Voltage Control Challenges on Weak Grids with High Penetration of Wind Generation: ERCOT Experience

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***Abstract*--More than 9 GW of wind capacity has been connected to the Electric Reliability Council of Texas (ERCOT) grid. In order to accommodate the installation of future wind generation, the Competitive Renewable Energy Zone (CREZ) transmission expansion project has been planned. The CREZ project includes over two thousand miles of new 345kV transmission lines and is expected to be completed by 2014. Planning studies have been conducted to ensure that new wind generation can be reliably delivered to the ERCOT grid through the CREZ transmission facilities. Voltage oscillations and temporary overvoltage were observed in the CREZ system dynamic studies. Weak grid as indicated by low Short Circuit Ratio (SCR) was considered to be the primary cause for those voltage issues. This paper presents the analysis, including causes and solutions, for these voltage stability issues. An actual oscillatory response of an existing wind power plant (WPP) captured on a Phasor Measurement Unit (PMU) and its post-event analysis supported all the findings in the CREZ planning studies. Both the real time operation events and planning studies demonstrate the voltage stability impacts of high penetration of wind generation on weak grids.**

***Index Terms*-- Low Short Circuit Ratio, Phasor Measurement Unit (PMU), Temporary Overvoltage, Voltage Oscillations, Wind Generation, Weak Grid**

I. Introduction

MORE than 9GW of wind capacity has been connected to the ERCOT grid. The existing system is serving 25~75GW, and the historical peak load is 68,379MW recorded on August 3, 2011. In order to accommodate additional future wind power, the Texas Legislature ordered the Public Utility Commission of Texas (PUCT) to designate Competitive Renewable Energy Zones (CREZ) in Texas and to order specific transmission improvements required to connect these CREZ with load centers in the Texas Interconnection (also known as the ERCOT region) [1], [2]. For the CREZ transmission improvements, the PUCT selected from among several options a plan that includes over 2,300 miles of new 345 kV right-of-way to accommodate an incremental 11,553 MW of wind generation capacity in West Texas. Fig. 1 shows the network topology of the CREZ plan.

Fig. 1. CREZ transmission system.

Planning studies had been conducted to ensure that new wind generation can be reliably delivered to the ERCOT grid through the CREZ transmission facilities. Voltage oscillations and temporary overvoltage were observed in the planning dynamic studies when large amounts of wind generation and dynamic reactive devices were modeled in the study case. The concerns and challenges to integrate wind generation into a weak grid have been addressed in several references [3]-[5].

In the CREZ planning studies, the weak grid as indicated by low Short Circuit Ratio (SCR) was considered the primary cause of voltage oscillation and temporary overvoltage. The SCR of a bus is an indication of the strength of the bus. The strength of a bus is defined here as the ability of the bus to maintain its voltage in response to injections of reactive power. A system having high SCR will experience much less change in bus voltage than another network with low SCR. Therefore, even though the SCR is calculated using steady state values, its value is a measure of how easily bus voltages are affected during dynamic system events. Some wind turbines (Type 3 and Type 4) have controls tuned for an SCR

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higher than some threshold (usually SCR > 3). When the SCR is lower than this threshold value, the turbine control does not behave well, resulting in voltage oscillations. This paper discusses this type of "voltage instability" associated with wind machine control in low SCR regions.

Virtual synchronous condensers were used in the study as a "place holder" to mitigate these stability issues. Although enhancing the system strength is generally considered as a first and rational option, the uncertainties associated with installing synchronous machines in the CREZ grid under the restructured power market and lengthy implementation times for transmission projects make it likely that wind power plants (WPPs) will operate under weak grid conditions. Therefore, it is important to understand the impact of WPPs and dynamic reactive devices on these stability issues in the CREZ planning studies without relying on virtual synchronous condensers. The findings of the key causes and solutions in the CREZ planning studies provide promising results in the simulation. In fact, voltage stability issues observed in planning studies have occurred in the ERCOT System. Voltage oscillations of an existing WPP in the ERCOT region were captured on a PMU in real time operations. The oscillatory responses started after a transmission line outage weakened the system. The recorded PMU data and post-event analysis results provided solid support of the findings in the CREZ planning studies and the feasibility of the proposed options to mitigate these voltage stability issues. This paper presents a summary of the major findings associated with voltage stability issues identified in the CREZ planning studies for high penetration of wind generation in an area where the grid is weak.

