SSRG International Journal of Electrical and Electronics Engineering (SSRG - IJEEE) - Volume 7 Issue 5 – May 2020

Development of a Technique for Identification of Critical Locations for Maintaining Voltage Stability with Penetration of Wind Generation in Power Systems

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Abstract

This paper discussed a technique for identification of critical locations for maintaining voltage stability with penetration of wind generation in power systems. When synchronous generation is displaced by wind, the loss of regulation capability have significant impacts, particularly on the voltage stability of the system, which will directly affect the rotor angle stability of the remaining convectional synchronous units present in the system. In this research paper, a small signal analysis was performed using appropriate mathematical notations. Some procedural steps were taken to identify critical locations for voltage stability. All existing and potential wind farms were modelled as full synchronous units, displacement of a single convectional generator existing in the system and re-examination of each mode identified from the previous step in great details. The process was repeated for the displacement of each of the existing synchronous units in the test system. Voltage stability analysis was carried out by subjecting a load bus in the system to a fault in order to determine the critical clearing times for each of the cases using the DSA tools software packages. Selected buses on the Nigerian 330 Kv grid system were displaced and active and reactive power flows were re-dispatched. The participation factors for the synchronous wind farms were computed.

The reactive power control from wind generation was utilized to control the bus voltages of transmission systems to improve the system voltage security when coupled with the variable and uncertain nature of the active power injections from wind generation. The under-excitation of the synchronous generator was greatly reduced by achieving balanced scheduled voltages at buses across the system,. The field voltage of the machine was improved and angular separation was minimized as a result of contingency occurrence. The rotor angle stability of the system was improved with an adequate maintenance of synchronism in the system. The results of this research paper showed that there were 28 participating wind farms on generator 33 while on generator 35, participating wind farms of 28, 26, 35 and 4 were recorded. Generators 26, 28, and 35 had significantly higher participation factors than the other wind farms and were therefore considered to be significant for the displacement of generator 28. In addition, 35 participating wind farms were recorded on generators 36 and 37 as a result of the configuration of the generators. Generators39, 40 and 41 recorded wind farms of 39, 4, 34, 28 and 26 with adequate participation. The same was computed for the displacement of each generator and the synchronous wind farms that displayed consistently high participation factors. There was no limit on the value of the participation factor, however for each system configuration; the value of each participating generator was compared to the others that were present. For generators 36 and 37, the participating factors were 0.08 and 0.04 respectively while for generator 39, participating factors of 0.13 and 0.06 were recorded on the same generator due to the configuration of the generator. The participating factor on generator 40 was 0.09 while the participating factor decreased from 0.08 to 0.06 on generator 41 due to the positional arrangement and configuration of generator 41.

After completing ten small-signal analyses, six farms presented consistently high average participation factors and were identified as critical farms. Buses 4, 26, 28, 34, 37 and 39 were noticeably higher in average participation factors compared to the other farms for each of the four scenarios and hence, were considered critical due to the fact that in *the power flow dispatch on these farms had a significantly higher reactive power. Generators 26, 28, and 35 had significantly higher participation factors than the other wind farms and were therefore considered to be significant for the displacement of generator 28. The farm with the greatest capability to provide the system with reactive power had the largest participation factors for each of the scenarios regardless of active power flows and loading level driven by the network configuration and impedances.*

The critical control case and the full control case were more secured as compared to the synchronous wind case due to the fact that the synchronism of the system was increased when there was lesser active power provided by the synchronous generation in the system. Thus, replacing synchronous generators with asynchronous wind farms increased the synchronous strength of the system and also, introducing wind generation increased the critical clearing times of the system. There was no significant difference between the critical control case and full control case, indicating that the stability of the system did not decrease as lesser control was applied by the wind generation. In addition, the critical clearing times were significantly lower at the lower penetration level as a result of larger percentage of the system's active power provided by the synchronous generator. Hence, the system was more sensitive to application of a bus fault and the critical clearing time decreased at the 23.9% penetration level. Thus, the critical clearing times for the synchronous wind case, full control case and the critical control case were 15.03, 16.98 and 16.60 respectively.

By supporting the voltage at the identified critical locations with the aid of wind generators, the voltage stability and rotor angle stability can be maintained while minimizing the levels of control required by the system. This research paper has contributed to the continued secure and reliable operation required of a modern power system which will assist to achieve government targets to increase the sustainability levels of power systems.

Keywords — *Critical locations, Critical clearing times, Voltage stability, Wind generations, Reactive power, Active power, Rotor angles.*

I. INTRODUCTION

An Variety of factors have changed the nature of modern power systems while the increased demand for sustainability rises in the price of oil and the need for the reduction of greenhouse gases, all of which have driven a large increase in the level of wind generation in the power system. Citations by the Intergovernmental Panel on Climate Change have revealed that wind energy will be the primary source of renewable generation in the electricity sector [1]. Wind generation has been confirmed to be the dominant renewable resource currently present in power systems in both Europe and the United States. In Europe, wind energy is set to triple in penetration by the year 2020, wind energy has tripled in penetration with 15.7% of the continent's total energy provided by wind generation in Europe [2]. There is currently 42,432 MW of installed capacity providing 2.3% of the U.S. electricity mix, with the number set to rise to 25% by the year 2025 in the United States (EWEA, 2011). With wind generation set to become a significant generation resource in power systems around the world, It will become increasingly important to fully understand impacts of wing generation and its interaction with the conventional elements in power systems as wind generation is set to become a significant generation resource in power systems around the world[3],

The design and operation of power systems have revolved around the oasis of generation delivery from large synchronous machines which have high levels of reliability and complex control systems that allow the system to maintain high levels of operational security [4],[5],[6],[7],[8],[9]. The correct operation and control of these machines across the full spectrum of time-frames is critical in order to maintain reliable power system operation and stability [10]. The time-frames associated with power systems vary over a variety of periods; long-term planning examines power systems for several months or even several years into the future. It focuses on how the development of power system for accommodation of specific types of generation as well as its expansion based on the availability of resources. Power system operation studies deal with the day-to-day operation of power systems, focusing on the commitment and dispatch of generating units in the system and the determination of reserve resources together with other operational considerations. Both planning and operational studies are important to a power system that is highly reliable and secured. The outcomes of these will impact the operational stability of the system. The stability of a power system occurs across an operational time-frame of hours down to milliseconds [11], [12], [13],[14]. Maintaining power system stability has to do with the interactions of the various components and elements of the system without any issue across all of the time- frames of the stability spectrum. New mitigation techniques will be necessary in order to continue operating the power system in a secured and stable manner as wind generation has significant impact across the power system stability time-frame and as wind generation becomes a more common source of generation in the system [15], [16],[17],[18],[19],[20].

