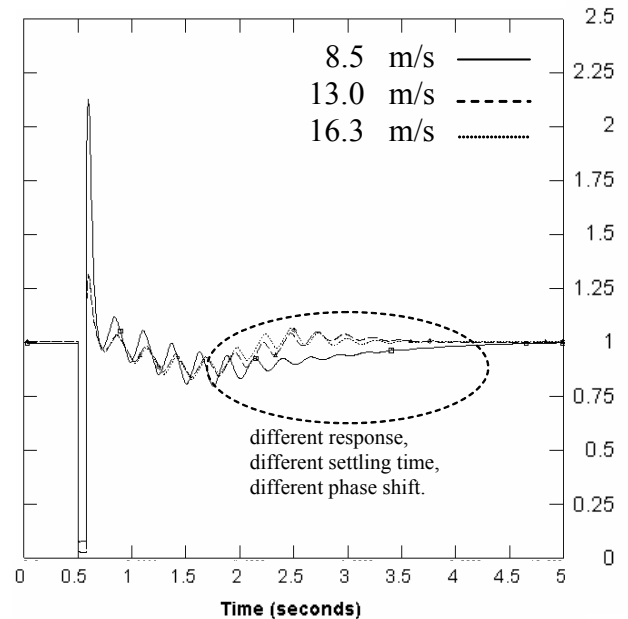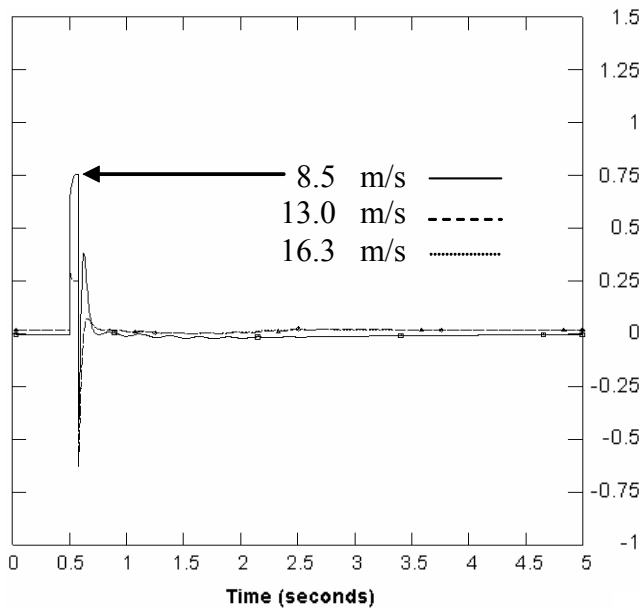Figure 13 shows the real power output of the wind farm for

Figure 11. Pitch angles (in degrees) for various wind speeds.

different response,
different settling time,
different phase shift.

**Figure 13. Real power output for various wind speeds.**

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Figure 14. Reactive power output for various wind speeds.

different wind speeds. Note that the number of turbines for the low wind speed case (8.5 m/s) is twice the number of turbines as for high wind speed cases. Thus the total output for all cases is 100 MW. It is shown that although in the pre-fault and post-fault steady-state conditions the wind farms produce the same total output power are the same at 100 MW; during the transient conditions there are deviations in the traces. Notice that the traces of real power do not seem to be in phase for different wind speeds. This is an important characteristic that will help to explain that during the fault and post fault oscillation, it is less likely that entire wind farm will synchronize to destabilize the systems. This is an important difference between a single large generator and a large wind farm consisting hundreds of wind turbines when it interacts with the outside power systems.

Figure 14 shows the reactive power variation. Because the reactive power is used to control the terminal voltage at the wind turbine site, the reactive power does not resemble the traces of the rotor speed nor the real power.

Figure 15 shows the voltages at bus 2 (the fault location) and at bus 5 (the bus terminal of the wind turbine). Look at the low wind speed (8.5 m/s) traces in Figures 14 and 15. When the wind is low, the power converter operates below its maximum current rating capability. Thus, there is some headroom to generate more current up to its rated value. When the fault occurs, the voltage at the wind turbine bus drops significantly, thus the power converter tries to correct the situation by injecting more capacitive current up to its rated current capability. As shown in Figure 14, the reactive power for the low wind speed is highest during the fault. In Figure 15, the voltage at the wind turbine bus is highest for the wind speed 8.5 m/s, which shows that the power converter can help in improving the voltage drops at the wind turbine terminals during the fault if there is sufficient capacity to generate reactive compensation.
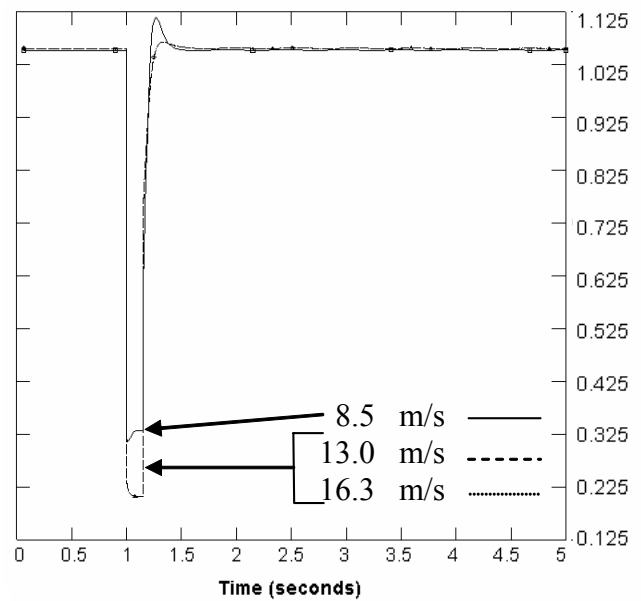

