Rotor Angle Stability with High Penetrations of Wind Generation

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***Abstract*—This paper explores the relationship between wind generation, particularly the control of reactive power from variable speed wind turbine generators, and the rotor angle stability of the conventional synchronous generators in the system. Rotor angle stability is a dynamic phenomenon generally associated with changes in active power flows that create angular separation between synchronous units in the system. With larger penetrations of wind generation being introduced into power systems, there will be large flows of active power from asynchronous generation in the system. These asynchronous active power flows can aid in maintaining the rotor angle stability of the system. However, the manner in which wind generation injects *reactive* power into the system can be critical in maintaining angular stability of the synchronous units. Utilizing wind generation to control voltage and reactive power in the system can ease the reactive power burden on synchronous generators, and minimize angular separation in the system following a contingency event and can provide a significant level of support which will become increasingly important in future power systems.**

***Index Terms*—reactive power, synchronous generators, transient analysis, wind power generation**

I. Introduction

As wind generation continues to be integrated into power systems in efforts to reduce emissions and reliance on fossil fuels it will become increasingly important to understand the impact large penetrations of wind generation will have on power system stability. Variable speed wind turbines (VSWT) provide electrical synchronism with the power system through power electronic convertors [1]–[3]; however, this power electronic coupling inhibits mechanical synchronism with the system effectively rendering wind inertia-less. How wind generation displaces conventional synchronous generation will significantly impact various stability aspects of the power system. The frequency stability of the system will be impacted if synchronous generation is displaced by wind generation [4], [5]. Insufficient reactive power support from wind generation can lead to voltage stability issues [6], [7]. How wind generation controls reactive power is an issue of considerable concern in power systems around the world [8]–[10]. This paper will assess how reactive power production from wind generation will directly influence the short-term rotor-angle stability of the system.

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Work has been completed that shows how wind generation will influence the inertial behavior of a power system. In [11], the impact of VSWTs on the small-signal stability of a large power system was assessed. The work in [11] shows 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 is different from an inertial aspect to that delivered by synchronous generation. Wind generation controls can be altered to emulate an inertial response for frequency stability, but have not been implemented widely in power systems [5], [12]. The work completed here looks to expand on the fundamental difference between the active power produced by VSWTs and that produced by conventional synchronous generators, particularly how they interact with the rotor angle stability of the system. Due to the fact that wind generation is inertia-less, the synchronous units that co-exist in 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 secure 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.

This analysis will examine how reactive power from wind generation can be used as a mitigation tool to ease the stress on synchronous generation and increase system security. *The aim is to show that when active power flows change minimally, the manner in which the wind generation provides reactive power support to the system is critical in maintaining rotor angle stability of conventional units in the system.* The improvement in stability is achieved by supporting bus voltages using reactive power injections from wind generation, in particular utilizing the terminal voltage control capabilities of VSWT wind turbines. This reduces the reactive power requirement from conventional synchronous generation and minimizes deviation in the field voltage. This allows synchronous generators to maintain their reactive power output inside their limits. By preventing reactive power from the synchronous generation from collapsing, the balance between electrical power output and mechanical input is maintained. This balance minimizes rotor angle deviation and improves rotor angle stability. To ease the reactive power burden on synchronous generation, the control strategy employed by the wind turbines is varied and the impacts on the angular stability of the conventional generation in the system are observed.

This paper is divided as follows: Section II describes the analysis methodology used in the study. Section III describes the test system and how wind generation was interconnected into the system. Section IV presents and discusses the results from the analysis and Section V concludes this paper.

II. Methodology

In order to determine how rotor angle stability and reactive power production from wind generation interact, it is important to isolate active power and reactive power. This section develops a methodology that isolates active power and reactive power and assesses their impact individually.

A. Active Power Analysis

Here wind generation is first compared directly to synchronous generation in order to achieve a baseline comparison for the rest of the analyses. This is achieved by creating a base case consisting of doubly-fed induction generator (DFIG) wind farms operating at a fixed 0.95 capacitive power factor spread across the system. Next, a second case is created where the wind generation is replaced by equivalently sized and rated synchronous machines with exciter systems; however no governors or stabilizers are modeled. The synchronous wind machines are modeled in this manner in order to see how 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 the same 0.95 capacitive power factor as the wind generation. A brief description of the two cases in the active power analysis can be seen in Table I. 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, dictates that there will be significant variations in the active power flows across the system, particularly, the ability to provide electromagnetic torque which is resolved into two components;

- *The synchronizing torque component*, is in phase with the rotor angle deviation. The lack of synchronizing torque leads to aperiodic or non-oscillatory stability [13].
- *The damping torque component*, is in phase with the speed deviation. The lack of damping torque leads to oscillatory instability [13].

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.

TABLE I
Active Power Comparison Scenarios

Case	Wind Generation Control Type
Capacitive Case	Fixed 0.95 capacitive power factor
Synchronous Wind Case	Fixed 0.95 capacitive power factor

B. Reactive Power Analysis

The active power analysis quantifies the impact of the active power delivered by wind generation and determines whether it is fundamentally different in comparison to the active power delivered by synchronous generation [11]. Reactive power however, is a purely electrical injection 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 analyzing 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 flows.

In this section two cases examine the behavior of the wind generation and how they control their reactive power output. In the first wind case, wind generation operates at a unity power factor, i.e. no MVArs are injected into the system. In the second wind case, wind generation is operated using terminal voltage control, where the reactive power is quickly controlled in order to achieve a specific voltage at a target bus [10], [14], [15]. The studied cases are listed in Table II

TABLE II
Reactive Power Comparison Scenarios

Case	Wind Generation Control Type
Unity Case	Fixed unity power factor
Terminal Voltage Case	Reactive power controlled to target voltage

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 changes 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.