Variable speed wind turbines (VSWT) provide electrical synchronism with the power system through power electronic convertors [21],[22],[23].This power electronic coupling inhibits mechanical synchronism with the system effectively rendering wind inertia-loss. The manner in which wind generation displaces conventional synchronous generator will significantly impact various stability aspects of the power system. However, it is necessary to understand how wind generation interacts with the active power flows in the system as this is how rotor angle stability is impacted in traditional power systems with low penetrations of wind.

In [24], the impact of VSWTs on the small-signal stability of a large power system was assessed. The work showed the sensitivity change of the inertia with respect to wind generation in the system. By replacing VSWT generation with equivalently rated synchronous units, the small-signal stability and transient stability of the system was assessed. It was determined that the active power delivered from VSWT generators was different from an inertial aspect to that delivered by synchronous generation. Wind generation controls could be altered to emulate an inertial response for frequency stability, but had not been implemented widely in power systems [25],[26]. The work looked to expand on the fundamental difference between the active power produced by VSWTs and that produced by conventional synchronous generators, particularly how they interacted with the rotor angle stability of the system. Due to the fact that wind generation is inertia-less, the synchronous units that co-existing the system with wind will be forced to provide the necessary resources, i.e. inertia and damping torque, required to mitigate any instability events. Carrying this extra burden, will stress the synchronous units and could lead to less secured system operation. By utilizing the built-in capabilities of wind generation, specifically reactive power control, the requirements placed on conventional synchronous generation could be eased and system security could be improved.

II. ROTOR ANGLE STABILITY WITH HIGH PENETRATIONS OF WIND GENERATION

Rotor angle stability is classified into two distinct subcategories:

i. Small-disturbance (or small-signal) rotor angle stability is defined as the ability of the system to maintain synchronism during small disturbances. These disturbances are sufficiently small that linearization of the system is made possible. Small-signal instability occurs when the system is insufficiently damped and the oscillation grows, resulting in a severe disturbance.

ii Large-disturbance rotor angle stability or transient stability refers to the ability of the system to maintain synchronism following a large disturbance such as a fault or loss of generation[19].

Both classifications of rotor angle stability occur in the short-term time-frame, which requires analysis in the time-domain. In traditional power systems having low penetrations of wind, the rotor angles of the synchronous generators are impacted by changes in active power flows in the system. When there is a change in active power, the synchronous generators in the system will respond with an electromagnetic torque that will dampen and minimize rotor angle deviations in the system. The presence of this electromagnetic torque, due to the fact that the bus voltages are tightly controlled by synchronous generation through the use of automatic voltage regulation (AVR) essentially decouples the behaviour of rotor angle from the voltage stability of the system. As wind generation increases and synchronous generation is displaced, the coupling between rotor angle stability and the voltage stability of the system is strengthened. There will be less electromagnetic torque present in the system to dampen angular deviations due to the asynchronous nature of wind generation. There will also be degradation in the voltage stability of the system due to lack of reactive power control as AVRs are displaced in order to accommodate the new wind generation which will result in a decreased ability to control voltage and directly influence the rotor angle stability of the remaining conventional synchronous units in the system. The rotor angle stability of the system can be improved and supporting the bus voltages in the system can be achieved by utilizing the reactive power control capabilities of wind generation, [1],[2],[11],[14].

III. ACTIVE POWER ANALYSIS

Wind generation is first compared directly to synchronous generation in order to achieve a baseline comparison for the rest of the analyses by creating abase case consisting of wind farms operating at a fixed 0.95 capacitive power factor spread across the system. In addition, a second case is created where the wind generation is replaced by equivalently sized and rated synchronous machines with exciter systems. In this case, no governors or stabilizers are modelled. The synchronous wind machines are modelled in this way to ensure that they respond in comparison to an asynchronous wind generator, which cannot increase its active power output by providing a governor response. The exciter is included to provide control for the field current and increase stability. The reactive power output of the synchronous units is fixed at them same 0.95 capacitive power factor as the wind generation. A transient analysis is then completed for a loss of generation event and the rotor angle, active and reactive power outputs are monitored for each of the synchronous units in order to assess the impact of wind generation on the system. The physical differences between the synchronous generators and wind generators, i.e. inertial contribution of the rotating mass indicates that there are significant variations in the active power flows across the system, particularly, the ability to provide electromagnetic torque which is resolved into two components [6],[7],[9],[26].;

i. The synchronizing torque component is in phase with the rotor angle deviation. The lack of synchronizing torque leads to aperiodic or non-oscillatory stability..

ii. The damping torque component is in phase with the speed deviation. The lack of damping torque leads to oscillatory instability.

Wind generators have very limited mechanical interaction with the rest of the power system due to the power electronic decoupling of the blades and rotor, and as a result do not have the capability to provide the system synchronizing torque or damping torque. In order to characterize the differences between synchronous generation the active power analysis will examine what aspects of the system are influenced by the change of generator type for the two cases [4],[5],[16].

It is necessary to utilize the available mitigation techniques available from wind generation to improve system stability. Modern wind turbines have the capability to provide the system with large levels of reactive power regardless of the level at which they are producing active power.

IV. REACTIVE POWER ANALYSIS

The reactive power analysis quantifies the impact of the power delivered by wind generation and determines whether it is fundamentally deferent in comparison to the power delivered by wind generation [8]. Reactive power however, is an electrical power injected into the system, i.e. there is no mechanical input required to create or deliver reactive power. As such, the reactive power delivered by a synchronous unit can be compared directly to that delivered by a wind generator. This analysis builds upon this concept by analysing the impact that varying the reactive power control strategy of the wind farms has on the system. By only changing the reactive power output from the wind farms, the active power flows across the system will remain fixed. The resulting change in rotor angle deviation between the cases can then be attributed to the changes in the system's reactive power flow.

Similar to the active power analysis, a transient analysis is completed for a loss of generation event and the active and reactive power flows are monitored along with the rotor angle stability for the most impacted machine. Any change in system stability can be attributed to changes in reactive power flows and the stability of the system under the varied reactive power control operating conditions is assessed [9],[12],[20].