Section II describes the CREZ system characteristics and addresses the stability concerns as observed in the CREZ reactive power compensation study. Section III describes the findings and potential solutions of the voltage stability issues addressed in section II. Section IV describes the operational experience with support of PMU recorded data to verify the findings in the planning study. Finally, Section V outlines the conclusions of voltage stability concerns at weak grid with high penetration of wind generations.

II. CREZ SYSTEM CHARACTERISTICS

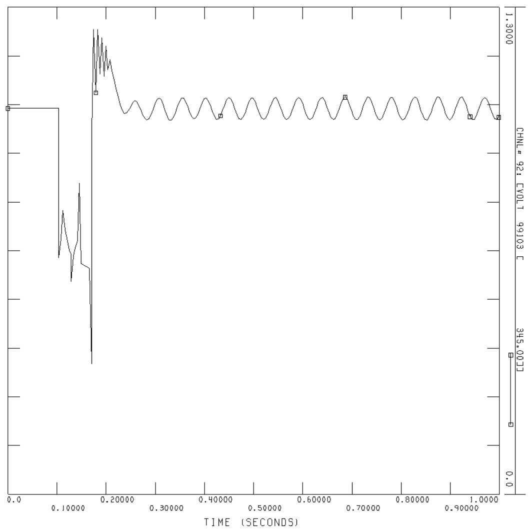
A. CREZ System Characteristics

Before addressing the stability concerns of the CREZ system, it is important to understand the system characteristics of the CREZ network. The purpose of the CREZ grid is to deliver future wind power located in areas remote from load centers. In the planning studies, both conventional synchronous generators and load centers were far away from the CREZ region. Considering the trend of wind turbine technology and ERCOT protocol requirements to have wind generators behave more like conventional generators, type 3 (Doubly Fed Asynchronous Generator) and type 4 (Full Converter) wind turbines were projected to be installed in the CREZ grid. Dynamic reactive devices, such as Static Var Compensator (SVC) or Static Synchronous Compensator (STATCOM), were also added to provide adequate dynamic voltage support. Both the wind turbines and dynamic reactive devices include a significant amount of power electronic components that provide limited short circuit current capability compared to conventional generators [6], [7]. Similar to the short circuit ratio calculation of a conventional AD/DC system interaction [8], the short circuit ratio (SCR) in this paper is defined as the ratio of the system three phase short circuit MVA at WPP's point of interconnection (POI) and the WPP's rated capacity in MW. A system is considered weak if the SCR is less than 3. In summary, the CREZ system characteristics can be listed as:

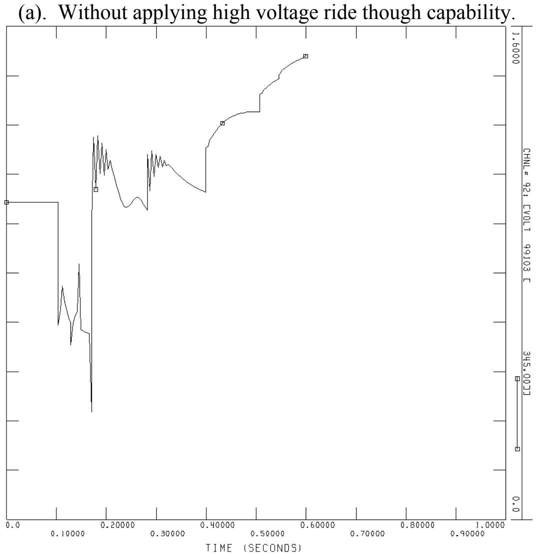
- Weak Grid. Large amounts of wind generation with limited short circuit current capability results in low SCR, hence, weakens the system strength.
- Challenge for voltage control. Under weak grid condition, the sensitivity of dV/dQ is high, which means the same amount of reactive support (injection or absorption) results in larger voltage deviation under weak grid conditions.
- Dynamic response is mainly driven by power electronic devices (WPP, SVC, etc). This is mainly due to the complete lack of synchronous generators and load connected to the CREZ system in the panhandle area.