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.

III. Test System

The New England 39 bus system was used as the test system in this analysis, Fig. 1 [16]. The ten synchronous

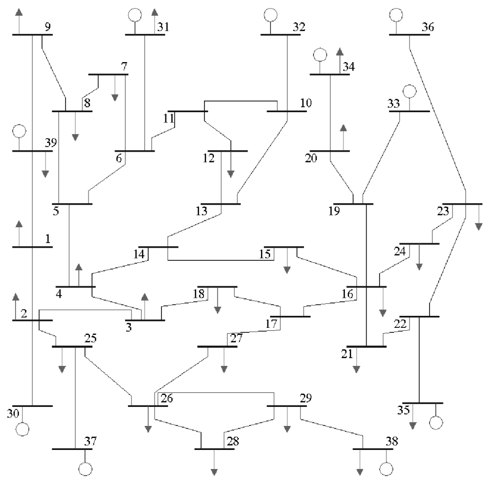

Fig. 1. One-line diagram of the New England 39 bus test system.

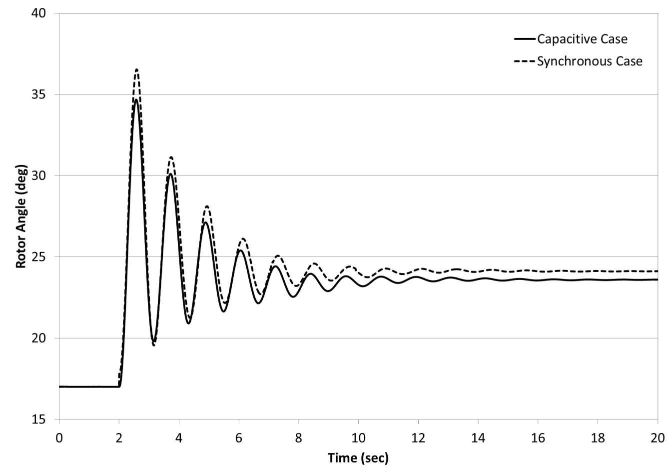

Fig. 2. Rotor angle traces from the synchronous wind case and the capacitive case at generator 34 for the loss of generation contingency.

units in the system were modeled as salient pole generators (GENSAL), with AC excitation systems (IEEEX1), steam turbine governors (TGOV1), and stabilizers (STAB1) [17]. The load was modeled to include 33% constant current, 33% constant impedance, and 33% constant power [18]. DFIG wind generation was added to the buses listed in Table III, to achieve a instantaneous penetration level of 21.6% (1250 MW) for a demand level of 5785 MW. The DFIG model used was a generic model of 1.5 MW GE DFIG machine and operated at a fixed 0.95 capacitive power factor for the base line analysis for the active power analysis. The control parameters of the wind turbine are the standard parameters as described by [19] and are in Table XII in the appendix. The wind turbines were operated at 100% of their capacity and each farm was 70 turbines aggregated into a single 104 MW farm. This configuration allowed for single-point voltage control to applied by the entire farm, simulating operation through a supervisory control and data acquisition (SCADA) system. Operating at 100% of rated power has no impact on the study since the transient analysis is completed as a snapshot of the system's most stressed operating point, in this case the point of maximum wind penetration. Active power that was displaced by the wind generation, was balanced by reducing the active power output of the ten original synchronous units uniformly, as a result none of the units are fully displaced. The reactive power limits of the ten original synchronous units were left unchanged in order for the system to reach a solution. The data for the ten synchronous machines can be seen in Table XIII in the appendix of this paper.

TABLE III
WIND GENERATION LOCATIONS

Connection bus	2, 6, 8, 12, 16, 18, 24, 26, 32, 33, 35, and 37

The type of control strategy employed by the DFIG farms was varied based on Tables I and II and a transient analysis of the system was completed. The contingency examined in all of the cases was the loss of the synchronous generator located at bus 33 operating at 632 MW. The synchronous unit that responded with the largest initial angular deviation was the generator located at bus 34, and thus was monitored for all of the comparison cases. The reference angle used for the studies was the angle of the machine located at bus 31. The active and reactive power flows at the ten original synchronous units from the test system were also monitored, the results of which are included in the following section.

IV. RESULTS AND DISCUSSION

The results and discussion is divided into two sections. The first assesses the difference between active power from wind generation and synchronous generation and how it interacts with the rotor angle stability of the system based on the methodology described in Section II-A. The second section will examine the mitigation strategies available to wind generation, i.e. reactive power control, and how they can contribute to improving the system stability, in particular the rotor angle stability based on the methodology described in Section II-B. It will examine how reactive power support from wind generation interacts with synchronous generation. All simulations were completed in the DSATools software package [20].

A. Active Power Results and Discussion

In Fig. 2 the rotor angle for generator 34 can be seen for each of the cases from Table I. In comparing the rotor angles, it can be seen that there is a variation between the two cases, but they are not dramatically different. The difference in the two cases is due to the fact that when wind generation is interconnected it is not providing any electromagnetic torque to the system. When synchronous units replace the wind farms, there is an inertial response and as such, there is a change in active power flows for the nine original synchronous generators that are still online for the two cases following the contingency event, Fig. 3. The change in active power flow is significant, but as seen in Fig. 2, the resulting impact on rotor angle is relatively benign.

