NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Impact of Distribution-Connected Large-Scale Wind Turbines on Transmission System Stability during Large Disturbances

Preprint

Y. Zhang, A. Allen, and B.-M. Hodge
National Renewable Energy Laboratory

To be presented at the IEEE Power and Energy Society General Meeting
National Harbor, Maryland
July 27–31, 2014

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Conference Paper
NREL/CP-5D00-60910
February 2014

Contract No. DE-AC36-08GO28308

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) photo by Pat Corkery, NREL 16416, photo from SunEdison, NREL 17423, photo by Pat Corkery, NREL 16560, photo by Dennis Schroeder, NREL 17613, photo by Dean Armstrong, NREL 17436, photo by Pat Corkery, NREL 17721.

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Impact of Distribution-Connected Large-Scale Wind Turbines on Transmission System Stability during Large Disturbances

Yingchen Zhang, *Member, IEEE*, Alicia Allen, *Member, IEEE*, and Bri-Mathias Hodge, *Member, IEEE*

Abstract—**Many favorable wind resources are located in rural areas that do not have direct access to the high-voltage transmission systems. Therefore, it is practical and cost-effective to seek the installation of utility-scale, megawatt-level wind turbine generators on distribution feeders. Common study for interconnection of distributed generation typically focuses on stability impacts within the distribution feeder itself, such as the impact on feeder voltages. Efforts to investigate the impact of transmission events on distributed wind generation, as well as the impact of distributed wind generation at high penetration level on transmission stability, are much needed.**

This study models a power system with both the bulk transmission grid as well as distribution feeders. Megawatt-level wind turbine generators are connected to distribution feeders. Transmission disturbances are simulated to analyze their impacts on distributed wind generators. This study also investigates the reaction from all the distributed generation to a single transmission disturbance when the wind penetration is high, which could have a great impact on system stability.

Index Terms—**distributed generation, wind turbine generator, wind energy**

I. Introduction

WIND power installations are growing rapidly worldwide, with total global installed capacity exceeding 318 GW at the end of 2013 [1]. In the United States alone, there are now more than 60 GW of installed capacity as of the third quarter of 2013 [2]. However, the vast majority of these U.S. installations are in large wind power plants that required building additional transmission lines to reach the best resources. These required transmission build-outs come with additional costs and are often delayed because of political difficulties in the siting process. Installing megawatt-scale wind turbines on existing distribution networks can help increase the amount of energy supplied by wind without the associated transmission build-outs.

Installing such large wind turbines on distribution feeders require interconnection studies to ensure that power quality and reliability are not impacted. There have been quite a few investigations on distributed-generation's impact on distribution feeder power quality [3-4]. In previous work, the authors also examined the impact of distributed wind power on feeder bus voltages as a function of wind power production and the electrical distance of wind turbine sites from distribution substations [5]. This work focuses on the dynamic impacts of distributed wind power at the transmission level. This is particularly relevant to bulk power system operators who are interested in the impact of IEEE 1547 standards [6] at higher penetrations of distributed renewable energy. These standards specify the actions distributed generators should take to protect themselves through disconnections in response to abnormal frequency and voltage conditions. However, with large amounts of distributed generation, the simultaneous disconnection of these generators during a contingency event could exacerbate voltage or frequency issues. The impact of distributed generation at high penetrations of renewable energy cannot be neglected, thus the transmission grid may need support from the distributed resources to maintain stability after certain disturbances. Distribution-connected generators are increasing world-wide. There is quite a bit of interest in looking into the impact from a legislative point of view [7]. There has been some study on the economic and commercial impacts of interconnecting distributed generation on a transmission system [8]. Probabilistic methods have been applied to determine the security impact from distributed generation on distribution and transmission systems [9] [10]. Transmission planning considering distributed generation was also studied [11]. This study will take a fresh look at the interactions between the distributed generation and transmission system in terms of stability impacts.

Section II describes the components of the test system model. The investigation of a transmission fault's impact on distributed wind is made in Section III. The analysis on a transmission disturbance with high wind penetration is made in Section IV. Conclusions are drawn in Section V.