B. Voltage Stability Issues in the CREZ Studies

This section describes the stability issues as observed in the CREZ reactive compensation study. Two main stability concerns, temporary overvoltage and voltage oscillations, were observed and as a temporary solution, the virtual synchronous condensers were used as a "place holder" to mitigate these issues. Fig. 2(a) shows the simulation result of a 345kV bus voltage response in CREZ grid with large amounts of wind generation modeled in the case without applying synchronous condensers. Depending on the magnitude of the oscillatory response, the power quality can be an issue to affect load customers. Furthermore, the study also indicated that the temporary overvoltage, as shown in Fig. 2(b) can lead to high voltage collapse if WPPs are equipped with limited high voltage ride through (HVRT) capability. The weak grid with low SCR was considered the primary cause for the response as shown in Fig. 2.



(a). Without applying high voltage ride though capability.



(b). Applying limited high voltage ride through capability.
Fig. 2 Voltage response at a 345kV bus in CREZ

III. CAUSES AND POTENTIAL SOLUTIONS

In addition to applying the synchronous condensers as a "place holder" to mitigate the stability issues described in section II, a further effort was taken to investigate the impact and potential solutions available by adjusting WPP and SVC dynamic models in the CREZ planning cases. This section describes the results of that effort, including the cause for these undesirable responses and solutions to resolve these stability issues. It is important to note that all the findings were based on the CREZ planning study case without applying virtual synchronous condensers.

The primary cause for the temporary overvoltage and voltage oscillations as shown in Fig. 2, is the weak grid with high sensitivity of dV/dQ. For example, in the CREZ study case, the same amount of 50 MVAr reactor switching at a 345kV bus could cause 0.01 p.u. voltage deviation in CREZ region compared to 0.003 p.u. in Houston region, where the system is considered strong. Additionally, the weak grid will cause faster closed-loop voltage control affecting the voltage response of a WPP or SVC and lead to the oscillatory response. Without a load component in the CREZ grid, the fast dynamic voltage support during and immediately after fault can also cause temporary overvoltage; the worse case is to have high voltage collapse as shown in Fig. 2(b).

Based on the identified causes of voltage instability, the solutions to resolve these issues include:

- Voltage controller tuning, including WPP and SVC
- Enhance the system strength

A. SVC Tuning

SVCs were modeled in the CREZ case as a way to provide adequate dynamic reactive support in the CREZ grid. An SVC is designed to provide fast voltage support with power electronic control. Under weak grid conditions, a faster response from the closed loop voltage control of the SVC could lead to unstable voltage oscillations. One solution is to reduce the transient gain to slow down the SVC's response [9]. Furthermore, better voltage response can be achieved through several small distributed SVCs compared to a large central SVC. The simulation results with tuned SVC response compared to the original setting, as shown in Fig. 3, demonstrate the effectiveness of the SVC tuning to mitigate the oscillations. It is also important to note that the consequence of tuning down the transient gain of SVC is to have a slower voltage response which will result in slower voltage recovery after fault. Therefore, there is a potential limitation to tune the SVC to avoid the slow voltage recovery that could violate the low voltage ride through requirement [10], [11].