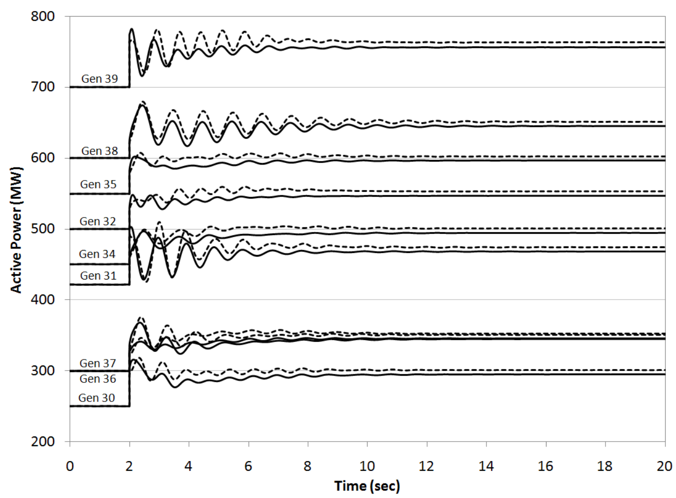

Fig. 3. Active power response from the nine original synchronous units that are still online for the synchronous wind case (solid line) and the capacitive case (dashed line).

A Prony analysis was completed on the rotor angle signal for generator 34 for each of the two cases in order to analyze the rotor angle differences in greater detail. By comparing the dominant mode for each of the two cases, the magnitude and relative damping of the oscillatory signal can be determined. These two characteristics of the mode are critical in determining how large the initial swing is and how quickly the oscillations are damped out. By examining the properties of the mode, further conclusions regarded the relative stability of each case can be determined, Table IV. From the table, it can be seen that the modes display similar magnitudes and damping levels in each of the cases, with the synchronous wind case providing slightly improved system damping.

TABLE IV
DOMINANT MODE COMPARISON

Case	Mag.	Phase	Freq (Hz)	Damping
Synchronous Wind Case	10.95	-1.17°	0.844	8.14 %
Capacitive Case	10.41	-1.589°	0.860	7.95 %

This is also reflected in the calculation of the exponential rate of decay given in (1).

$$y = \alpha e^{\beta x} + \delta \tag{1}$$

The coefficients for each case can be seen in Table V. Once again, the magnitude and rate of decay coefficients are similar, reflecting the behavior seen in the rotor angle traces, Fig. 2.

TABLE V
RATE OF DECAY COEFFICIENTS

Case	α	β	δ
Synchronous Wind Case	42.4	-0.49	23.3
Capacitive Case	39.1	-0.46	23.4

The analysis completed in this section demonstrates that the capacitive generation and synchronous wind generation are comparable from a rotor angle perspective, with the synchronous wind case providing slightly improved damping levels. The more significant system impact of synchronous generation is demonstrated in the change of the active power flows, which is a result of the physical difference between synchronous generation and asynchronous wind generation. This demonstrates, that in order to achieve damping levels comparable to the synchronous wind case, the 10 original synchronous units in the capacitive case are required to provide larger active power outputs and increased damping support. In a system with high levels of wind generation, this places an increased burden on conventional synchronous generation and could lead to less secure system operation. With the continued installation of wind generation in power systems, it will become important to understand and improve system security utilizing the built-in capabilities of wind generation. As such, the next section focuses on using reactive power control as a mitigation technique that can help improve system stability.

B. Reactive Power

1) Loss of Generation Contingency: The previous section demonstrated that with increasing penetrations of wind generation, that increased responsibility will be placed on existing synchronous generation in a system. With wind generation composing a significant percentage of a system's generation portfolio, it will become critical to utilize the available mitigation techniques available from wind generation in order to improve system stability.

Modern DFIG 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. In the previous section the wind turbines were operated at a 0.95 capacitive power factor. This control strategy will now be compared to the two others described in Table II, first the unity case and then the terminal voltage case. In Fig. 4, the rotor angle trace for the capacitive case is plotted along with the unity case. It is clear from Fig. 4 that there is a significant change in the behavior of the synchronous machine at bus 34. Unlike the synchronous generation case, the active power flow from the original synchronous units do not change greatly. This is confirmed by the active power outputs for the nine original synchronous units that are still online for the two cases seen in Fig. 5. For the loss of generation contingency, the conventional units respond with nearly the same active power outputs, the average deviation in relation to the generation output for the capacitive case across the time steps is 0.33%. Since there is a very small change in the active power flow, the change in rotor angle seen in Fig. 4 must be due to the change in reactive power production from the wind generation. Once again, a Prony analysis was completed in order to identify the dominant mode for the unity case and compared to the dominant mode for the capacitive case. The details of the mode can be seen in Table VI.

The mode for the unity case is similar to the capacitive case (Table IV). This is further confirmed by fitting an exponential decay for the unity case, Table VII. Here, the rate of decay

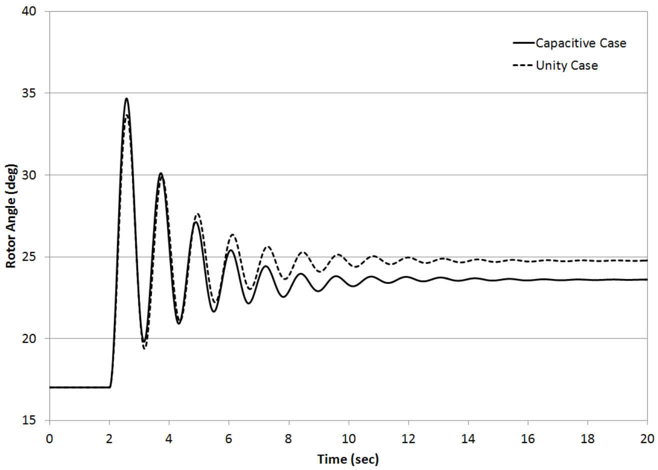

Fig. 4. Rotor angle traces for generator 34 from the capacitive case and the unity case for the loss of generation contingency.