II. Test System Model

The purpose of this study is to investigate the stability issue on both transmission and distribution systems when megawatt-scale wind turbine generators (WTGs) are installed on

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

Y. Zhang, A. Allen, and B-M. Hodge are with are with National Renewable Energy Laboratory, Golden, CO 80401 USA.

distribution feeders. Thus, a transmission system with a distribution feeder connection needs to be modeled in a dynamic simulation environment. For this purpose, the 23-bus, 6-generator test system provided by the Power System Simulator for Engineering (PSS/E) tool [12] is utilized. The system diagram is shown in Fig. 1. This test system mainly consists of 230-kV and 500-kV lines.

This system has a total load of 3,200 MW. Since the system has such few buses, the loading and generation levels are apparently an aggregation compared with a real-world system (e.g., the Western Interconnection of North America has approximately a 100-GW load and 20,000 buses [13]). If several megawatt-scale WTGs were connected to some distribution feeders embedded in such a system, their impact on the entire grid would be essentially negligible. Therefore, the test system needs to be modified to a smaller scale to make the small amount of distributed wind generation become visible. The total load and generation in the modified system are displayed in Table 1. Part of the reactive load is served by shunt capacitors installed in the system.

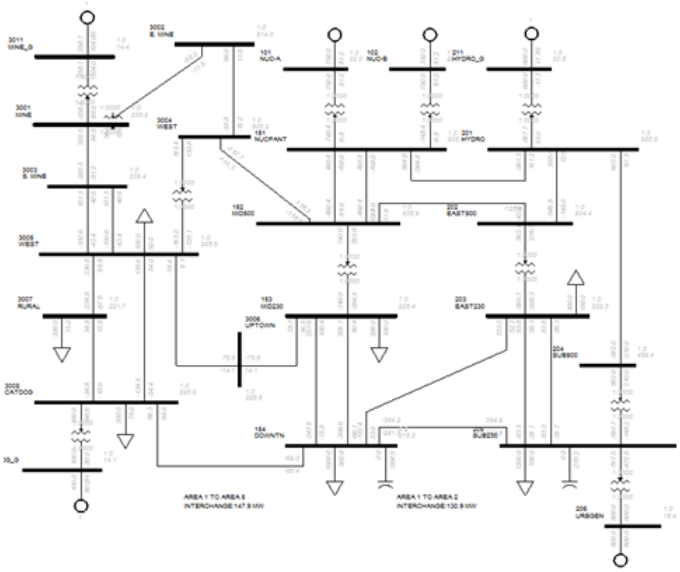

Fig. 1. PSS/E 23-bus transmission system

TABLE 1. FACT SHEET FOR THE MODIFIED 23-BUS SYSTEM

Total Load (MW)	Total Load (MVar)	Total Gen (MW)	Total Gen (MVar)
320	195	325.8	96.4

The most ideal locations to install WTGs are usually rural feeders, which typically have radial configurations [5]. The 5-bus distribution feeder shown in Fig. 2 was selected from the IEEE 16-bus distribution test system [14] to be applied to this study. The original 16-bus system contains three separate radial feeders connected at the same substation. For this study, only Feeder 1 in the 16-bus system was used. The branches and load parameters of this distribution feeder are given in Table 2. This entire distribution feeder consists of three-phase balanced lines and loads at 12.65 kV, because utility-scale WTGs are most certainly connected at three-phase buses.

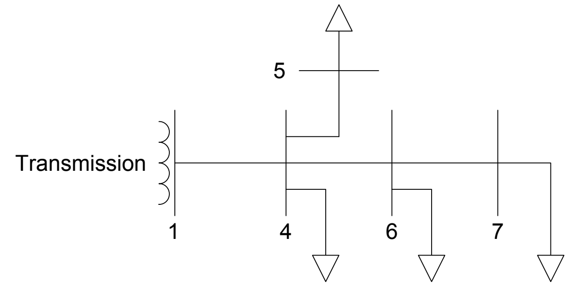

Fig. 2. Distribution feeder from IEEE 16-bus distribution system

TABLE 2. FACT SHEET FOR THE DISTRIBUTION FEEDER

Section	Section Resistance (p.u.)	Section Reactance (p.u.)	End Bus Load (MW)	End Bus Load (MVar)
1-4	0.075	0.1	2	1.6
4-5	0.08	0.11	4.6	1.5
4-6	0.09	0.18	1.5	0.4
6-7	0.04	0.04	1.5	0.5