A fault analysis is also completed for the capacitive case and the terminal voltage case in order to compare the generator response to a severe low voltage event. A bus fault is applied and cleared at a load bus in the system, and the rotor angle, bus voltage and reactive power output for the generators are monitored. This allows for a further insight into how reactive power interacts with the rotor angle stability of synchronous machines [6],[8], [10],[20].

V. IMPACT OF REACTIVE POWER ON ROTOR ANGLE STABILITY

The relationship between voltage stability and rotor angle stability and the impact of reactive power control on system security is important. As wind generation penetration increases in the system, conventional synchronous generation will be displaced, along with their AVRs. This will limit the capability of the system to regulate reactive power. Implementing a coordinated control strategy such as terminal voltage control in wind turbines can be difficult in power systems with high penetrations of wind because wind generation can be embedded within distribution networks [1],[3],[13],[23].

VI. MATERIALS AND METHOD

A. Small-Signal Analysis

The small-signal analysis will identify modes that arise as a result of an electro-mechanical interaction between synchronous generators in the system. The dynamics of the system can be expressed as shown in equation 1,

$$\dot{x}= f(x, u)$$

$$y = g(x, u)$$

(1)

$$\Delta\dot{x}= A\Delta x+ B\Delta u$$

where x represents the state variables of the system, and u and y represent the inputs and outputs respectively.

The expression in (1) can be linearized around a single operating point and represented as Jacobian matrices of the states A, B, C and D along with the change in states, Δx, and the inputs and outputs, Δu and Δy, respectively.

$$\Delta y= C\Delta x+ D\Delta u$$

(2)

$\det (A - \lambda I) = 0$

The solution of (2) gives the eigenvalues, λ, of the linearized system (3).

For $\lambda 1, \lambda 2, . . . ,\lambda n$ eigenvalues

(3)

From the eigenvalues the right eigenvector, φi, and left eigenvector, ψi, of each oscillatory mode were identified in (4) and (5).

$A\varphi i= \lambda i\varphi i$ for $i=1,2,. . . ,n$

(4)

$\psi iA=\psi i\lambda i$ for $i=1,2,. . . ,n$

(5)

The right eigenvector will determine the relative activity of the element in the i^{th} mode, while the left eigenvector weighs the contribution of activity to the i^{th} mode. Oscillatory modes that occur at low frequencies, between 0.1 and 2.0 Hz, and have low levels of damping below 10%, can often lead to instability in machines or lines in the system. Utilizing the right and left eigenvectors, the participation factor of each element, defined as k, can be identified. The participation factor, Pki is the measure that relates the states and modes of the eigenvectors that measures the net participation of each element, akk, in the system and is given as:

$$\frac{\partial \lambda_i}{\partial a_{kk}} = \psi_{ik}\varphi_{ki} = P_{ki} \qquad (6)$$

In (6), akkcan represent any state of any element in the system, e.g., generator speed and controller gains states, etc. Further examining a particular electromechanical mode associated with a particular generator, the other generators that havean oscillatory relationship, i.e. the oscillatory behaviour of one generator influencing the rotation of another, can be identified. These generators are identified using participation factors. By identifying generators with high participation factors, the machines that play a significant role in maintaining the rotor angle stability of the system was identified.

In a system with high penetrations of wind this becomes more complicated since wind farms are asynchronous and do not have any electro-mechanical interaction with the system. The power electronic convertors in wind turbines decouple the mechanical side of the system from the electrical side.

B. Steps Involved in Identification of Critical Locations for Voltage Stability

The steps required for identification of critical locations are explained below.

1. Selection of the scenarios that the study will focus on to determine what the system conditions will be during the small-signal analysis.
2. Modelling of all existing and potential wind farms as full synchronous units with all the necessary control systems, i.e. governors, excitation control and stabilizers.
3. Displacement of a single conventional generator that previously exists in the system in order to solve the power flow.
4. Running small-signal analysis.
5. Identification of the machines that present low-frequency un-damped rotor angle modes.
6. Each mode identified from the previous step was examined in greater detail. These modes are exclusive to the existing conventional synchronous units and within each mode, the participation factors will be observed. Now, the synchronous wind machine with the highest participation factors was identified.
7. Repetition of the process for the displacement of each of the existing synchronous units in the test system until all the synchronous wind farms with consistently high average participation factors were identified. These farms are critical to maintaining rotor angle stability and the case was defined as the Critical Wind Case.

C. Voltage Stability Analysis

After completing the rotor angle stability assessment, a voltage stability analysis was carried out for each of the three cases to ensure that implementing terminal voltage control at selected farms did not compromise the voltage security of the system. To complete this analysis, a fault was applied at a load bus in the system.

The critical clearing times for each of the three cases was determined. Based on these three analysis techniques a comprehensive assessment regarding the rotor angle stability and voltage stability of the system was done. The DSA Tools software package was used for this analysis.

Selected buses on the Nigerian 330 kV grid system were individually displaced and the active and reactive power flows were-dispatched. For each of the selected ten units, this was completed and the modes and the accompanying participation factors for the synchronous wind farms were observed. The same was completed for the displacement of each generator and the synchronous wind farms that displayed consistently high participation factors were recorded. In each iteration of the small-signal analysis, synchronous wind farms with larger than average participation factors were noted.

There was no limit on the value of the participation factor, however for each system configuration; the value of each participating generator was compared to the others that were present.

VII. DISCUSSION OF RESULTS

Four scenarios were studied for the small signal analysis with varied wind and load conditions to ensure that the results are valid regardless of the system conditions.

The wind output levels for different scenarios are shown in Figure 1. Scenarios A and B had wind output levels of 2600MW and 2600MW respectively while scenarios C and D had wind output levels of 1300MW and 1300MW respectively as well which might be due to the configurations of the signals. The load levels of the four scenarios are also illustrated in Figure 2. Scenarios A and C had the same load level of 5915MW while scenarios B and D also had the same load level of 6015MW due to the alternate arrangement of the signals for scenarios A and C as well as for scenarios B and D.

Figure 3 shows the comparative analysis of the wind output levels and the load levels for the four scenarios. The wind output level and load level for scenario A were 2600MW and 5915MW respectively while for scenario B, wind output level and load level of 2600MW and 6015MW were recorded as a result of the signal configurations. For scenario C, wind output level and load level of 1300MW and 5915MW were recorded respectively while wind output level and load level of 1300MW and 6015MW were recorded for scenario D as a result of the signal arrangement.

