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Preprint

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National Renewable Energy Laboratory

To be presented at the International Conference on Wind Energy Grid-Adaptive Technologies
Jeju, Korea
October 20–22, 2014

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Conference Paper
NREL/CP-5D00-62568
September 2014

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Wind Power Plant Voltage Stability Evaluation

Eduard Muljadi* and Yingchen Zhang*

Abstract – Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance during a given initial operating condition. Voltage stability depends on a power system's ability to maintain and/or restore equilibrium between load demand and supply. Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses. Possible outcomes of voltage instability are the loss of load in an area or tripped transmission lines and other elements by their protective systems, which may lead to cascading outages. The loss of synchronism of some generators may result from these outages or from operating conditions that violate a synchronous generator's field current limit, or in the case of variable speed wind turbine generators, the current limits of power switches. This paper investigates the impact of wind power plants on power system voltage stability through using synchrophasor measurements.

Keywords: Wind Power Plant, Voltage Stability, Phasor Measurement Unit

1. Introduction

The U.S. power industry is undertaking several initiatives that will improve the operations of the electric power grid. One of those is the implementation of wide-area measurements using phasor measurement units (PMUs) to dynamically monitor the operations and status of the network and provide advanced situational awareness and stability assessment.

Wind power as an energy source is variable in nature. Similar to other large generating plants, outputs from wind power plants (WPPs) impact grid operations; conversely, grid disturbances affect the behavior of WPPs. The rapidly increasing penetration of wind power on the grid has resulted in more scrutiny of every aspect of WPP operations and the demand that large WPPs should behave similarly to conventional power plants under normal and contingency grid conditions. The low-voltage ride-through requirement for WPPs is one such example. Other proposed requirements include frequency response and simulated plant inertia.

To completely describe the system condition (state) of the electric power grid at any instant, it is necessary to know the voltage (V), current (I), and apparent power (S) of every point (node/bus) on the system. All three quantities in an alternating-current power system are complex numbers that can be represented by phasors with both a magnitude and a phase angle. Of the three phasor quantities, only two (any two) are needed to derive the third based on the equation $S = VI^* = P + jQ$. Advanced computing power and the worldwide availability of global positioning system (GPS) time signals make it possible for a PMU to measure voltage and current at a precise time and output these quantities in phasor form. GPS time signals can be accurate within 1 microsecond (μs) anywhere the signal is available. GPS time signals enable the synchronization of measurements across the very large distances that power system interconnections span. This new technology not only produces very accurate phasor measurements, but it also enables synchronized measurements in the same instant [1-9].

2. WPP Voltage Stability Evaluation

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in a system after being subjected to a disturbance from a given initial operating condition. Voltage stability depends on a power system's ability to maintain and/or restore equilibrium between load demand and supply. Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses.

Possible outcomes of voltage instability are the loss of load in an area or tripped transmission lines and other elements by their protective systems, which may lead to cascading outages. A loss of synchronism of some generators may result from these outages or from operating conditions that violate a field current limit of synchronous generator; or in the case of variable speed wind turbine generator, the current limits of power switches. Voltage stability may vary during the event; it can be short term (< 1 minute), or it may evolve during many hours [10–11].

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2.1 Parallel Compensation

Reactive power losses in a transmission line can be supplied from Bus 1 or Bus 2, or they can be shared by both sides. Parallel compensation can be implemented on both sides. Reactive compensation can be implemented by controlling the generator itself, or it can be provided from external compensation, such as adjustable capacitor banks, synchronous condensers, and static power compensation (static VAR compensator, SVC, or static compensation, STATCOM).