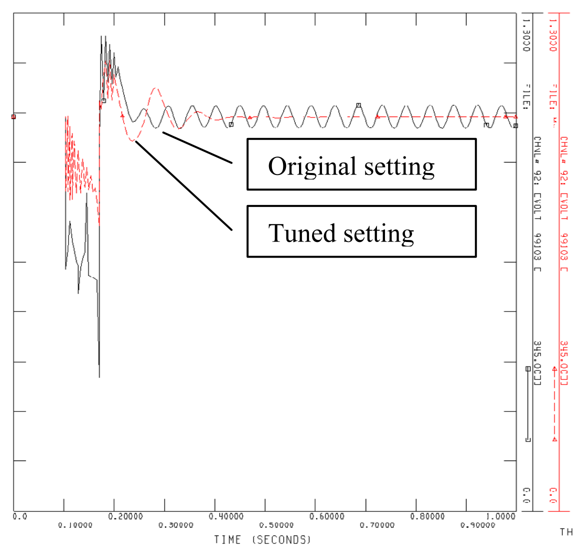


Fig. 3. Voltage response at a 345kV bus in CREZ (Black: original setting, Red: tuned setting)

B. Wind Turbine Controller Tuning

Since the voltage instability occurred during and immediately after the fault, the focus of the wind generator was on the controller that could have the largest impact on that time frame. Two major controllers were identified as the key elements that could mitigate both temporary overvoltage and voltage oscillations [12], [13].

- Voltage Controller
- Low Voltage Power Logic Controller

The voltage controller of a WPP can further be categorized as turbine level and plant level control. The turbine level control provides an initial response to address severe disturbance, and plant level control provides a slower response for voltage refinement. The simulation results in Fig. 4 show the impact of the wind turbine voltage control gain on a CREZ 345kV bus voltage response during and immediately after the fault. High voltage control gain can have faster voltage response that can effectively mitigate the temporary overvoltage. However, too aggressive voltage control gain, especially at weak grid, could result in the poorly-damped or even un-damped oscillations. The wind plant level voltage control impact, as shown in Fig. 5, indicated very limited impact on voltage response during and immediately after the fault.

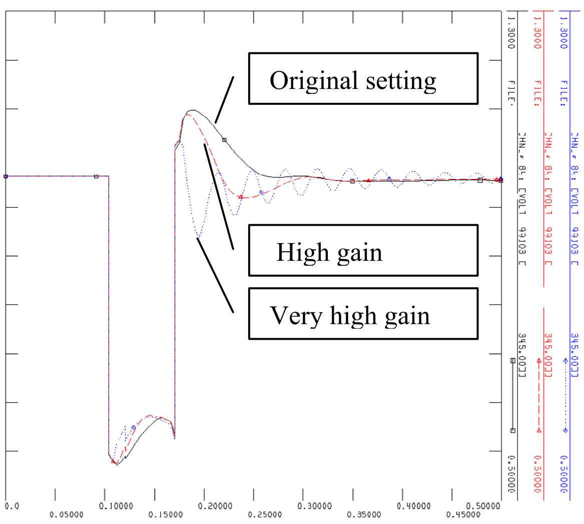


Fig. 4. Voltage response at a 345kV bus in CREZ (Black: original gain, Red: high gain, Blue: very high gain)

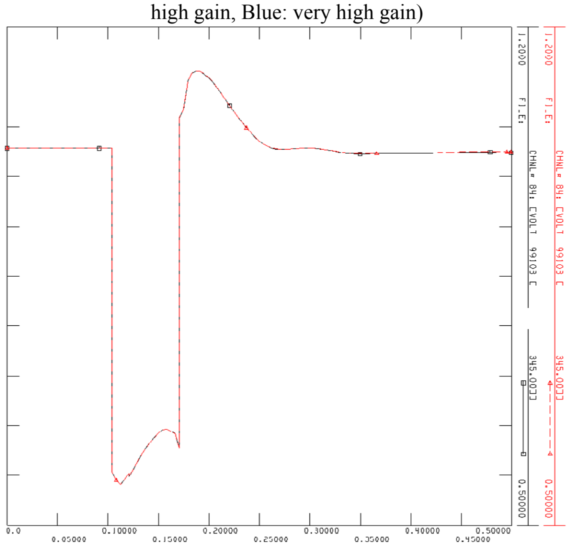


Fig. 5. Voltage response at a 345kV bus in CREZ (Black: original set, Red: high gain)