Figure 4 illustrates the participating wind farm for the generator mode. There were 28 participating wind farms on generator 33 while on generator 35, participating wind farms of 28, 26, 35 and 4 were recorded. Generators 26, 28, and 35 had significantly higher participation factors than the other wind farms and were therefore considered to be significant for the displacement of generator 28. In addition, 35 participating wind farms were recorded on generators 36 and 37 as a result of the configuration of the generators. Generators39, 40 and 41 recorded wind farms of 39, 4, 34, 28 and 26 as having adequate participation.

The participating factor for the generator mode is shown in Figure 5. The participating factor did not actually obey a definite pattern. Thus, the participating factor for generator 33 was 0.06 while as the generator increased to 35, the participating factors increased to 0.92 and later decreased to 0.16 and 0.13 within the same mode. During this same generator mode of 35, the participating factor assumed values of 0.88, 0.82,0.27 and 0.14 because of the peculiar nature of generator 35.The same was completed for the displacement of each generator and the synchronous wind farms that displayed consistently high participation factors. There was no limit on the value of the participation factor, however for each system configuration; the value of each participating generator was compared to the others that were present. For generators 36 and 37, the participating factors were 0.08 and 0.04 respectively while for generator 39, participating factors of 0.13 and 0.06 were recorded on the same generator due to the configuration of the generator. The participating factor on generator 40 was 0.09 while the participating factor decreased from 0.08 to 0.06 on generator 41 due to the positional arrangement and configuration of generator 41.

After completing ten small-signal analyses, six farms presented consistently high average participation factors and were identified as critical farms.

The average participation factors for each scenario were presented in Figure 6.Buses 4, 26, 28, 34, 37 and 39 were noticeably higher in average participation factors compared to the other farms for each of the four scenarios and hence, were considered critical due to the fact that in the power flow dispatch, these farms had a significantly higher reactive power margin. Generators 26, 28, and 35 had significantly higher participation factors than the other wind farms and were therefore considered to be significant for the displacement of generator 28. Thus, the participating factor for wind farm at buses 4 and 8 for scenario A were 0.309 and 0.060 respectively. For scenario B, the participating factors were 0.345 and 0.071 for wind farms on buses 4 and 8 respectively as illustrated in Figure 6. When the wind farms were on bus locations 37 and 39, participating factors of 0.123 and 0.301 were recorded for scenario A. On this same bus location, participating factors of 0.093 and 0.314 were recorded for scenario B.

Figure 7 showed the reactive power production for the synchronous wind farms for the four scenarios. For wind farms on buses 4 and 8, the reactive powers for scenario A were -90.18 and 102.0 respectively. However, on this same bus location, the reactive powers for scenario B were -98.61 and 102.0 respectively. From Figure 7, the farm with the greatest capability to provide the system with reactive power had the largest participation factors for each of the scenarios regardless of active power flows and loading level and was driven by the network configuration and impedances. This indicated that when, active power flows were re-dispatched, the ability of a farm to provide reactive power support to the system was critical and as such, these farms should have terminal voltage control enabled. This would allow the farm to provide dynamic reactive power support at a designated remote bus due to the fact that the reactive power requirement was a function of system impedances and loading rather than active power flows. When the wind farm was on buses 34 and 35, the reactive power produced were 11.94 and -42.91 respectively for scenario A while for scenario B, the reactive power produced were -2.42 and -71.35 respectively. For scenario C, the reactive power produced were 44.2 and -43.73 respectively while for scenario D, reactive powers of 23.1 and -53.42 were produced respectively for the synchronous wind farms.

Figure 8 showed the critical clearing times for voltage stability analysis to ensure that the critical control case did not decrease the level of voltage stability in the system due to the decreased level of control. This was achieved by subjecting the studied cases to critical clearing time analysis with the application of a three- phase fault at bus 21 while the critical clearing time was recorded. From Figure 8, it could be seen that the critical control case and the full control case were more secured as compared to the synchronous wind case due to the fact that the synchronism of the system was increased when there was lesser active power provided by the synchronous generation in the system. Thus replacing synchronous generators with asynchronous wind farms increased the synchronous strength of the system and also, introducing wind generation increased the critical clearing times of the system. There was no significant difference between the critical control case and full control case, indicating that the stability of the system had not decreased as lesser control was applied by the wind generation**.** When bus 16 was subjected to a fault, the critical clearing times at 43.5% for synchronous wind case, full control case and the critical control case were 16.28, 17.55 and 17.55 respectively.

Figure 9 showed the critical clearing times at 23.9% for fault applied on bus 16.

At the 23,9% penetration level, the same trend as the 43.5% was observed and the critical control case and full control case showed an improved critical clearing time over the synchronous wind case. In addition, the critical clearing times were significantly lower at the lower penetration level as a result of larger percentage of the system's active power provided by the synchronous generator. Hence, the system was more sensitive to application of a bus fault and the critical clearing time decreased at the 23.9% penetration level. Thus, the critical clearing times for the synchronous wind case, full control case and the critical control case were 15.03, 16.98 and 16.60 respectively.