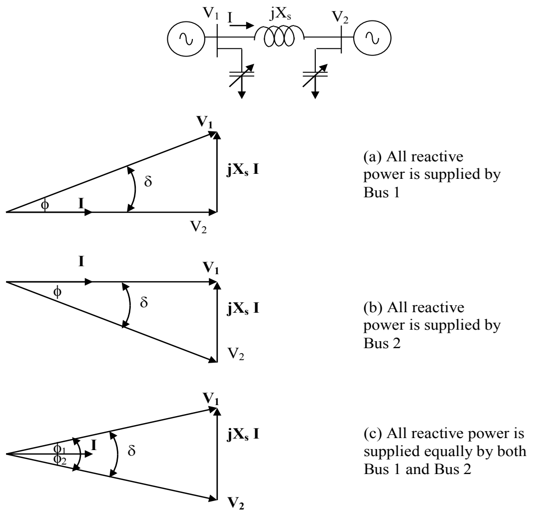

Figure 1. Two-bus system with available reactive power resource

Two possible compensations are commonly implemented in a WPP: one is reactive compensation at the turbine level (mostly in Type 1 and Type 2 wind turbine generators); the other is at the plant level (usually at the low side of the substation transformer). Plant-level compensation is usually added when a WPP is connected to a weak grid. Type 3 and Type 4 wind turbines are equipped with power converters that can provide controllable reactive compensation.

Consider Figure 1 (c), which shows that the voltage at Bus 1 and Bus 2 is maintained constant, and there is equal magnitude at 1.05 p.u. The reactive power is supplied by both Bus 1 and Bus 2. The voltage is adjusted to be constant; thus, as the output power from Bus 1 fluctuates, the reactive power must also be adjusted to follow the output power generated by Bus 1.

In this case:

$$\phi_1 = \phi_2 = \delta/2$$

Thus, the reactive power generated by Bus 1 must follow:

$$Q = V_1 \, I \sin(\delta/2)$$

And the reactive power can be commanded to follow the rules:

$$Q = P \tan(\delta/2)$$
$$P = V^2 \sin\delta / X_s$$

With an active adjustment of reactive power generated by reactive power compensation at Bus 1 and Bus 2, the voltage level can be kept constant at varying wind power output. Note that this control helps to keep the voltage adjusted, but the power angle δ is not affected for the same amount of power delivery. Figure 2 shows an example of controlling reactive power to maintain equal contribution of reactive power from both sides of the buses.

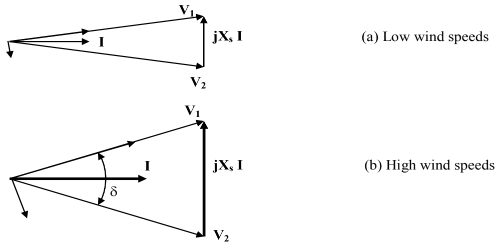

Figure 2. Voltage phasor diagram with equal contribution of reactive power from both sides

2.2 Series Compensation

Reactive power compensation can also be accomplished by using series compensation (see Figure 3). The advantage of this is that the voltage and current rating of the series compensation is relatively small considering that it is intended to compensate for the voltage drop of the line impedance. Series compensation is commonly used to compensate long transmission lines; however, care must be taken not to make it prone to cause subsynchronous resonance.

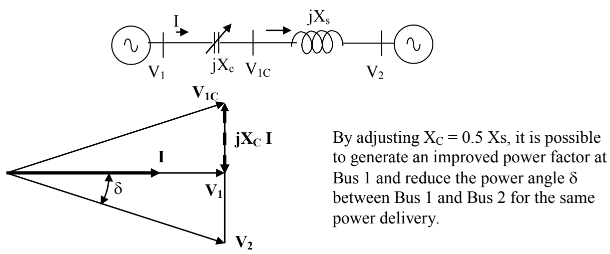

Figure 3. Single-line diagram of a series-compensated system and a diagram of its voltage phasor

A typical WPP representation is shown in Figure 4. Note that the equivalent generator, pad-mounted transformer, and collector system can be derived easily from the actual collector system schedule [12–15].

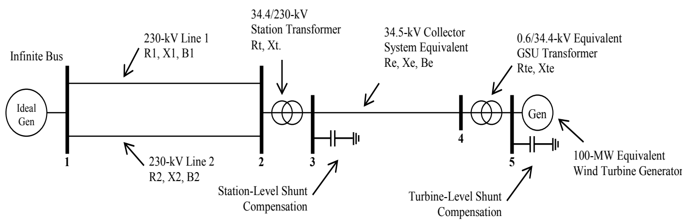

Figure 4. WPP represented by a single generator

2.3 PV and PQ Curves

In this section, we show how to perform power-voltage (PV) and voltage–reactive power (VQ) power system stability analysis on a WPP. We use a single-turbine representation of a WPP. The WPP uses 1.5-MW Type 3 (variable-speed doubly-fed induction generator) wind turbines operated in variable-speed mode with a constant power factor, PF = 1.0. The total output power of the WPP is rated at 204 MW. The WPP is connected to the rest of the power system via its point of interconnection. Two grid conditions are used in this study: the stiff-grid and weak-grid conditions. The stiff-grid condition is simulated by connecting both of the transmission lines between Bus 1 and Bus 2. The weak-grid condition is simulated by disconnecting one of the parallel lines between Bus 1 and Bus 2. The transmission lines are overhead lines with a very small shunt capacitance.