As stated in reference [13], the low voltage power control logic controls the MW contribution during and immediately after the fault. The ramp rate limit is the key to the post-fault power recovery, which is also the key to the post-fault voltage recovery. The control is originally designed to slow/smooth power recovery, which is desirable in the normal system with high SCR to prevent slower or unstable voltage recovery. However, considering the no load and weak system characteristics in CREZ, such control feature may need to be revised. The generic maximum ramp rate was already applied in the CREZ study but it is expected to have less temporary overvoltage response with larger ramp rate limit. Although increasing the ramp rate limit of the low voltage power control can potentially mitigate the temporary overvoltage, the physical limitation of the wind turbine design needs to be considered in consultation with the wind turbine manufacturers for secure operation. Similar to the tuning of an SVC, all the WPP's controller tunings need to be carefully reviewed and coordinated with other voltage control devices.

C. *System Strength Enhancement*

The virtual synchronous condensers were modeled in the planning studies as a solution to improve the CREZ network strength. Fig. 6 shows that voltage oscillation can be effectively mitigated by adding synchronous condensers which strengthen the system.

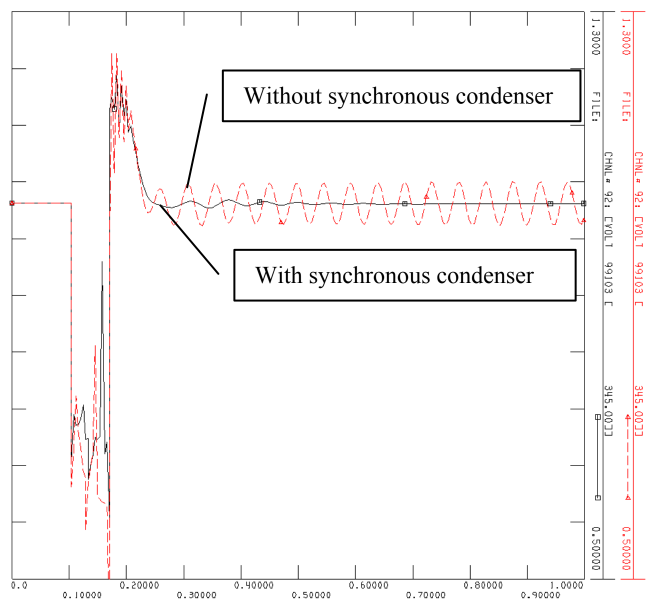


Fig. 6. Voltage response at a 345kV bus in CREZ (Black: with Synchronous Condensers, Red: Without Synchronous Condensers)

D. *Summary*

Both the temporary overvoltage and voltage oscillation conditions have been effectively mitigated through identified options, including SVC tuning, wind generation control tuning, and system strength enhancement. The impacts of individual solution options were presented in this section. However, it is important to recognize that interactions between all components in the CREZ, including WPP, SVC and the transmission grid can affect the response and coordination in tuning the individual elements is required. At this point, key causes and solutions to resolve the stability issues have been well identified with simulations. However, can such phenomena occur in actual power system? The answer is YES. Section IV describes the operational experience with the support of PMU recorded data to verify the findings in the CREZ planning study

IV. OPERATION EXPERIENCE

An existing WPP experienced undesirable poorly damped and un-damped voltage oscillations under weak grid conditions. The description of the event and the post event analysis are presented below.

A. Wind Power Plant (WPP) Description

A simplified network topology of the WPP connected to the ERCOT region is shown in Fig. 7. The WPP was modeled as an equivalent wind turbine to represent the total number of turbines within the WPP. To ensure the accuracy of the WPP's response, the equivalent collector system of the wind generation resource was calculated based on the methodology described in reference [11]. Under normal operating conditions, the WPP is connected to the ERCOT grid through two 69kV transmission lines. One phasor measurement unit (PMU) is installed on a 69kV line (Bus 5-Bus 7) to provide real time voltage and current data back to ERCOT with a resolution of 30 samples per second. The SCR is approximately 4 in normal operation conditions. If one of the 69kV lines is out of service, the SCR is reduced to 2 or less.