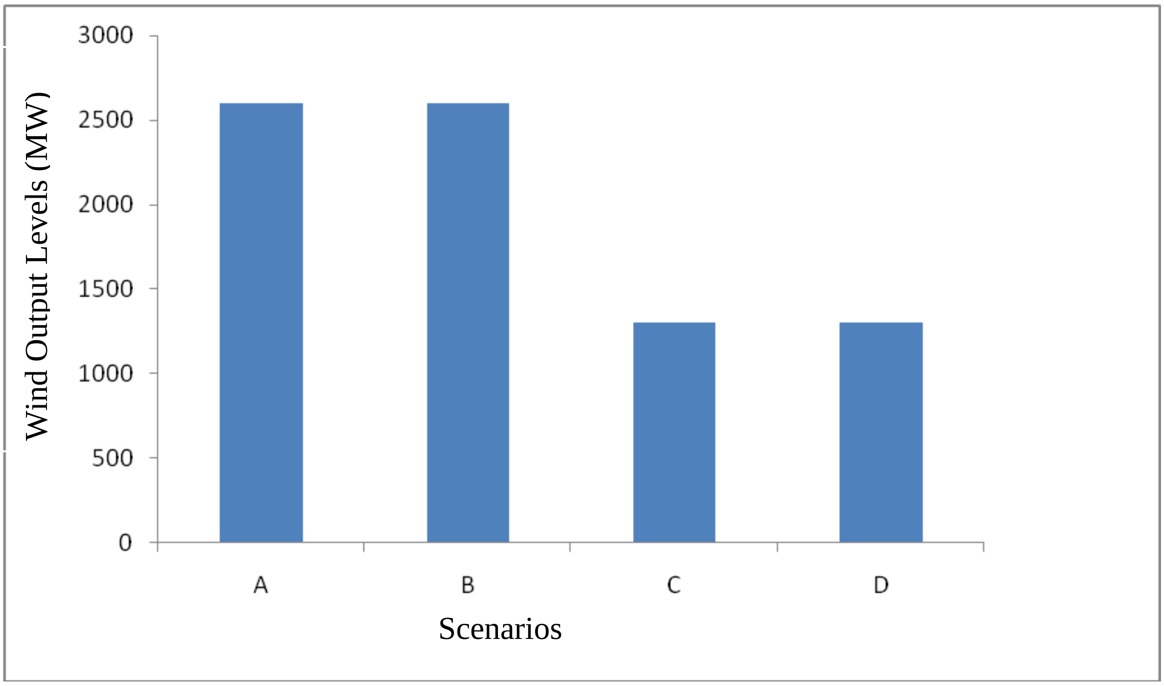

Figure 1: Wind Output Levels for Different Scenarios

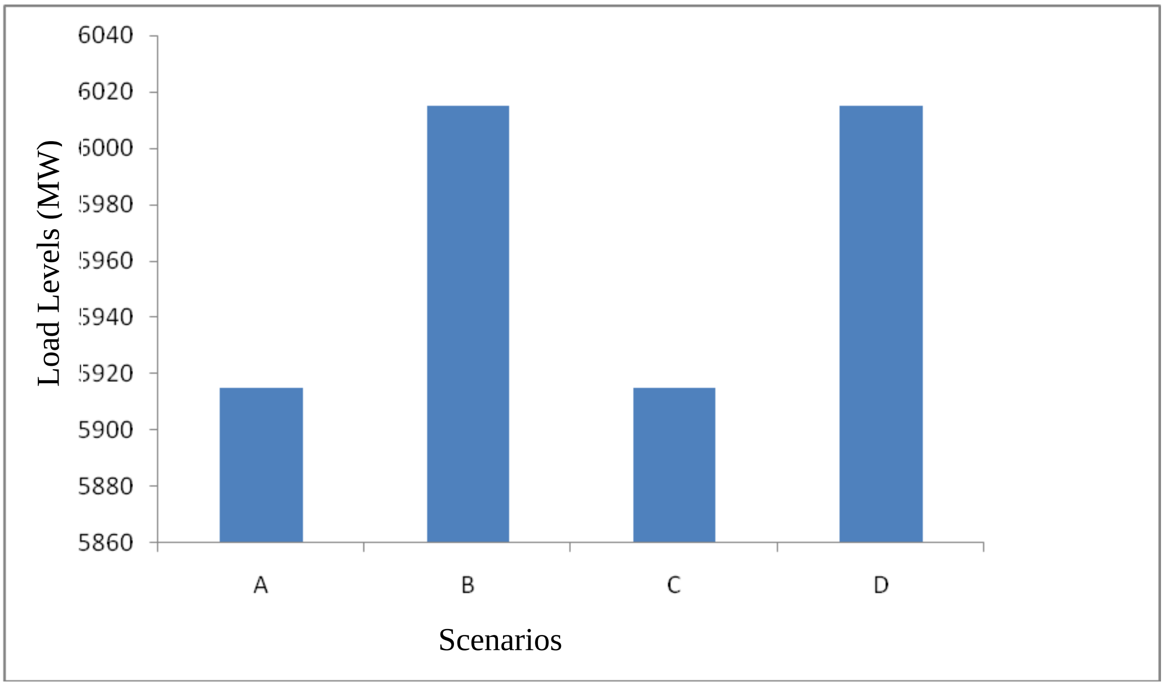

Figure 2: Load Level for Different Scenarios

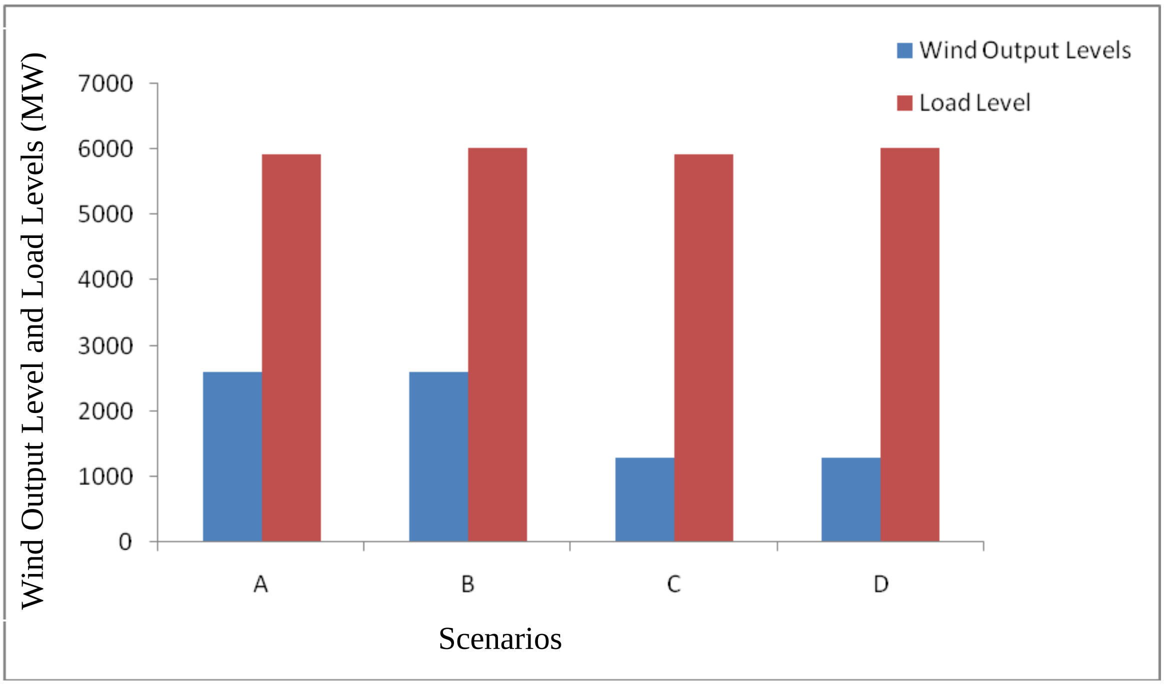

Figure 3: Comparative analysis of Wind Output Levels and Load Levels

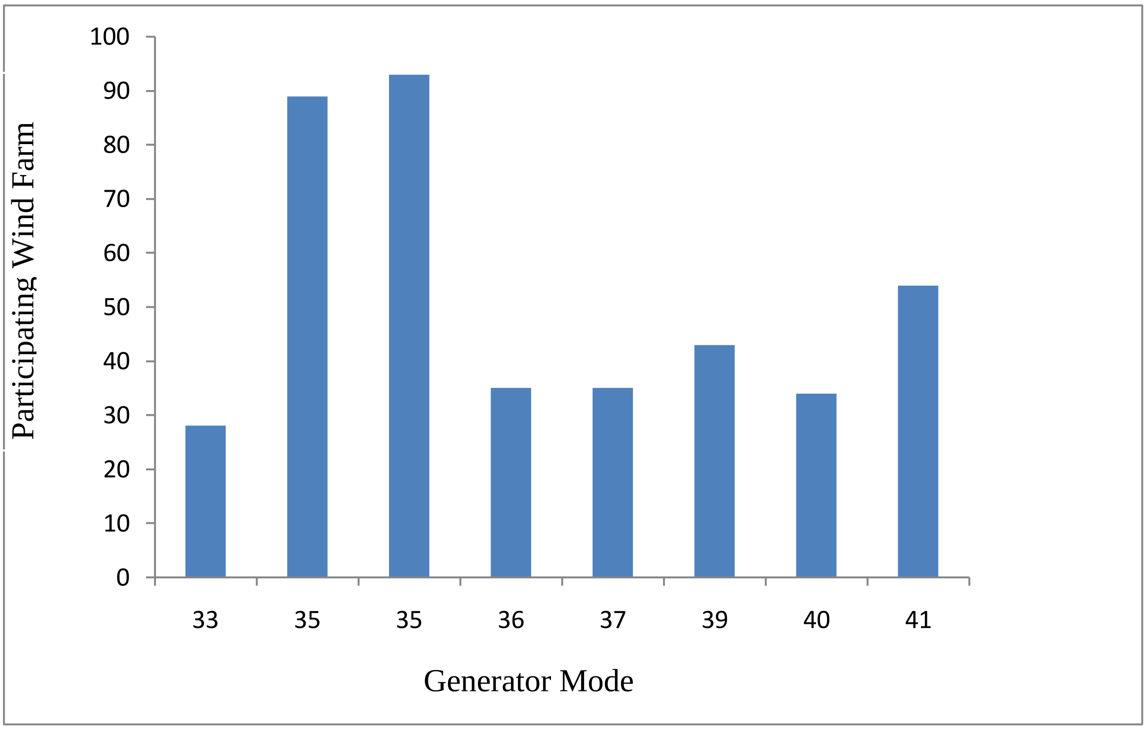

Figure 4: Participating Wind Farms for the Generator Mode

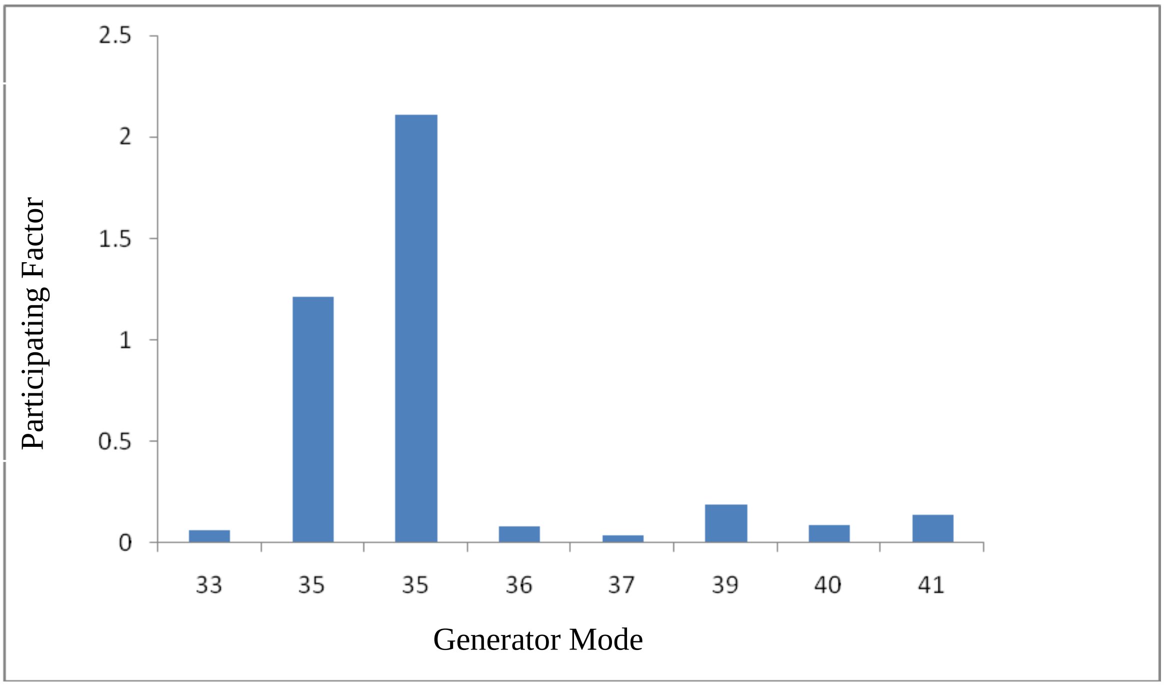

Figure 5: Participating Factor for the Generator Mode

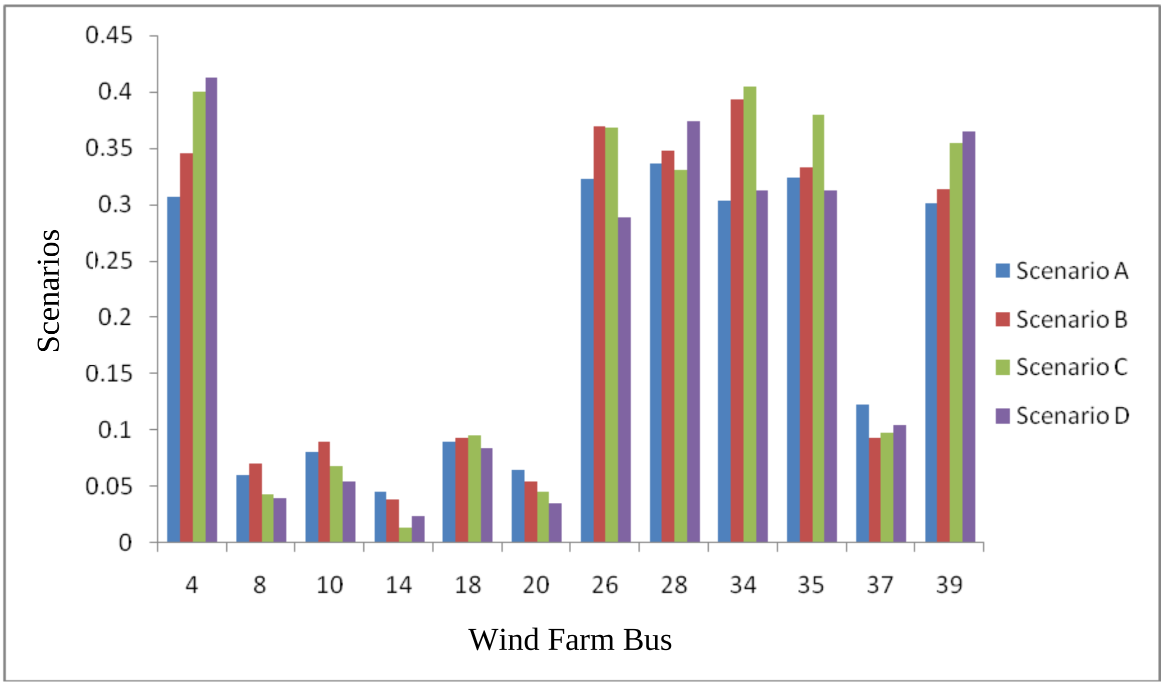

Figure 6: Average Participating Factor for each Scenarios

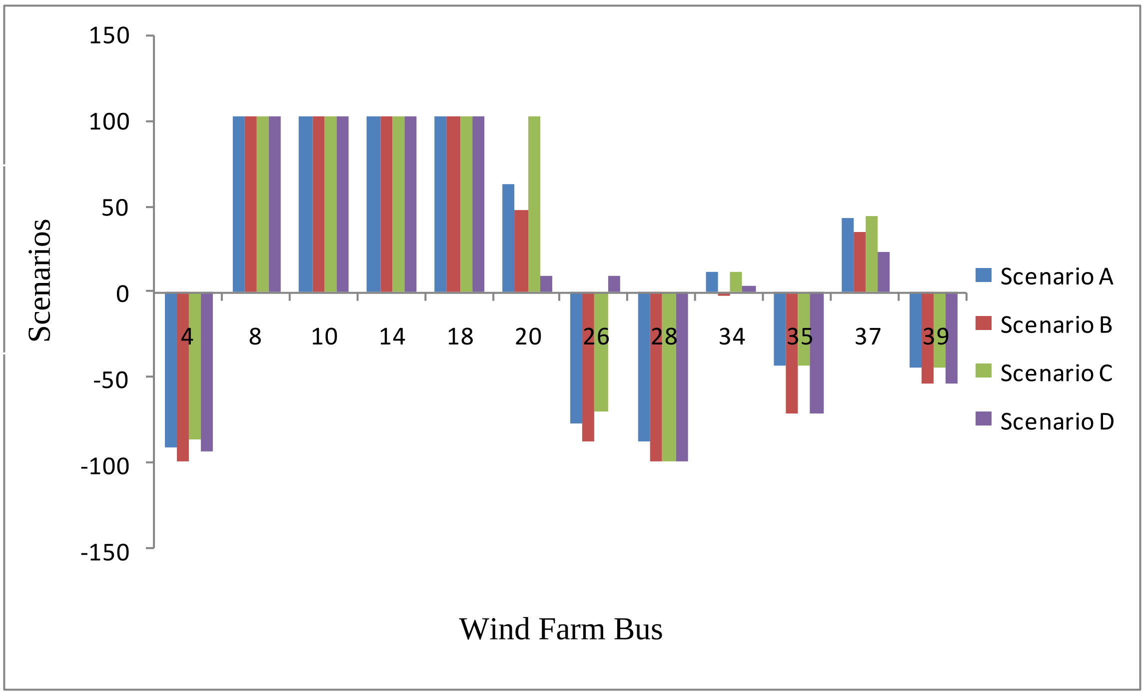

Figure 7: Reactive Power Production for the Synchronous Wind Farm

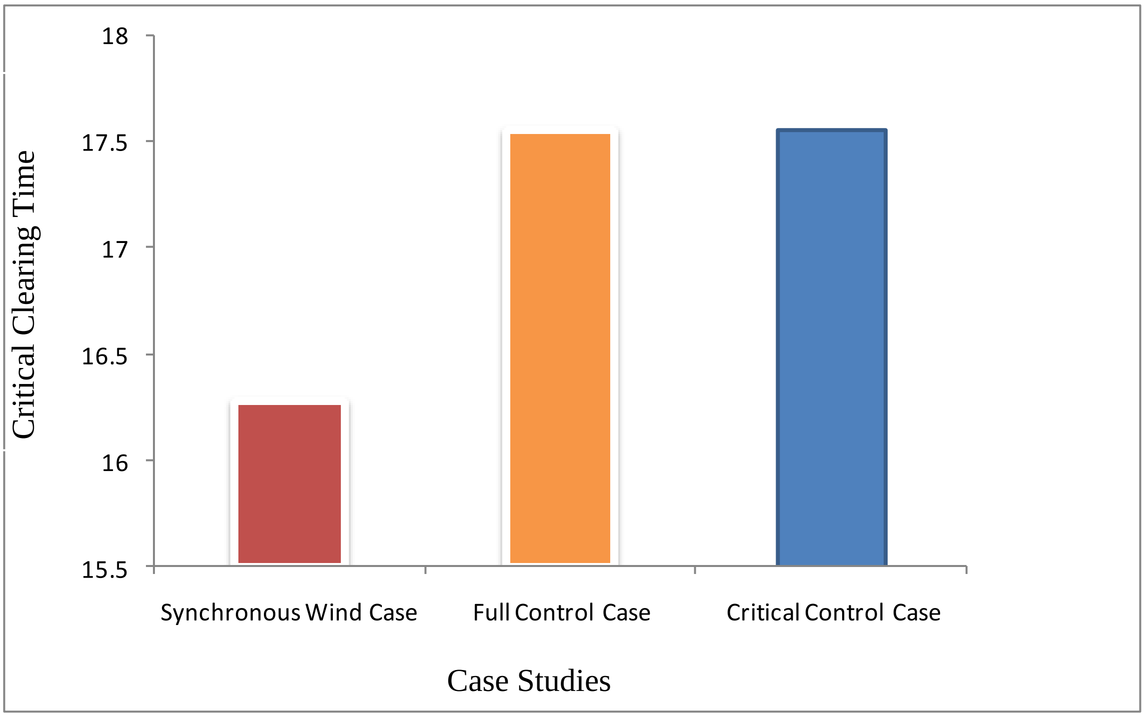

Figure 8: Critical Clearing Times at Bus 16 for the three Case Studies

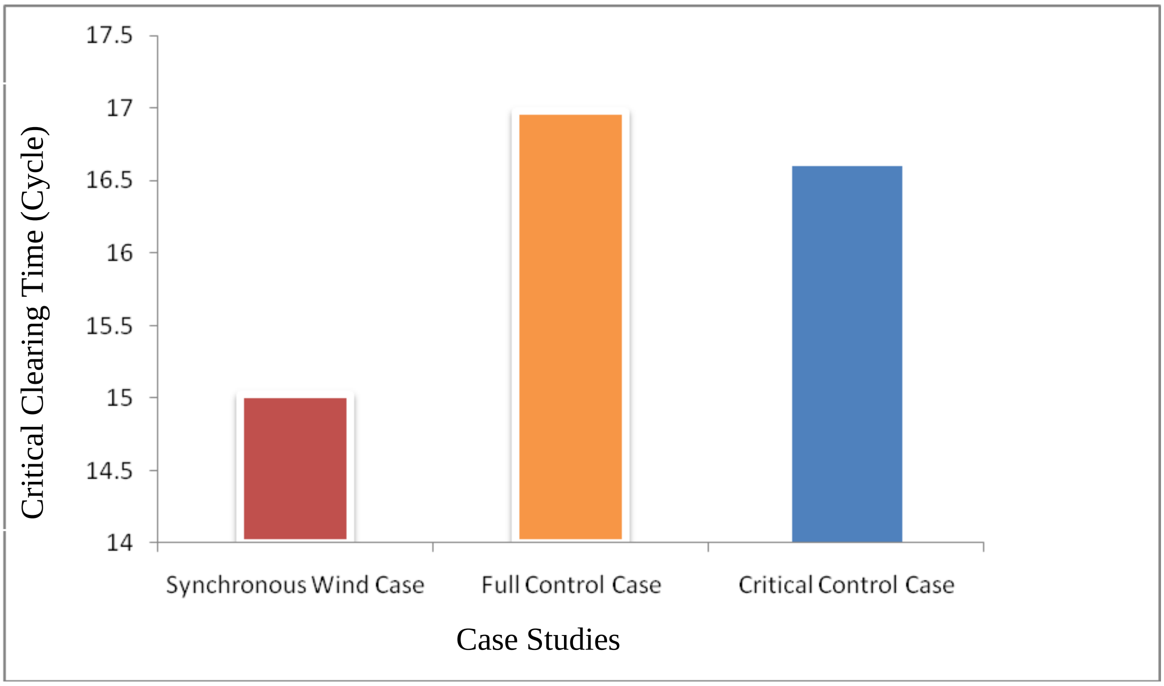

Figure 9: Critical Clearing Times at Bus 14 for the three Case Studies

VIII. CONCLUSIONS