The collector system is built with underground cables and some overhead lines. Because the size of the WPP area is very large, the effective impedance between the substation and a turbine is different for each turbine.

2.3.1 PV Capability Curve

A PV capability curve is normally conducted to measure the proximity of the rated operating condition of a WPP to the voltage collapse. In a large power system network, the level of the output power of a group of generators in the area and zone of interest are usually varied, and the other group of generators is reduced by the same amount of power to develop net-zero additional output power. For a WPP, a PQ characteristic map of the WPP is generally used, and the WPP is operated from a low-wind to higher-wind condition with a pair of P&Q from the PQ characteristic map. Most wind turbine generators (Type 1 and Type 2) are normally compensated to have a unity power factor operation by using a switched capacitor. Type 3 and Type 4 wind turbine generators are built with the capability to vary reactive power and can be operated to control voltage, reactive power, or the power factor output via a power converter control. Additional information related to PV and VQ curves as discussed in this section and the next and can be found in the references [10–11].

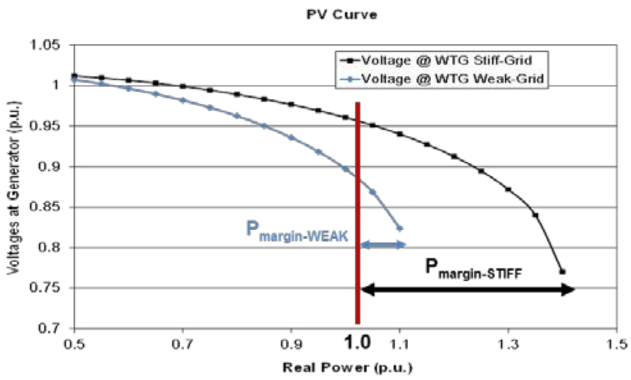

Figure 5. Voltage at the generator during stiff-grid and weak-grid conditions

In this investigation, we operate a Type 3 wind turbine at a unity power factor, thus generating only real power at the terminals. No other reactive power compensation is provided at the turbine level or at the WPP level. The PV curves shown in Figure 5 were derived by measuring the bus voltage at the generator as we varied the output power of the wind turbine. Figure 5 shows both the weak grid and stiff grid. The real power margin for the grid is measured from the rated power (P = 1.0 p.u.) to the knee point at which the voltage collapses. Usually the computation does not converge beyond the knee point. In the simple case we study, the real power margin for the stiff grid is $P_{margin\text{-}STIFF}$ = 1.4 p.u. (= 280 MW) at voltage V = 0.77 p.u. Similarly, the real power margin for the weak grid is $P_{margin\text{-}WEAK}$ = 1.1 p.u. (= 220 MW) at voltage V = 0.82 p.u. The voltage characteristic indicates that for a stiff grid we can increase the level of generation to 125% of rated power while keeping the bus voltage above 0.9 p.u.; however, for a weak grid the level of generation can be adjusted up to 97% rated before the voltage drops below 0.9 p.u.

Wind turbine generators are operated in unity power factor mode; thus, no reactive power is supplied by the generator to the grid to compensate for the reactive losses within the collector systems inside a WPP, in the transformers, and the transmission lines. As shown in Figure 6, the reactive power losses are supplied by the grid (Bus 1 as the infinite bus). In both cases, the reactive power is shown to exhibit a nonlinear (slightly quadratic) function of the WPP output power, which is expected. Note that the reactive power needed for an output of 1.0 p.u. real power is 38% rated power for a stiff grid and 56% for a weak grid.