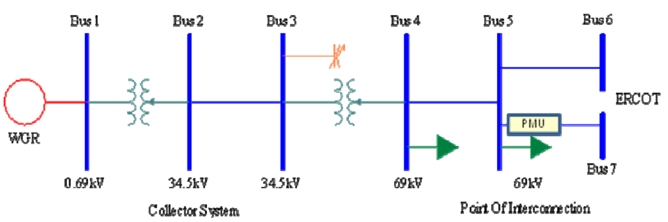
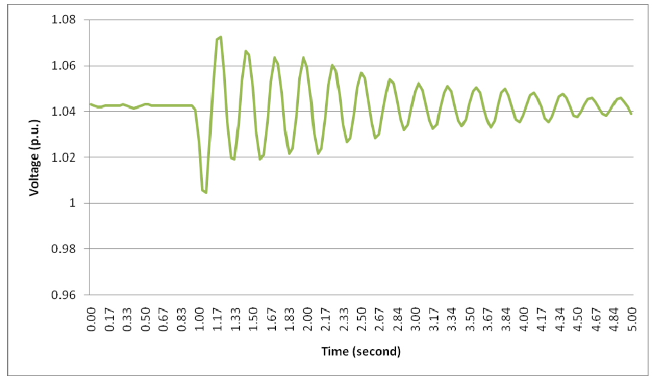


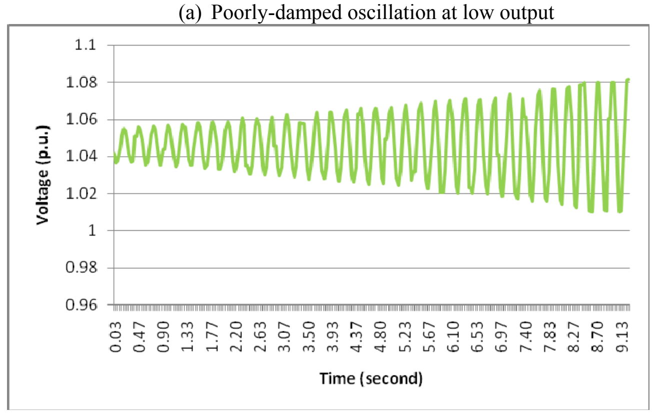
Fig. 7. Simplified network topology of the WPP

B. Voltage Oscillations

After one 69kV line (Bus5-Bus6) was taken out of service, the WPP started to experience a weak grid condition. With the PMU located on the remaining 69kV line (Bus5-Bus7), the PMU data represented the whole WPP's response to the ERCOT grid. Two types of voltage oscillations, poorly damped and un-damped, as shown in Fig. 8, were observed in the PMU recorded data. The poorly damped voltage oscillations, as shown in Fig. 8(a), were observed at lower wind output while the un-damped oscillation, as shown in Fig. 8(b), were observed at high wind output and eventually tripped the WPP.



(a) Poorly-damped oscillation at low output



(b) Un-damped oscillations at high output

Fig. 8. Recorded voltage oscillations at the WPP's POI

C. Post-Event Analysis

A real time operational case, including all ERCOT generation, load and network conditions during the event of the poorly damped oscillation was retrieved from the ERCOT Energy Management System (EMS) as the base case to perform the off-line stability analysis. There were two main objectives of this post-event analysis.

1. Re-create the oscillations as captured in the PMU
2. Identify the cause and solutions for the oscillations.

The wind dynamic model was tuned to have the simulation response match the PMU record data. Fig. 9 shows the results between the simulation and PMU data at low wind output with poorly damped voltage response. The result in Fig. 9 provides a wind dynamic model validation benchmark. By increasing the wind output in the study case, the un-damped oscillation as observed in the PMU data was successfully re-created, as shown in Fig. 10.