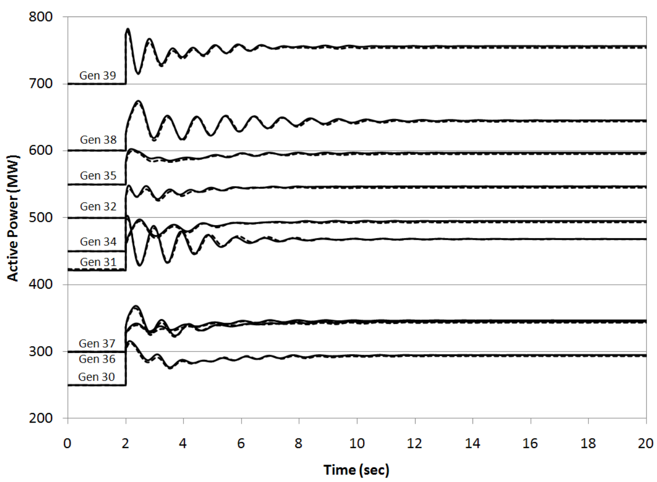

Fig. 5. Active power response from the nine original synchronous generators online from the capacitive case (solid line) and the unity case (dashed line).

TABLE VI
DOMINANT MODE FOR THE UNITY CASE

Case	Mag.	Phase	Freq (Hz)	Damping
Unity Case	10.11	-10.99°	0.855	7.40%

TABLE VII
RATE OF DECAY COEFFICIENTS FOR THE UNITY CASE

Case	α	β	δ
Unity Case	31.4	-0.48	24.8

coefficients are very similar to the capacitive case (Table V). These results indicate that providing bulk MVArs to the system is nearly as effective as providing no reactive power support to the system whatsoever. There is little to no improvement between the two cases, and as such a third case is studied, terminal voltage control by the wind farm. In this case, MVArs are dynamically controlled by the wind farm in order to achieve a target voltage, 1.0 pu in this case, at a

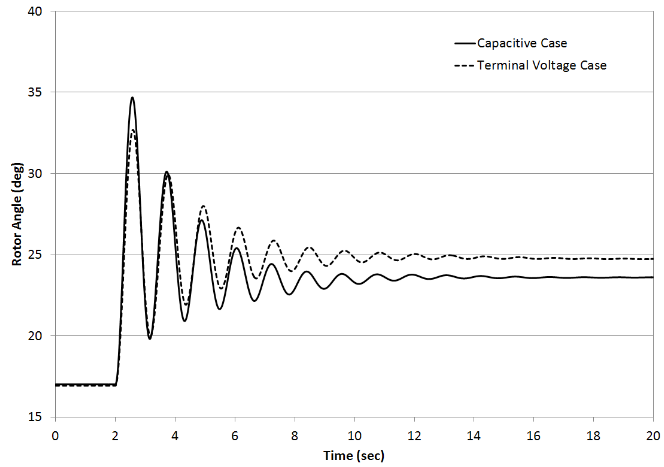

Fig. 6. Rotor angle traces for generator 34 from the capacitive case and the terminal voltage case for the loss of generation contingency.

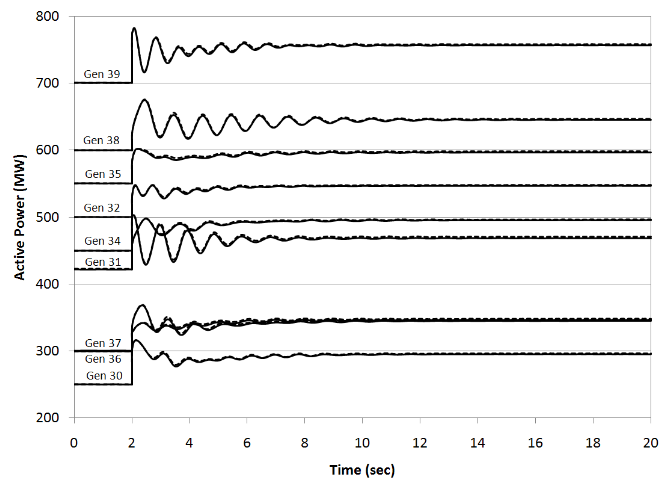

Fig. 7. Active power response from the nine original synchronous generators online from the capacitive case (solid line) and the terminal voltage case (dashed line).

designated bus within the time-frame of contingency events. This provides more direct support to the synchronous units in the system, allowing for more robust system operation. The terminal voltage case was compared to the capacitive case for the same loss of generation contingency and the resulting rotor angle traces for generator 34 can be seen in Fig. 6.

As done in the previous cases, the active power output of the conventional units is monitored to ensure there are minimal changes in active power flows, Fig. 7. As with the unity case, the average deviation in relation to the generation output of the capacitive case was calculated and determined to be 0.23%. The change in active power for this case is even less than for the unity case. The mode studied for the terminal voltage case from the Prony analysis can be seen in Table VIII. In comparison to the other two reactive power control strategies for the wind generation (Tables IV and VI), there is a significant improvement in the damping of the mode, given the similar initial swing magnitudes. This indicates that when reactive power is controlled to achieve a specific target voltage, the oscillation is more effectively damped. When examining the rate of decay for the terminal voltage case (Table IX) an interesting change is observed in comparison to the other two cases (Tables IV and VII).

TABLE VIII
DOMINANT MODE FOR THE TERMINAL VOLTAGE CASE

Case	Mag.	Phase	Freq (Hz)	Damping
Terminal Voltage Case	10.2	49.3°	0.872	10.8%

TABLE IX
RATE OF DECAY COEFFICIENTS FOR THE TERMINAL VOLTAGE CASE

Case	α	β	δ
Terminal Voltage Case	22.0	-0.39	24.7

The rate of decay for the terminal voltage case is significantly less in comparison to the three cases that have already been examined, -0.39 sec^{-1}, however, the magnitude of that decay, α is significantly less as well. This demonstrates a distinct difference in system behavior when MVArs are actively controlled; the initial swing in rotor angle immediately following the contingency event is considerably reduced, by 3.85°, Fig. 6. This results in the lower rate of decay, as the system is nearer to the last stable operating point.