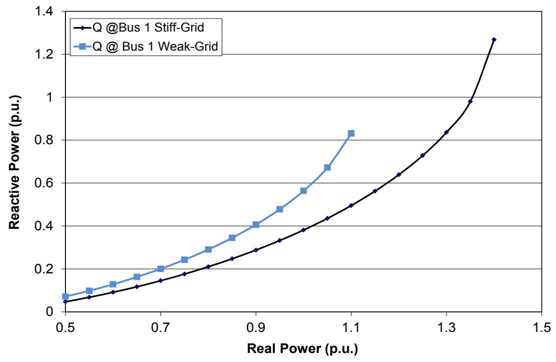

Figure 6. Reactive power comparison at the infinite bus during weak-grid conditions

The above exercise is conducted by setting the generator to produce a unity power factor output power. It will give different results if the WPP is operated at different modes (e.g., constant power factor, constant voltage, constant reactive power).

2.3.2 VQ Capability Curve

A VQ capability curve is normally investigated to determine the reactive power adequacy in a WPP. Reactive power capability is an important aspect of controlling the voltage and influencing the PV characteristic behavior.

As mentioned previously, the WPP uses Type 3 wind turbine generators. All of the wind turbines are controlled to regulate Bus 3 (at the low side of the substation transformer). The setting point of the regulated voltage is varied from 0.6 p.u. to 1.0 p.u., and the reactive power is plotted against the regulated voltage. The grid voltage (infinite bus) is set to 1.05 p.u. all the time, and the generator real power output is set to 1.0 p.u.

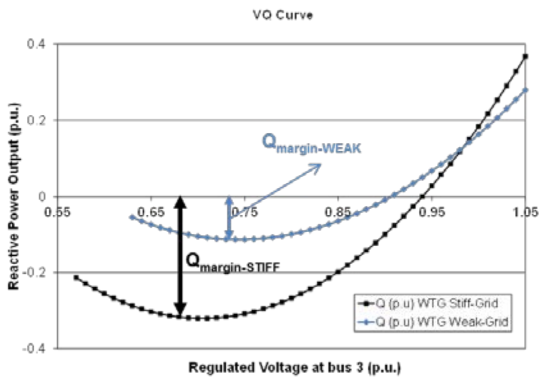

Figure 7. VQ characteristics of a wind turbine generator during stiff-grid and weak-grid conditions

Figure 7 shows the VQ curve of the wind turbine generator for both stiff- and weak-grid conditions in the normal operating region (0.95 p.u. < V < 1.05 p.u.). We assume that the participation factor for the generator in this case is 100% for each wind turbine generator; therefore, the output reactive power contribution for each individual generator is equal to each other.

The reactive power margins, at the minimum points of the curves, are shown by the different colors in Figure 7. The reactive margin for the stiff grid is $Q_{margin-STIFF} = 0.32$ p.u. (= 64 MVAR) at V = 0.69 p.u. Similarly, the reactive margin for the weak grid is $Q_{margin-WEAK} = 0.113$ p.u. (= 22 MVAR) at V = 0.75 p.u. This simple margin measurement is intended as an illustration only. For a larger network, the area and zone considered with many generators and loads need to be included.

2.4 PMU-Enhanced Dynamic Stability Assessment

PV and VQ capability curves are used without the need to know the phase angle of the phasor voltage. However, with the recent large-scale synchrophasor deployment, the availability of the phase angles can be used to enhance the prediction of voltage instability in a power system network.

To conduct a simple analysis performance in Positive Sequence Load Flow (PSLF™) computer program, we use the same network shown in Figure 4. We observe three conditions:

1. A stiff power system network in which both parallel lines connecting the infinite bus and substation transformer are online
2. A stiff power system network with a reduction of infinite-bus voltage by 4%
3. The same initial condition as (1), but representing a weak power system by removing one line of the parallel lines connecting the infinite bus and the substation transformer

Then, at constant reactive output power, we increase the generation from 50% to above 100%, until the load flow does not converge, indicating the voltage collapse when the system reaches its instability limit. The operation is repeated at different values of reactive power. As expected, the power system reaches its instability operation at different output power levels depending on the size of reactive power.

2.4.1 Impact on the Voltage Magnitude

As we vary both the real and reactive power output of the WPP, the voltage magnitude and the phase angle at the generator change as the level of real power generation and the reactive power generation varies. Because the voltage is usually maintained within a tight range (0.95 p.u. < V < 1.05 p.u.), whereas the phase angle has a wider range, it is common practice to keep the voltage as steady as possible.