The WTG models used are the Western Electricity Coordinating Council standard models [15] [16] for Type 4 turbines. Type 4 generators are full-power-converter generators that have power electronic controls that allow for power factor and voltage control at the terminals. This model was chosen because most new megawatt-scale wind turbines installed in the United States are either Type 3 (doubly-fed asynchronous) or Type 4 generators. Type 1 and Type 2 generators, known as fixed-speed and variable-slip WTGs, are much less common at this scale and do not have the ability to provide decoupled real and reactive power control. The chosen models, Type 3 and Type 4, represent the dynamic response of the WTG to various voltage and frequency issues experienced during disturbance, including the ability to control the magnitude and angle of current injection. The WTGs in this study are rated at 3.6 MW because typically the Type 4 WTGs are rated from 1.5 to 3.6 MW, therefore we want to push the distribution generation capacity to higher end. The WTG uses power factor controls to maintain unity power factor output so that the analysis will isolate the pure impact from the WTG power output from a mixed control scenarios.

III. TRANSMISSION DISTURBANCE IMPACTS ON DISTRIBUTED WIND

Although we are ultimately interested in seeing what impact utility-scale wind turbines installed on the distribution system will have on the transmission system, it is important to first consider the impact of the WTGs on local distribution system. In this section, we examine the impact of transmission contingencies on the WTGs installed at the distribution level. For this, we simulated the 23-bus system shown in Fig. 3 in the PSS/E environment, modified with a distributed feeder connected at the bus marked by the blue circle.

When connecting the feeder at the marked location, the load at the transmission bus was reduced to keep the total load at this bus unchanged—i.e., the new load equals the old load minus the total load of the distribution feeder. As a result, the existing generation—real power, in particular—in the test system was reduced roughly equal to the WTG output.

To simulate a transmission disturbance that has immediate effect on the distribution feeder, a fault at an adjacent bus (as marked by the red arrow in Fig. 3), was applied at 5 seconds. The fault cleared at 5.18 seconds, which might be too long in reality, but would be explicit for demonstration purposes.

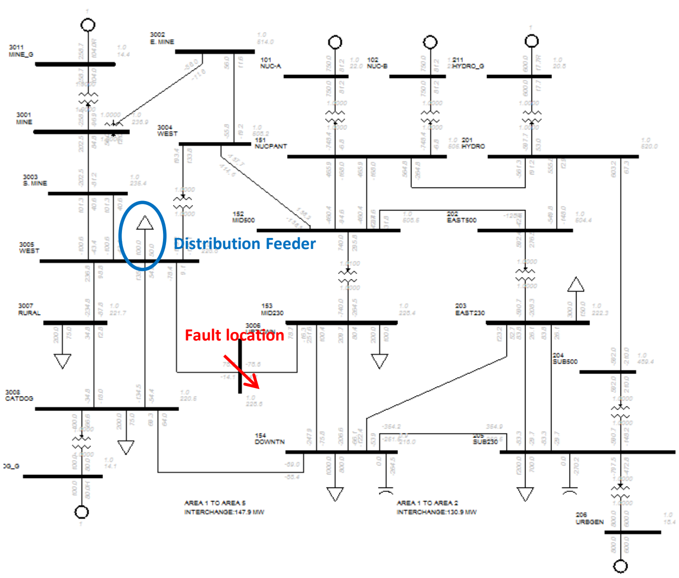

Fig. 3. Locations of the distribution feeder as well as the fault

The main goal of this practice is to determine whether the impact from a transmission contingency will be the same when a WTG is connected at different locations on the distribution feeder. First, Fig. 4 illustrates the voltages at all distribution buses when the transmission contingency occurred. The Y-axis in Fig. 4 (and in Fig. 5 and Fig. 6) is the percentage of voltage at the current time step to the initial voltage, which is kept close to 1per unit. In this case, a WTG was connected at Bus 7. It is obvious that the voltage at Bus 7 changed the most during the event, and, according to the IEEE standard 1547, the distributed generation at this bus should be disconnected after 0.16 second.