Since the only variable that sees any dramatic change in the three wind cases is the manner in which reactive power is produced by the wind generation the increase in damping can be attributed to providing dynamic reactive power support. By quickly controlling voltage to a specific set-point value, the system is better able to damp oscillatory behavior that may lead to rotor angle instability. This demonstrates the critical role that reactive power support can play in improving rotor angle stability.

2) The WECC Full Voltage Controller and DFIG: The previous analyses relied on utilizing the GE 1.5 DFIG wind turbine and controller model. This section will explore whether the improved results with the implementation of terminal voltage control are a result of the model specifics or a fundamental system response. As such, the GE 1.5 DFIG model was compared to the WECC voltage source full-convertor turbine model (WECC VSC) and the WECC DFIG model and convertor using the standard control parameters defined by [21], [22] and are given in Table XIV and Table XV in the appendix. It should be noted that due to the limited availability of wind turbine models the control philosophy behind these three is very similar. In more detailed studies, that explore local transient impacts, the variety of active and reactive power control loops may have significant impacts on the results. The same contingency as before, the loss of generator 33, was applied and the rotor angle of generator 34 was observed. The resulting rotor angle traces were compared for each of the three terminal voltage cases and can be seen in Fig. 8.

As seen in Fig. 8 the rotor angles behave in a relatively similar manner for all three cases; there is very little difference in the initial swing immediately following the contingency, 0.26° and 0.11° for the WECC VSC and WECC DFIG cases respectively. The main variation in the rotor angle is the damping level seen by the two WECC wind models. This is further reflected by examining the Prony mode in greater detail, Table X. In each of the two additional cases, the magnitude of the mode is reduced in comparison to the terminal voltage case (Table VIII), and correspondingly the damping level is reduced. As seen earlier with the rates of decay, this indicates that there is less of a burden on the system to respond and return the system to a stable operating point. This is further confirmed by examining the rate of decay for the two new cases, Table XI. As with the behavior of the terminal voltage case (Table IX), the magnitudes of the decay are similar, and the rates of decay are slightly improved. This reflects what is seen in the rotor angle trace as well and demonstrates that the implementation of terminal voltage control as a transient stability mitigation strategy is effective and not isolated to a specific model type.

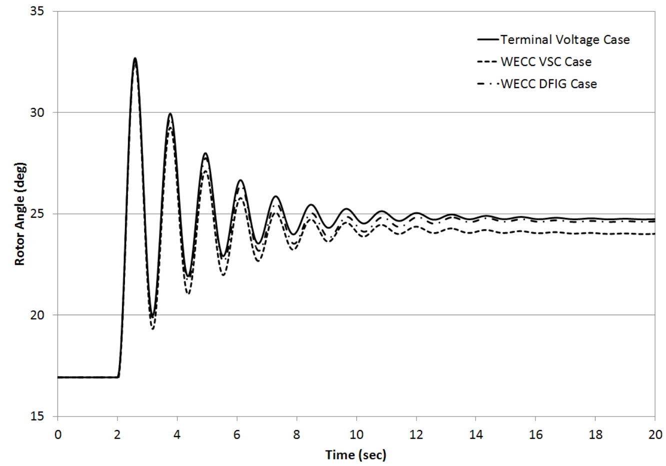

Fig. 8. The rotor angle of generator 34 for the three terminal voltage control cases.

TABLE X
DOMINANT MODE FOR THE WECC WIND MODEL CASES

Case	Mag.	Phase	Freq (Hz)	Damping
WECC VSC Case	6.86	-7.80°	0.852	6.93%
WECC DFIG Case	8.04	-11.4°	0.850	6.96%

TABLE XI
RATE OF DECAY COEFFICIENTS FOR THE WECC WIND MODEL CASES

Case	α	β	δ
WECC VSC Case	26.1	-0.44	24.1
WECC DFIG Case	22.6	-0.40	24.3

3) Reactive Power and Field Voltage: As seen in Fig. 5 and 7, the active power flows of the conventional generation units are not impacted by the type of reactive power control employed by wind generation, however, there is a significant impact on the reactive power flows of the conventional generation units. In Fig. 9, the reactive power flows for generator 34 following the loss of generation contingency are seen. For each

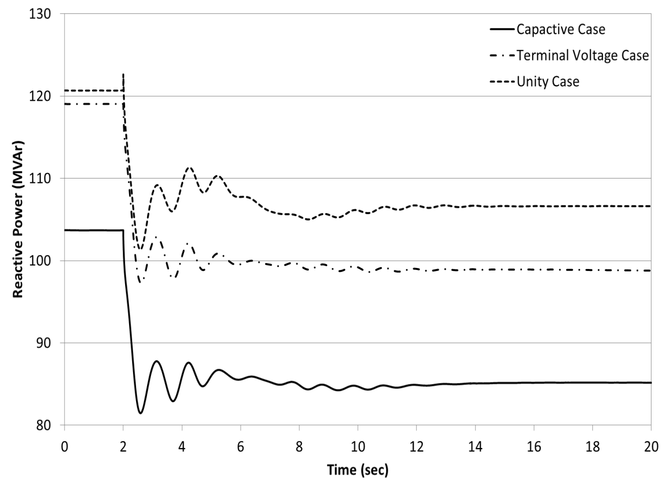

Fig. 9. The reactive power output of generator 34 for the three wind cases.