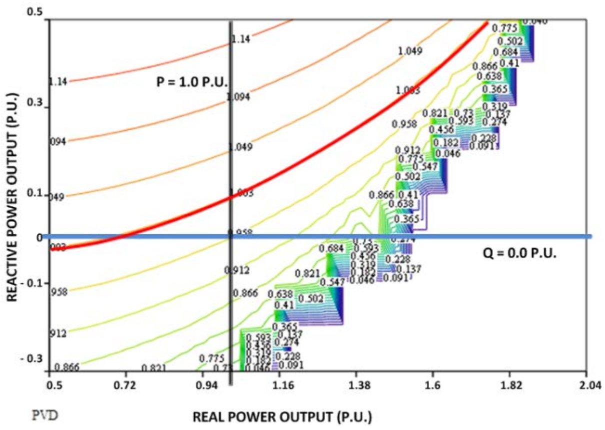

Figure 8. Voltage characteristics of a wind turbine generator during stiff-grid conditions

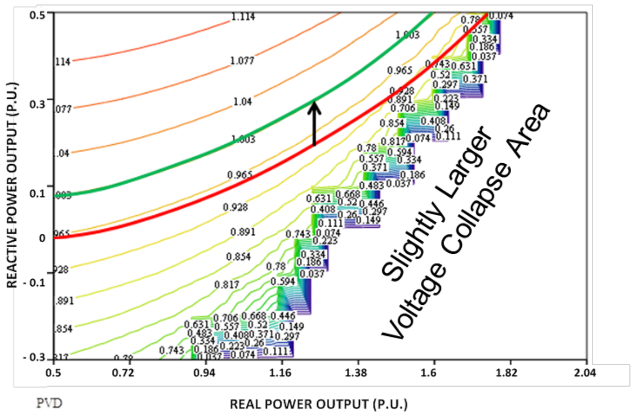

Figure 9. Voltage characteristics of a wind turbine generator during stiff-grid conditions with the infinite bus reduced by 4%

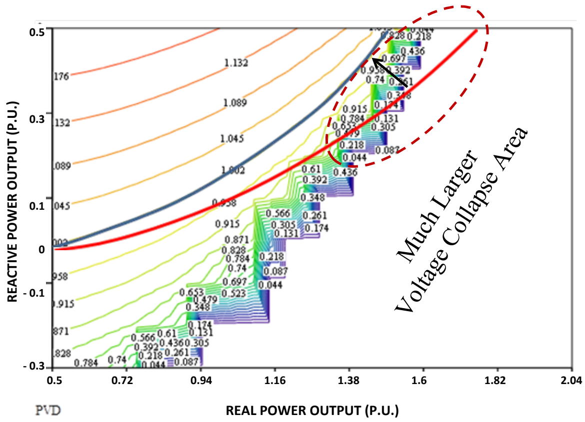

Figure 10. Voltage characteristics of a wind turbine generator during weak-grid conditions

As shown in Figure 8 through Figure 10, the reactive power output has a major impact on the generator voltage compared to the impact from the real power output.

Figure 8 illustrates an operation of a WPP connected to a stiff grid. First, consider that the WPP is operated at 1.0 p.u. output real power and the reactive power is set from Q = -0.3 p.u. (generator-absorbing reactive power), which is increased to Q = 0.5 p.u. As shown on the contour map, the operating point moves along the vertical black line, and the generator voltage increases with additional reactive power supplied to the grid from Vt = 0.75 p.u. to 1.14 p.u. when the reactive power output is close to 1.14 p.u. This method of operation is also represented by the black line in Figure 7, which shows the VQ characteristic of the wind turbine generator operated with a stiff grid at rated power P = 1.0.

Similarly, when the generator is operated at unity power factor (Q = 0.0 p.u.) and the real power output is varied from 0.5 p.u. to 1.4 p.u., the operating point moves along the horizontal blue line. As shown, the generator voltage decreases from 1.01 p.u. to 0.75 p.u., at which point it is obvious that the voltage collapses (Vt = 0.75 p.u. at P = 1.14 p.u.). This characteristic is illustrated in Figure 5 as the PV characteristic of the wind turbine generator operated with a stiff grid at unity power factor.

On the other hand, if the voltage is maintained at 1.0 p.u., the operating point follows the red line, the amount of reactive power varies from Q = -0.02 p.u. to Q = 0.5 p.u., and the voltage collapse does not yet occur. Note that at Q = 0.5 p.u., the output power that can be transferred through the transmission line is P = 1.75 p.u. (stable operation).