From [3], we know that when a WTG is at different buses, the feeder voltage profile will be different. In the previous simulation, the WTG happened to be installed at the bus with the most voltage change during the event. But what if a WTG is connected at another bus? Fig. 5 demonstrates the voltage at Bus 7 when a WTG was connected at different buses. The voltage at Bus 7 changed the most when the WTG was connected at the same bus. It changed the least when the WTG was connected at the substation. But what happens when a WTG is actually connected at Bus 1? Will the voltage change at Bus 1 be big enough to trip the generator? Fig. 6 demonstrates voltages at different buses when the WTG was connected at the same bus. When the WTG was connected at Bus 4, Bus 5, and Bus 6, the maximum changes were well below the tripping threshold (50%) as defined in the IEEE standard 1547. However, only the voltage at Bus 7 exceeded the threshold long enough (0.16 second) to trigger generation trip action.

WTGs installed at different locations will be impacted differently by transmission disturbances. In this simulation, the worst case was when a WTG was installed at Bus 7.

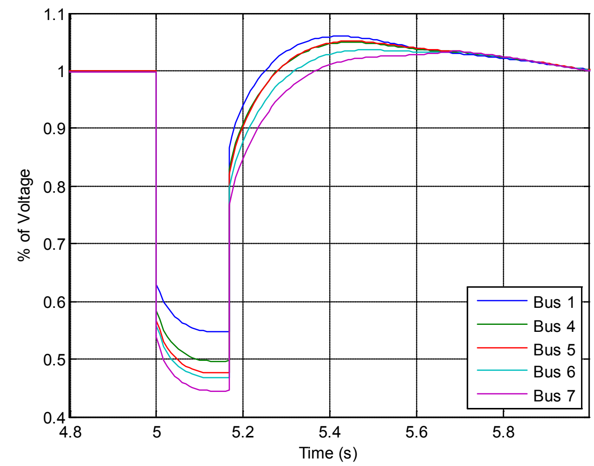

Fig. 4. Voltages at different buses when a WTG was connected at Bus 7

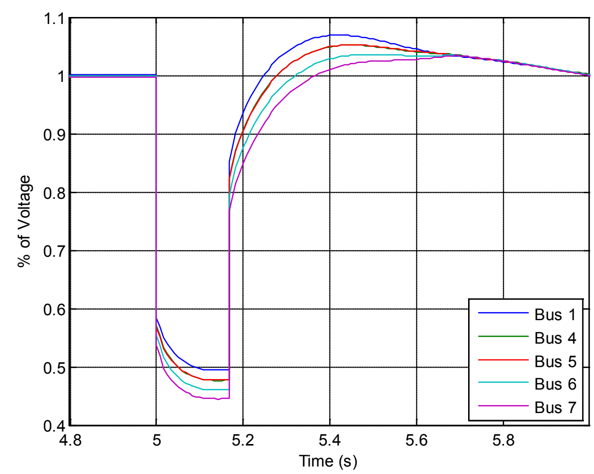

Fig. 5. Voltages at Bus 7 when a WTG was connected at different buses

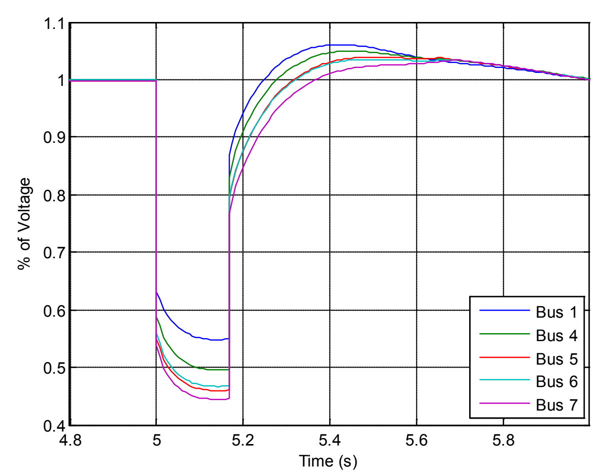

Fig. 6. Voltages at buses when a WTG was connected at the very same bus

IV. TRANSMISSION IMPACT FROM DISTRIBUTED WIND

Having shown the local distribution system impacts associated with distributed utility-scale WTGs during a contingency event, we next examine how these changes will propagate back up in the bulk power system. Obviously, at very small distributed wind power penetrations the impact on the transmission system will be negligible. For this reason, we produced a scenario in which approximately 8% of the power is supplied by distributed WTGs and examined how various voltage and frequency issues experienced at the WTG can impact the transmission system depending on the WTG response.