Figure 15. Voltages at bus 5 (in p.u.) for various wind speeds

3) Multiple Turbine Representation:

To simulate a condition of a very large wind farm, emphasizing the diversity in the wind farm, a single line diagram, as shown in Figure 16, is used. The system simulated is similar to the one described in Section IV-2. It has a short circuit ratio of 10. The wind farm is divided into 5 distinct groups and each group produces approximately 20 MW of wind power. Each of the turbines is controlled using voltage control to keep a constant voltage at the high side of the pad mount transformer (bus 311 through bus 315). The wind speeds for wind1, wind2, and wind4 are set to rated value at 13 m/s. Wind3 is set to 8.5 m/s, and wind5 is set to 16.3 m/s. The collector impedances are set to simulate higher impedance (Z_1 = 0.25 p.u.) and lower impedance (Z_2 = 0.0625 p.u.). The rest of the collector impedances (Z_3 through Z_5) are set to 0.1 p.u.. Each of the group is set to generate 20 MW.

Figure 17 shows the voltage at the terminals of the wind turbines. As shown, due to the diversity listed above, there are differences in the voltage levels at the output terminals of the wind turbines under the steady-state conditions or during the faults.

The behavior of the turbines has been explained previously based on the unique characteristics described in section IV-1
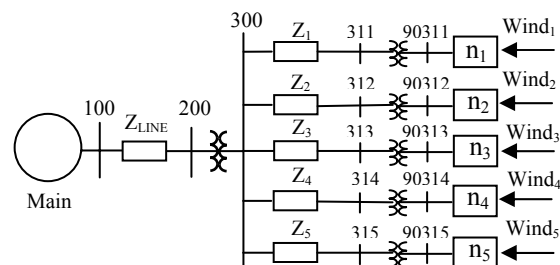
Figure 16. Single line diagram of a wind farm with 5 groups of turbines.

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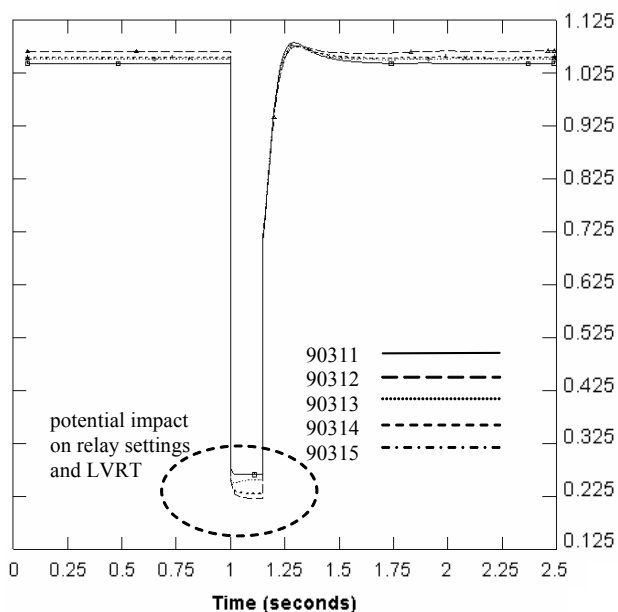
Figure 17. Voltage at the terminals of the wind turbines.

and section IV-2, and it will not be repeated here. These differences can affect the behavior of the wind turbine based on the trigger settings of the relay protections (i.e. LVRT). During severe disturbances or transient events (faults), only some of the turbines will be disconnected instead of the entire wind farm.

V. CONCLUSION

This paper presents alternatives to simulating a wind farm. In the past, many wind farm simulations were performed using a single turbine to represent the entire wind farm. It is similar to representing a conventional power plant with a single large synchronous generator. It has been very successful for predicting instabilities, such as sub-synchronous resonance, in simulating conventional large synchronous generator power plants.

A wind farm is usually very large. There are diversities in the wind farm (wind speed, line feeder impedance etc.) that make individual turbines respond differently to the same fault. Several examples, both in normal operation and during the fault conditions, are described in this paper.

In a real wind farm, there are many wind turbines connected to the point of interconnection. Most of the generators used are induction generator or combination of generator and power converter. Although the wind turbines are connected to a single point electrically, the generator mechanical shafts of all the turbines are not physically connected to each other. The mechanical and aerodynamic damping provided by each turbine will differ from one turbine to the next. Thus, unlike conventional synchronous generator, any mechanical oscillations at a single turbine are not necessarily synchronized to other turbines in the same wind farm. Each turbine in the wind farm is free to operate at its own operating condition.

In conclusion, a single turbine representation approach leads to the worst-case scenario. To represent a large wind farm, unique attributes of the wind farms should be included to represent the unique characteristic of the wind turbines or a group of wind turbines. Thus, during transient events, although there may be a group of turbines disconnected from the wind farm, the entire wind farm will not be disconnected.

VI. ACKNOWLEDGMENT

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1. REPORT DATE *(DD-MM-YYYY)* March 2006	2. REPORT TYPE Conference paper	3. DATES COVERED *(From - To)* February 27 - March 2, 2006

4. TITLE AND SUBTITLE Comparing Single and Multiple Turbine Representations in a Wind Farm Simulation: Preprint	5a. CONTRACT NUMBER DE-AC36-99-GO10337
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) E. Muljadi and B. Parsons	5d. PROJECT NUMBER NREL/CP-500-39510
	5e. TASK NUMBER WER6.2112
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	8. PERFORMING ORGANIZATION REPORT NUMBER NREL/CP-500-39519

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) NREL
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
This paper compares single turbine representation versus multiple turbine representation in a wind farm simulation.

15. SUBJECT TERMS
wind turbine; wind farm; wind energy; aggregation; power system; variable-speed generation; renewable energy; low voltage ride through

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	UL		19b. TELEPHONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(12/2004)