Figure 9 represents a condition similar to that shown in Figure 8; however, the entire surface map shows a reduction in voltage. It is probably easier to view this in three-dimension (3D) with the mountain shown in Figure 8 shrunk as the voltage at the reactive power of Q = 0.5 p.u. drops from 1.15 p.u. to 1.11 p.u. The voltage collapse area is shown to be slightly larger than it was in the previous one. Note that the shape of the curves remains very similar to those shown in Figure 8, but the new trajectory of Vt = 1.0 p.u. (represented by the green curve) must be shifted upward in parallel to the old one (red curve) by approximately 4%.

Figure 10 also represents a condition similar to that shown in Figure 8; however, one of the parallel lines is tripped offline. This figure shows the higher slope of the voltage contour, larger area of the voltage collapse, and the equipotential line previously represented by the red line becomes the equipotential line represented by the blue line. Also shown is that the red line that was previously located in the stable region during a stiff-grid condition (Figure 8) is now part of the red line that enters the unstable (voltage-collapse) area, indicated by the area encircled by the dashed line.

2.4.2. Impact on the Voltage Angle

As we vary both the real and reactive power output of the WPP, the voltage magnitude and the phase angle at the generator change as the level of real power generation and the reactive power generation varies. The contour map in Figure 11 shows the phase-angle variation as the real and reactive power is varied during stiff-grid conditions. The rated output power P = 1.0 p.u. at voltage V = 1.0 p.u. requires a reactive power of 0.1 p.u. and voltage angle of δ = 23°. Compare this to the weak grid shown in Figure 12. In Figure 12, obtaining the voltage of V = 1.0 p.u. requires Q = 0.15 p.u. of reactive power and the voltage angle of 30°. The line angle from Figure 11 was transferred to Figure 12 for reference. The $\delta_{stiff} = 23^o$ becomes $\delta_{weak} = 31°$ with a lower slope. As shown in Figure 11 and Figure 12 for different grid strengths, the operating point in the PQ plane is represented by a pair of V, δ. Thus, by operating the generator in the normal operating voltage range, we can observe the value of the voltage angle; an increase δ angle after an event for the same power indicates a weaker grid condition.

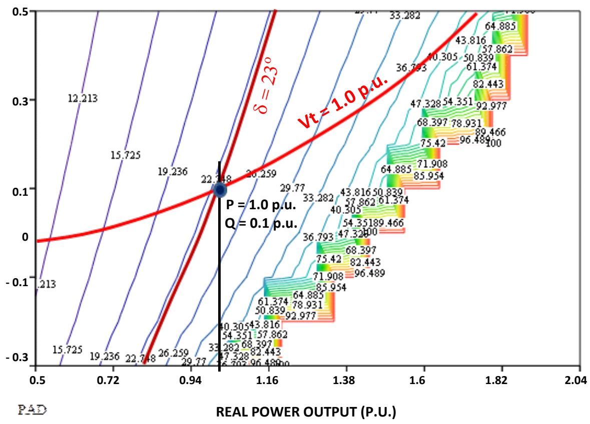

Figure 11. Angle characteristics of a wind turbine generator during stiff-grid conditions

In addition, the increase of reactive power needed to maintain per-unit voltage will always be an indication of a weaker grid. Caution must be taken when considering the impact on the size of the voltage-collapse area. A weaker grid means a larger voltage collapse area. One way to gauge the operating condition is to run or record an operation in a normal condition as the baseline, find a set of weaker grid conditions to map the operating characteristics of the WPP under different grid conditions, and eventually use these maps to guide the operation of the WPP and the proximity to an instability condition.

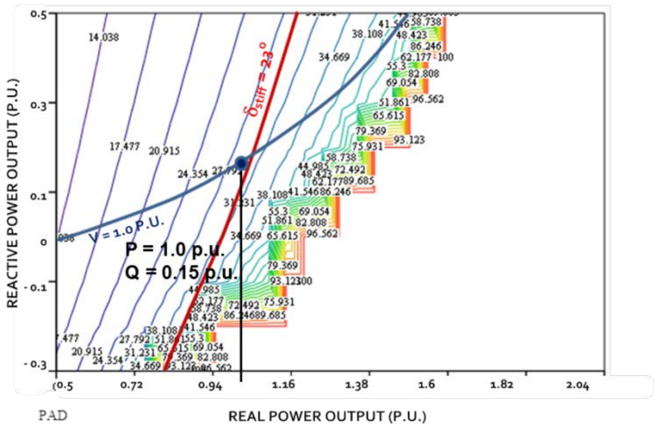

Figure 12. Angle characteristics of a wind turbine generator during weak-grid conditions