The same feeder that was modeled in Section III was duplicated and connected to all the load buses in the 23-bus system, as shown by the blue circles in Fig. 7. Each feeder had a 3.6-MW WTG, so the total wind generation in this scenario was 25.2 MW. Each WTG was connected at Bus 7 of each feeder, so that when a transmission contingency occurred, they were most likely to be affected.

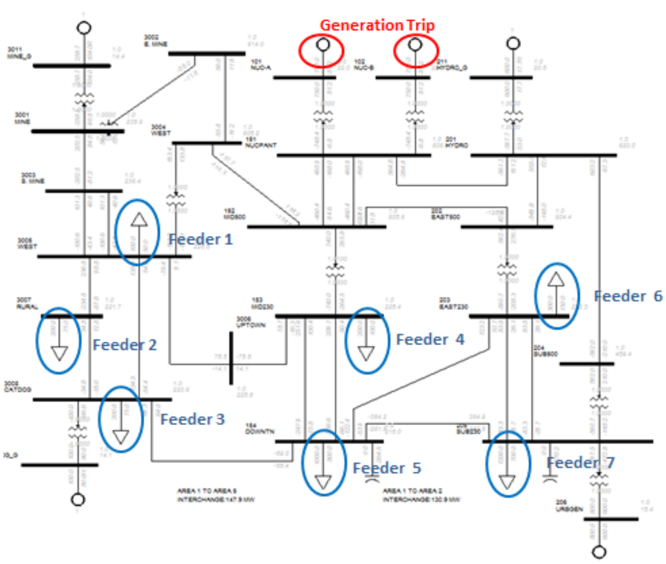

Fig. 7. 8% of wind penetration at distribution level

Section III concentrated on studying the bus voltage change under disturbances. However, voltage change is a localized problem when propagated from distributed generation to the transmission system; distributed generation at other locations will not have a great impact on the event. The aggregated effect from all the distributed wind will be of concern with regard to the system frequency. The current IEEE standard 1547 has rather big security margins in terms of under-frequency tripping; however, if a big event happens, such as the N-2 generation tripping as described in Fig. 7, the system frequency may fall below 59.8 and remain below for a certain period of time. Fig. 8 illustrates the frequency at all the distribution feeder connection points when the large generation tripping event happened. All distributed wind stayed online during the event.

If the distributed wind follows the standard and trips offline when the system frequency reaches 59.8 and stays there for more than 0.16 second, the endangered system is further pushed down, as displayed in Fig. 9. This could lead to under-frequency load-shedding thresholds and trigger a series of severe events. It is worth noting that in this system the electromechanical wave propagated fairly fast and thus the time delay between each bus was small. Thus the WTGs roughly tripped simultaneously. Compare the frequency trace in Fig. 9 with in Fig. 8, the portion above 59.8 Hz are identical. Below 59.8 Hz, the frequency slope in Fig. 9 is much steeper than in Fig. 8, plus the lowest frequency is much smaller in Fig. 9 than in Fig. 8.

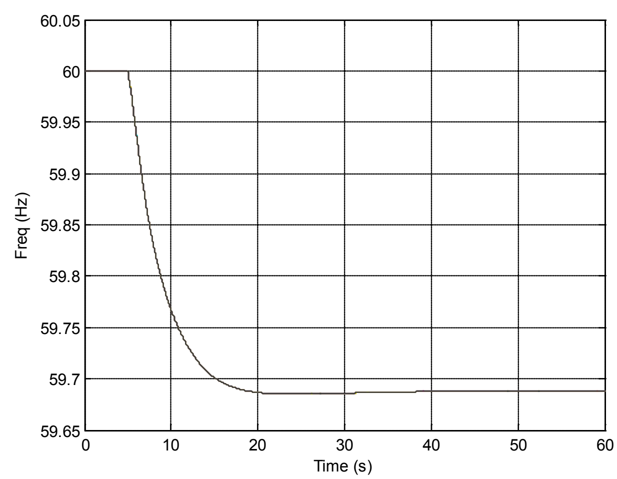

Fig. 8. System frequency response when distributed WTGs rode through a contingency