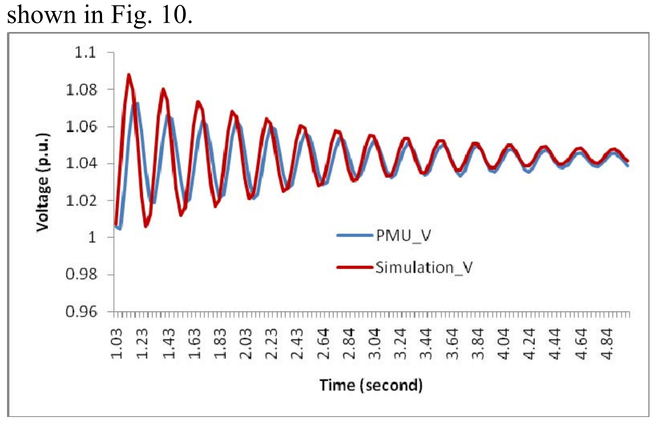


Fig. 9 Voltage response at WPP's POI.

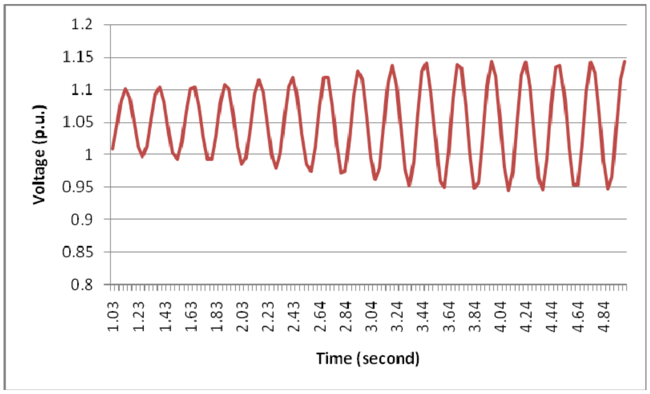


Fig. 10. Voltage response at WPP's POI at high wind output.

Based on the findings in the CREZ planning studies and the tuning of wind dynamic model to re-create the PMU recorded oscillatory response in the real events, the voltage regulator of WPP was determined to be the key cause for the oscillations. Under weak grid conditions, the closed loop voltage control would have a faster response compared to the normal grid with high SCR. The key causes for the oscillatory response captured by PMU are the combination of weak grid conditions and aggressive voltage control of the WPP. As a result, the potential solutions to mitigate these oscillations include the improvement of system strength and tuning of the WPP voltage controller. To test the system strength impact on these oscillations, the outaged 69kV line was put back in service. It is clearly shown that oscillation is effectively damped with higher SCR as shown in the purple color in Fig. 11. Tuning WPP's voltage controller also provides an improvement of oscillatory response as shown in the green color in Fig 11. An immediate mitigation plan before the ultimate solution can be implemented is to constrain the WPP's output and such effect has been demonstrated in Fig. 9 and Fig. 10.

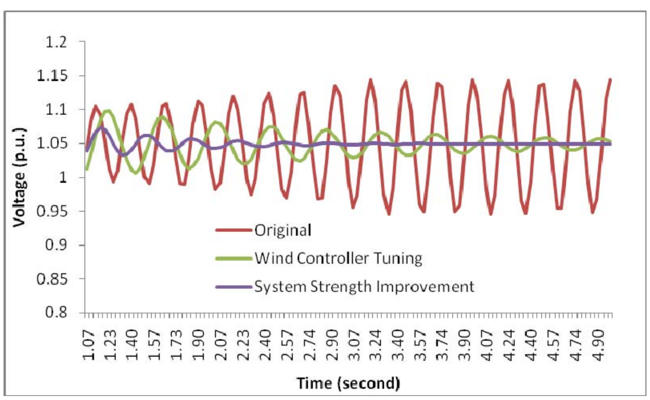


Fig. 11. Voltage response at WPP's POI. (Red: original, Green: wind voltage control tuning, Purple: High SCR)

V. CONCLUSION

This paper presents the causes and solutions for voltage stability issues associated with high penetration of wind generation in areas with a weak grid. Voltage oscillations and temporary overvoltage are not desirable in the real time operations. Oscillatory voltage response could affect the power quality to the load, and temporary overvoltage could lead to high voltage collapse depending on the duration of overvoltage.