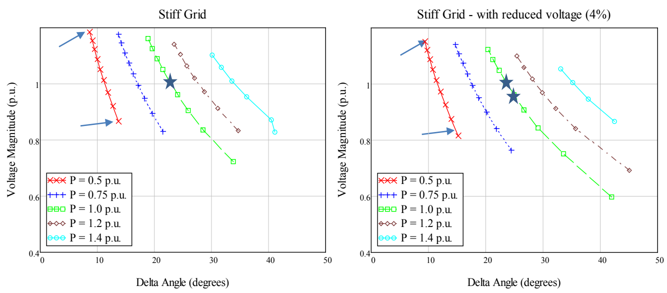

Figure 13. Voltage-angle characteristics for a stiff grid with a change in the voltage magnitude

Figure 13 illustrates the movement of the operating point when there is a voltage reduction downstream. Assume that the operating Point A of the WPP is at rated power (P = 1.0 p.u., V = 1.0 p.u., Q = 0.1 p.u.) on a stiff grid with the star symbol (δ = 23°). If there is a voltage reduction at the infinite bus by 4% without any changes in the line impedance, without changing the reactive power output of the generator the operating point moves to Point B (the voltage is reduced to 0.96 p.u. and the phase angle is increased δ = 25°). To maintain the voltage at V = 1.0 p.u., the reactive power must be increased by 0.1 p.u. (Point B'), with the phase angle (δ = 24°) slightly higher than the original Point A. Figure 14 shows the significant change in angle δ because of the exposure to a weaker grid. Assume that instead of a voltage reduction at the infinite bus, a parallel line is disconnected and we are exposed to a weak grid. The operating point of the WPP at rated power (P = 1.0 p.u.) moves from Point A (V = 1.0 p.u.; δ = 23°) to Point C (V = 0.97 p.u.; δ ≃ 30°). There is a significant change in the phase angle $\Delta\delta = 7°$ from A to C. Increasing the reactive power Q by 0.05 p.u. will return the voltage back to 1.0 p.u. and initiate a small reduction of the phase angle $\delta = 28°$).

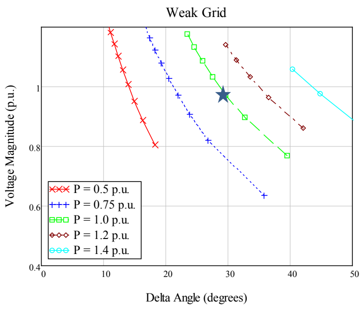

Figure 14. Voltage-angle characteristic for a weak grid

With this understanding, we can trace the operating point and understand the changes that occur in the power system network.

3. Summary

In modern WPPs, wind turbine generators are equipped with power converters to allow variable-speed operation. The use of power converters basically isolates the mechanical response from the grid, thus allowing more flexible operations of WPPs compared to conventional plants.

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in a system after being subjected to a disturbance relative to a given initial operating condition. It depends on the ability to maintain and/or restore equilibrium between load demand and load supply from the power system. Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses.

In a conventional power plant, the balance of reactive power is shared among the generator, line impedance, and reactive component of the load. Very often, the imbalance is caused by sudden changes in the loads (in/out), and the limitation of the tap changer steps in a transformer or the limitation of the generator to provide additional reactive power when the upper limit of the exciter or the limitation of switched bank capacitors has been reached to provide a fine adjustment to match the required reactive compensation.

The same limitation is also applicable to WPPs, because there is a current-carrying limit of the ability of the power electronic switches to carry the instantaneous reactive current demand needed. Another factor in WPPs is that the size of a WPP can be very large, as such that the farthest wind turbine generator from the substation cannot provide reactive power as effective as the turbine closest to the substation. This is because, to provide reactive power, the sending end will have higher voltage, and if the line impedance between the turbine and the substation transformer is too large, the voltage limit of the power converter is sometimes reached before the amount of reactive power demand can be supplied.

Acknowledgement

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

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