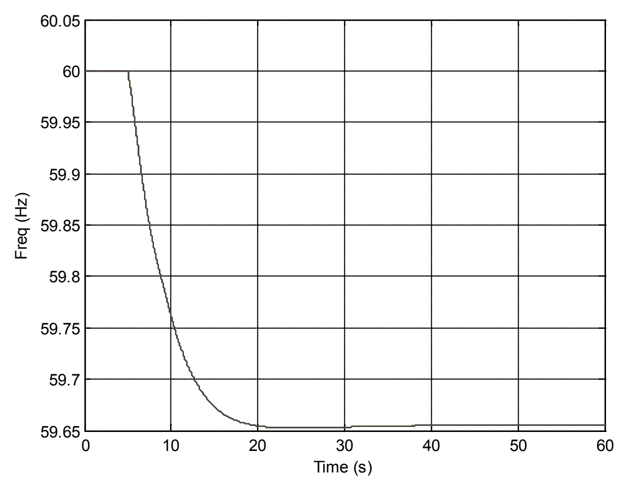

Fig. 9. System frequency response when distributed WTGs tripped offline during a contingency

In such a small system dropping two major generation units can cause the system to be non-recoverable. Fig. 8 shows that when the event happens, there is not enough frequency response to bring the system frequency close to the pre-fault conditions. Operating under frequency could lead to synchronous machines unstable and eventually causing system cascading failure. However in reality, a large interconnected system will have sufficient frequency response from inertias, primary and secondary frequency reserves to bring the system frequency back to nominal after severe N-1 or N-2 contingencies.

Fig. 10 shows a real-time frequency event occurs in Western Interconnection. The data is collected by a real-time measurement device in NREL campus at a distribution circuit. During the event, the system frequency dropped down as low as 59.7Hz but then stabilized approximately to 59.8Hz due to the reaction from inertias and primary frequency response. It fully recovered to 60Hz after roughly 20minute due to the response from secondary and tertiary reserves. So we can conclude that the problems discovered in Fig. 9 will be definitely possible given certain system conditions.

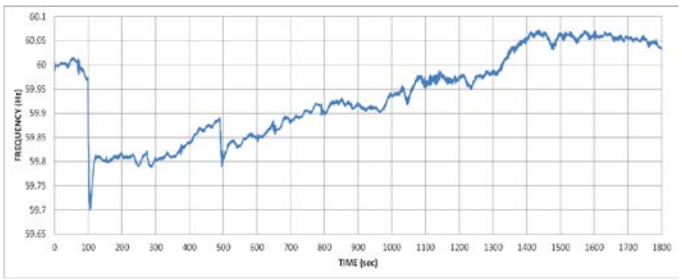

Fig. 10. Example of Real Grid Frequency Response After a disturbance

In a case like this, if the penetration of distributed generations in the system is high, and they starting to response to frequency as specified in IEEE standard 1547, the event will definitely be exacerbated.

V. Conclusion and Future Work

In this work, we examined the dynamic impacts of distributed utility-scale wind power during contingency events on both the distribution system and the transmission system. A transmission disturbance can propagate into distribution feeders and cause distributed, megawatt-level WTGs to trip offline. The interconnection location within the feeder matters because it decides the severity of the impact from the transmission disturbance. When the distributed wind reaches higher penetration levels, the aggregate effect of their response to a transmission contingency can lead to more severe system conditions.

This work will be the first step to investigate the high penetration of distribution-connected wind power's impact on both distribution and transmission stability. Future work includes determining the impact of the distributed generation providing low voltage and frequency ride through, and how this will impact transmission system. It also includes studying the combined distributed generation with controllers such as capacitors and batteries to support transmission system should disturbance occurs. Furthermore, the potential islanding issue with high penetration of distributed wind will be examined.