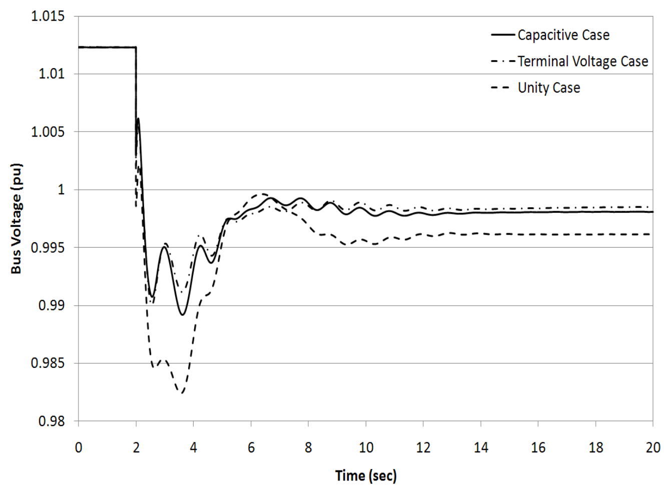

Fig. 10. The voltage of bus 34 following the contingency for the three wind cases.

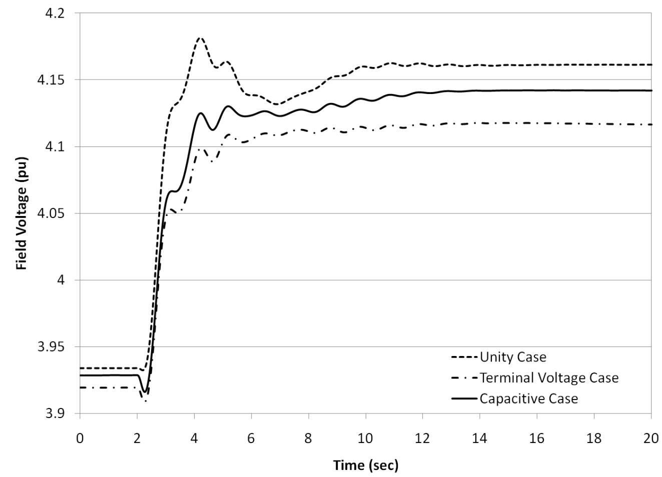

Fig. 11. The field voltage of generator 34 following the contingency for the three wind cases.

wind case, generator 34 has a different initial reactive power set point and responds to the event with a varying reactive power response, Fig. 9. This is due to the change in reactive power output from the wind farms.

In Fig. 10, the loss of generation event degrades the bus voltage the greatest for the unity case, where wind generation is providing no reactive power support to the system. In the capacitive case, the support in the form of bulk MVAr production from wind generation improves bus voltage compared to the unity case. In the terminal voltage case, where MVArs are controlled to a target value, the bus voltage performs the best following the contingency and the voltage recovers quicker to a steady-state value. Fig. 10 indicates that the bus voltage suffers due to the excessive reactive power production requirements placed on the conventional generation by the reactive power control strategy employed by wind generation. The variation in bus voltage is directly reflected in the field voltage of the generator at bus 34, Fig. 11. By supporting the field voltage, the machine does not suffer under-excitation, and synchronism with the system is maintained. The variation in the machine's field voltage is due to the change in reactive power flows, since there is no change in active power flows across the system. The stress placed on conventional generation by the wind generation's reactive power control strategy degrades the field voltage of the machine, directly impacting angular separation within the machine. In further examining Fig. 11, the unity case suffers from the largest field voltage deviation and as a result has the worst rate of decay in its rotor angle. The terminal voltage case has the smallest deviation and the best rate of decay. The capacitive case lies between the two other control cases. This demonstrates how built-in mitigation techniques of wind generation can be utilized in order to improve rotor angle stability in a system with a high penetration of wind.

This is the manner in which reactive power and rotor angle can interact and impact the stability of the system. This relationship between reactive power and rotor angle has been discussed in [23], where a clear link between voltage instability and rotor angle instability is presented. In modern power systems, this issue has been mitigated using automatic voltage regulation (AVR) and as a result, has not been a significant issue. With higher penetrations of wind generation there will be more remotely located generation units and a weakening of the system's AVR capability. As such, the control of reactive power by wind generation in the system will become more critical for system operation under high penetrations of wind generation.

Further insight into the impact on field voltage can be seen by examining the peak to peak deviation in the field current, Fig. 12, of generator 34 for each of three wind cases. The field current set-points before the contingency reflect the reactive power set-points of generator 34. The peak to peak deviation was 0.26 pu, 0.25 pu, and 0.26 pu for the capacitive, unity and terminal voltage cases respectively. Since they were all very similiar, this indicates that generator 34 changed its reactive power at the same level for all three cases and the large change in field voltage, Fig. 11, is not a result of over-excitation, but due to the deterioration in bus voltage as a result of inadequate