Weak grid conditions are the primary cause for these voltage stability issues. Such weak grid conditions are due to limited synchronous generators in the local area and a significant amount of power electronic devices in the CREZ grid. Although enhancing the system strength is generally considered as a first and rational option, the uncertainties associated with installing synchronous machines in the CREZ grid under the restructured power market and lengthy implementation times for transmission projects make it likely that wind power plants (WPPs) will operate under weak grid conditions. Voltage control of WPP and SVC are shown to be feasible solutions to solve the stability issues under weak grid conditions. However, it is important to note that such tuning can result in slower voltage recovery. Proper tuning and coordination of WPPs and SVCs are crucial to provide a stable response under weak grid conditions. Actual oscillatory voltage responses of an existing WPP under weak grid conditions were captured by PMU. The post event analysis including model validation of WPP further supported all the findings as identified in the planning studies.

In an effort to resolve these voltage stability issues, WPP owners need to have a better understanding of the system and have proper controller settings to accommodate various system conditions in terms of system strength. Wind turbine manufacturers should recognize the need to have a robust controller to provide stable responses under weak grid conditions. The system operator needs to provide guidance regarding the necessary HVRT requirements for wind generation resources taking into account the system characteristics. Finally, economically justifiable projects to improve the system strength should also be identified.

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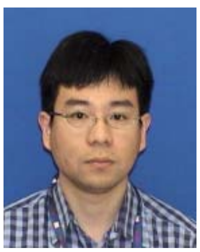
VII. Biographies



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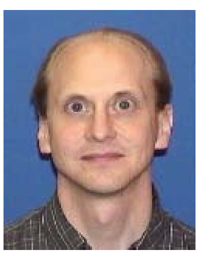
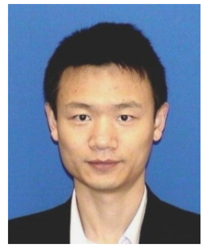


John Schmall received a BS degree in Electrical Engineering from Rose-Hulman Institute of Technology in 1991. He worked for Commonwealth Edison in Chicago, IL prior to joining ERCOT in 2005 where he is currently a Senior Planning Engineer in their Dynamic Studies group. He is a Registered Professional Engineer in the State of Illinois.

José Conto (M'87) received his BSEE from the University of Engineers, Lima, Peru in 1981 and his MSEE from the University of Tokyo, Tokyo, Japan in 1985. He stayed with CRIEPI, Japan for one year. Mr. Conto worked for Electric Research & Management (State College, PA) and for Tokyo Electric Power in Washington, D.C. prior to joining ERCOT in 2000. As Supervisor of the Dynamic Studies group within System Planning, Mr. Conto oversees power system dynamic studies, including voltage and transient stability studies with full modeling of wind plants.

John Adams received his B.S.E.E. from the University of Texas at Austin in 1982. He has 29 years of experience in power systems operations at integrated utilities and at the ERCOT ISO. He is currently a Principal Engineer managing Resource Integration at ERCOT and is a Registered Professional Engineer in the state of Texas.



Yang Zhang (M'08-SM'10) received the B.S. degree from North China Electric Power University in 1997, the M.S. degree from China Electric Power Research Institute (CEPRI) in 2001 and the Ph.D. from Washington State University in 2007. He is currently working with Electric Reliability Council of Texas (ERCOT) as a planning engineer. His research includes power system stability and control, and renewable energy integration.

Cathey Carter has been at ERCOT since 2000. After earning her BSEE at Rice University (Houston), she worked at Virginia Power in the System Protection and Transmission Planning departments. Much of her work at ERCOT has been focused on transmission planning and system integration of increasing levels of wind power.