VI. Acknowledgment

The authors gratefully acknowledge Mr. Dave Bertagnolli, Mr. Jonathan Black, and Mr. William Henson from ISO New England for their involvement in the technical discussions for this project. The authors are greatly appreciative of the data provided by Dr. Vahan Gevorgian from NREL to illustrate the real system event shown in Fig. 10.

VII. References

[1] Global Wind Energy Council, "Global wind statistics 2013," Brussels, Belgium, May 2014.

[2] U.S. Energy Information Administration, "Electric Power Monthly," Washington, D.C., 2013.

[3] K. P. Schneider, Y. Chen, D. P. Chassin, R. G. Pratt, D. W. Engel, and S. Thompson, *Modern grid initiative: Distribution taxonomy final report*: Pacific Northwest National Laboratory, 2008.

[4] W. U. Consulting, "Distributed Wind Generation Study for Northeast Colorado," 2005.

[5] A. Allen, Y. Zhang, and B.-M. Hodge, "Impact of increasing distributed wind power and wind turbine siting on rural distribution feeder voltage profiles," in *Int. Workshop on Large-Scale Integration of Wind Power into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants*, London, UK, 2013.

[6] IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems

[7] A. Moreno-Munoz, J. De La Rosa, M. Lopez, A. Gil De Castro, "Grid interconnection of distributed generation: The Spanish normative", in *Int. Conf. on Clean Electrical Power*, Capri, Italy, 2009.

[8] L. Dale, "Distributed generation and transmission", in *IEEE PES Winter Meeting, New York*, USA, 2002.

[9] R. Allan, P. Djapic, G. Strbac "Assessing the Contribution of Distributed Generation to System Security", *in Int. Conf. on Probablistic Methods Applied to Power Systems*, Stockholm, Sweden, 2006.

[10] D. Newman, B. Carreras, M. Kirchner, I. Dobson, "The Impact of Distributed Generation on Power Transmission Grid Dynamics", In *the 44th Hawaii International Conf. on System Sciences,* Kauai, USA, 2011.

[11] J. Zhao, J. Foster, Z. Dong, K. Wong, "Flexible Transmission Network Planning Considering Distributed Generation Impacts", in *IEEE Trans. Power Sys.,* vol. 26, no. 3, pp. 1,434-1,443, Aug. 2011.

[12] PSS/E operation manual, Siemens PTI, 2005.

[13] TSS base cases, www.wecc.biz

[14] S. Civanlar, J. Grainger, H. Yin, and S. Lee, "Distribution feeder reconfiguration for loss reduction," in *IEEE Trans. Power Del.*, vol. 3, no. 3, pp. 1,217–1,223, July 1988.

[15] E. Muljadi and A. Ellis, "Final project report: WECC wind generator development," Prepared by National Renewable Energy Laboratory, University of California–California Institute for Energy and Environment, March 2010.

[16] W. W. G. M. Group, "WECC Wind Power Plant Power Flow Modeling Guide," Western Electricity Coordinating Council 2008.

VIII. Biographies

Yingchen (YC) Zhang received his B.S. from Tianjin University, Tianjin, China, in 2003, and his Ph.D. degree from Virginia Polytechnic Institute and State University, Blacksburg, in 2010. He is currently with the National Renewable Energy Laboratory. His research interests include power system stability with large-scale integration of renewable energies, power system wide-area monitoring, and PMU applications for renewable integrations. Dr. Zhang previously worked for the California Independent System Operator developing and implementing steady-state and dynamic analysis tools to improve power system situational awareness.

Alicia J. Allen received the B.S., M.S. and Ph.D. degrees from The Department of Electrical and Computer Engineering at The University of Texas at Austin. She is currently at the National Renewable Energy Laboratory, Golden, CO, USA. Her research interests include distributed wind and solar, distribution system modeling, power quality, system protection and synchronized phasor measurements.

Bri-Mathias Hodge is a senior engineer in the Transmission and Grid Integration group at NREL. He has experience in dealing with a number of different grid integration issues, including: wind and solar power forecasting, distributed wind power, power systems modeling, and the impacts of electric vehicles. He has a Ph.D. from Purdue University.