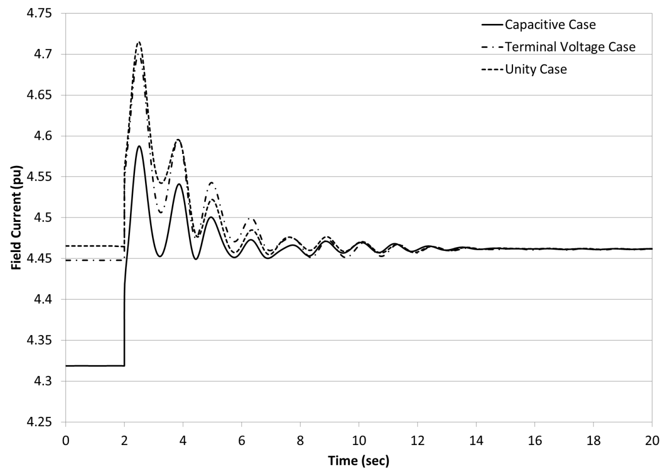

Fig. 12. The field current of generator 34 for the three wind cases

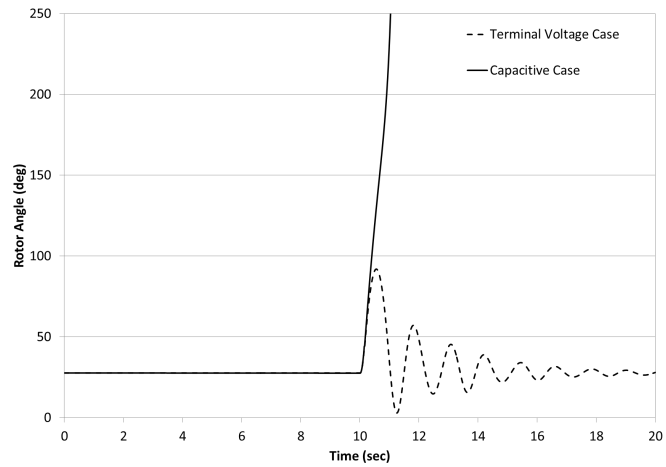

Fig. 13. The rotor angle of generator 33 following a 7 cycle fault at bus 33 for the capacitive case and terminal voltage case.

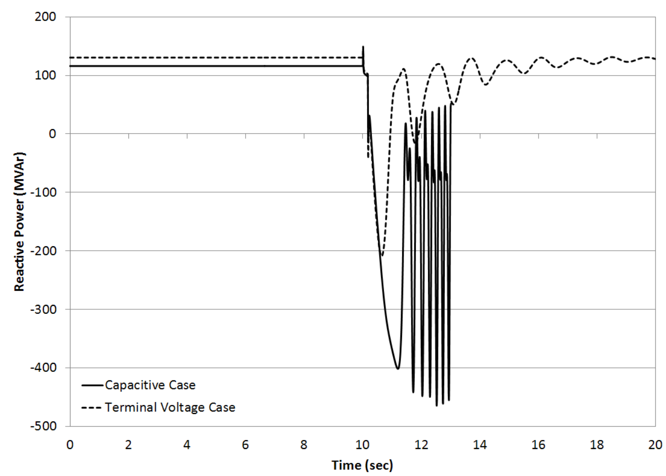

Fig. 14. The reactive power collapse of generator 33 following the clearance of the fault at bus 20. The limit on generator 33 is -300 MVAr.

reactive power support.

C. Fault Analysis

The previous sections demonstrated that for a large system disturbance, i.e. the loss of a generator, the terminal voltage cases decrease the burden on the remaining conventional synchronous units and helps improve the rotor angle stability of the system. In this section, a localized voltage event will be analyzed in order to further reinforce the importance of appropriate reactive power control. For a loss of generation contingency, the impacts are felt across the system, and all of the synchronous units in the system respond to the event. A fault contingency is a much more localized event, and as such the system reacts in a different manner. Here, a three phase-to-ground fault is applied at bus 20, a load bus in the system, for seven cycles. Following the fault clearance, the impact on rotor angle stability is observed for two wind cases, the capacitive case and the terminal voltage case (GE DFIGs only).

In Fig. 13, the rotor angles for the capacitive case and terminal voltage case are seen. Following the clearance of the fault, the first machine to lose synchronism in the capacitive case is located at generator 33. The same machine in the terminal voltage case is able to return to a stable operating point. The synchronous machine in both cases is loaded at the same level and capable of providing the necessary dynamic support services, but in the capacitive case the machine loses synchronism. This is a result of reactive power collapse at the synchronous machine, Fig. 14. In the capacitive case, the wind farms are providing bulk levels of reactive power to the system. Initially this eases the reactive power burden on generator 33, i.e. the reactive power set-point is lower for the capacitive case than in the terminal voltage case, however, the machine is unable to overcome the fault. This is seen in the reactive power production of the wind farm located at bus 33, Fig 15. In the terminal voltage case, the reactive power of the farm is initially absorbing a large amount of reactive power, and at the time of the fault suddenly increases its reactive power output in order to help maintain bus voltage (Fig. 16) and aid the stability of generator 33. In the capacitive case this is not possible and as a result the machine continues to absorb MVArs beyond its limit and eventually loses synchronism. This is due to the fact that the wind farm is operating at its maximum reactive power output and is unable to supply enough supporting MVArs to overcome the fault. The model used in this case does have the fault ride-through capability; however even the additional reactive power support immediately following the fault is insufficient to maintain the synchronism at generator 33. This may be the case when farms are configured to produce bulk MVArs to support grid voltages, and in this case, during a worst-case scenario cannot provide the necessary support. Other manufacturers may have varying fault-ride through strategies; however in this case, the farm is simply unable to provide the necessary support to ride-through the event.

V. Conclusion

The asynchronous nature of wind generation places an increased responsibility on conventional synchronous generation to provide the necessary resources to mitigate a contingency

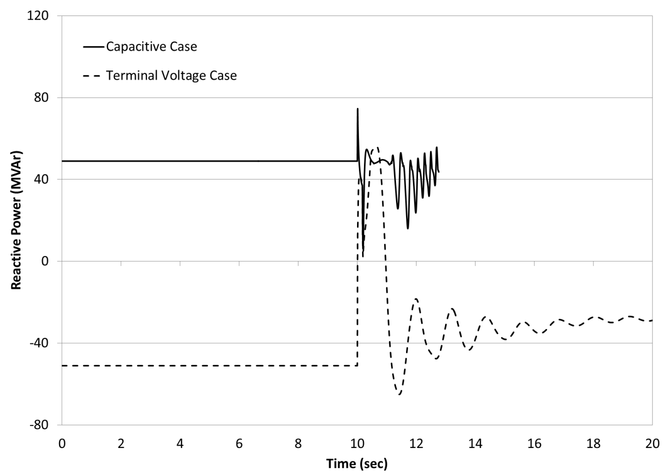

Fig. 15. The reactive power output of the wind farm at bus 33.