A technique for identification of critical locations for maintaining voltage stability with penetration of wind generation in power systems has been presented. Small signal analysis was performed using appropriate mathematical notations. Procedural steps were taken to identify critical locations for voltage stability. Voltage stability analysis was carried out.

The results of the research paper indicated that there were 28 participating wind farms on generator 33 while participating wind farms of 28, 26, 35 and 4 were recorded on generator 33Generators 26, 28, and 35were considered to be significant for the displacement of generator 28 because they had significantly higher participation factors than the other wind farms. There was no limit on the value of the participation factor, however for each system configuration; the value of each participating generator was compared to the others that were present. For generators 36 and 37, the participating factors were 0.08 and 0.04 respectively while for generator 39, participating factors of 0.13 and 0.06 were recorded on the same generator due to the configuration of the generator.

Buses 4, 26, 28, 34, 37 and 39 were noticeably higher in average participation factors compared to the other farms for each of the four scenarios and hence, were considered critical due to the fact that in the power flow dispatch, these farms had a significantly higher reactive power. The farm with the greatest capability to provide the system with reactive power had the largest participation factors for each of the scenarios regardless of active power flows and loading level driven by the network configuration and impedances.

Thus, replacing synchronous generators with asynchronous wind farms increased the synchronous strength of the system and also, introducing wind generation increased the critical clearing times of the system. There was no significant difference between the critical control case and full control case, indicating that the stability of the system did not decrease as lesser control was applied by the wind generation**.** In addition, the critical clearing times were significantly lower at the lower penetration level as a result of larger percentage of the system's active power provided by the synchronous generator. Hence, the system was more sensitive to application of a bus fault and the critical clearing time decreased at the 23.9% penetration level.

By supporting the voltage at the identified critical locations with the aid of wind generators, the voltage stability and rotor angle stability was maintained while minimizing the levels of control required by the system.

The system was more sensitive to application of a bus fault and the critical clearing time decreased at the 23.9% penetration level. Thus, the critical clearing times for the synchronous wind case, full control case and the critical control case were 15.03, 16.98 and 16.60 respectively.

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