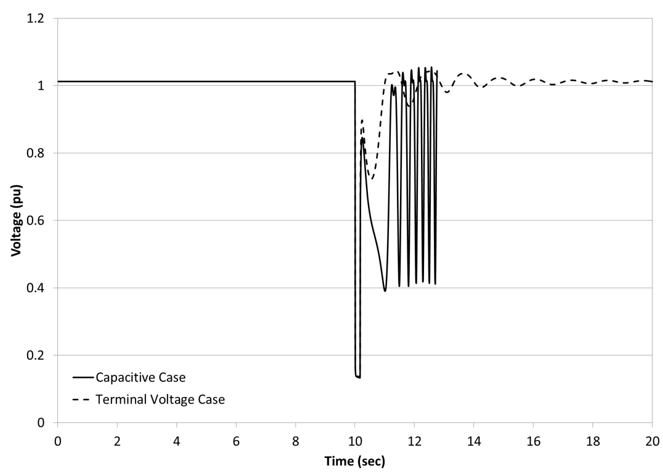

Fig. 16. The bus voltage of generator 33.

event. By utilizing the built-in capabilities of wind generation to provide the synchronous generation with reactive power support, the onus on synchronous generation can be eased. It is shown that the rotor angle of synchronous generators is directly influenced by the type of reactive power control employed by the wind generation. The implementation of appropriate control strategies in wind farms, particularly the implementation of terminal voltage control, can lessen the reactive power requirements of conventional synchronous units and help mitigate large rotor angle swings and aid conventional generation in damping the oscillatory signal following a loss of generation event. Furthermore, it is shown that reactive power support from wind generation can aid in mitigating severe low voltage events, thus minimizing angular separation in synchronous units.

The displacement of the conventional synchronous units will have consequences beyond loss of inertia and synchronizing and damping torque. The loss of mitigation capabilities such as AVRs, dynamic VAR support, and governor action will also have significant impacts on system stability.

TABLE XII
GE 1.5 MW DFIG WIND TURBINE CONTROLLER PARAMETERS

Variable Name	Value	Variable Name	Value
T_r (sec)	0.02	Q_{min} (pu)	-0.436
T_v (sec)	0.05	T_{pwr} (sec)	0.05
f_N	1.0	X_c (pu)	0
T_c (sec)	0.15	V_{ermn} (pu)	-0.1
K_{pv}	18	V_{ermx} (pu)	0.1
K_{iv}	5	V_{frz} (pu)	0.7
Q_{max} (pu)	0.436		

TABLE XIII
SYNCHRONOUS GENERATOR LIMITS

Connection Bus	MW Max	MW Min	MVAr Max	MVAr Min
30	250	100	250	-50
31	580	230	500	-250
32	650	260	300	-300
33	632	250	300	-300
34	508	200	300	-200
35	650	260	300	-300
36	560	220	250	-250
37	540	220	200	-200
38	830	330	400	-400
39	1000	400	500	-500

VI. APPENDIX

Note: Generator 31 is not listed due to the fact it is used as the reference bus in the calculations.

TABLE XIV
WECC VSC WIND TURBINE CONTROLLER PARAMETERS

Variable Name	Value	Variable Name	Value
T_{fv} (sec)	0.15	V_{MAXCL} (pu)	1.2
K_{pv} (pu)	18.0	V_{MINCL} (pu)	0.9
K_{IV} (pu)	5.0	$X_{Q_{min}}$ (pu)	-0.5
X_c (pu)	0	$X_{Q_{max}}$ (pu)	0.4
T_{FP} (sec)	0.05	T_v (sec)	0.05
K_{pp}	3.0	K_{qi} (pu)	0.05
K_{IP} (pu)	0.6	T_p	0.05
dP_{MX} (pu)	1.12	F_n (pu)	1.0
dP_{MN} (pu)	0.1	ω P_{pwr} (pu)	0.69
Q_{MX} (pu)	0.296	ω P_{20} (pu)	0.78
Q_{MN} (pu)	0	ω P_{40} (pu)	0.98
I_{PMX} (pu)	1.1	ω P_{60} (pu)	1.12
T_{RV} (sec)	0.05	P_{min} (pu)	0.74
R_{PMX} (pu)	0.45	ω P_{100} (pu)	1.2
R_{PMN} (pu)	0.45	K_{qv} (pu)	40.0
T_{Power} (sec)	5.0		

VII. ACKNOWLEDGEMENT

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TABLE XV
WECC DFIG WIND TURBINE CONTROLLER PARAMETERS

Variable Name	Value	Variable Name	Value
T_{fv} (sec)	0.15	T_{power} (sec)	0.05
K_{PV} (pu)	18.0	V_{MINCL} (pu)	0.9
K_{IV} (pu)	5.0	V_{MAXCL} (pu)	1.1
K_{pp} (pu)	0.05	K_{VI} (pu)	120.0
K_{ip} (pu)	0.10	T_v (sec)	0.05
K_f (pu)	0.0	T_p (sec)	0.05
T_f (sec)	0.08	I_{maxTD} (pu)	1.7
Q_{MX} (pu)	0.47	I_{ph} (pu)	1.11
Q_{MN} (pu)	-0.47	I_{ph} (pu)	1.11
$I_{P_{MAX}}$ (pu)	1.1	dP_{MX} (pu)	0.5
T_{RV} (sec)	0.0	dP_{MN} (pu)	-0.5
K_Q (pu)	0.1		

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