Impact of Wind Turbine Control Strategies on Voltage Performance

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***Abstract*—This study examines the 2013 Irish electricity network and its ability to accommodate large levels of wind generation while maintaining appropriate voltage levels across the system. The network provides a fully functional test system that is suitable for large scale power flow and dynamic simulations. In the next decade, wind generation is expected to consistute large percentage of the country's new renewable generation portfolio due to the rich wind resource available in Ireland. As wind penetration grows, larger levels of conventional generation will be displaced and there will be an increased need to provide both voltage and frequency stability support. Many wind turbines have the capability to perform certain mitigation tasks such as reactive power support; in particular, this study will examine the wind turbine's ability to provide terminal voltage control in order to improve the system's voltage performance. This will be achieved using steady-state power flow analysis with historical loading patterns while taking into account the inherent variability of the wind resource. It will show that increased application of terminal voltage control strategies will allow for more robust voltages both locally and systemically.**

***Index Terms*—Wind generation, time-series, power flow, wind turbine, doubly-fed induction generator, voltage.**

I. Introduction

THIS paper aims to provide a realistic study that assesses the impact of a large penetration of wind generation on an electricity network, and in particular, the impact on the system's voltage performance during normal operating conditions. The predominant technology used in wind installations today is the doubly-fed induction generator (DFIG). DFIGs have the capability to control their reactive power production and depending on the controller settings, they can control the reactive power production at a wind farm to a specific power factor (PF) or to a terminal voltage value [1]–[3].

This is an inherent ability in the DFIG due to the power electronic components used in their design. The goal of this study was to utilize the built-in control features of the DFIG in an effort to increase voltage performance across an electricity network. To assess this impact, the level and type of control applied by the DFIGs were varied in the power flow simulations. The level at which the wind farm is connected was also studied; farms connected at the distribution level will often control reactive power production around a fixed power factor, while transmission level connected farms will attempt to control reactive power at a terminal voltage value.

Previous studies have used a stochastic approach or used meteorological data to generate wind speeds for time-series power flow simulations [4]–[7]; essentially most studies are completed using random wind speeds along with loading data in order to determine the system response. This study, however, uses an extensive set of corresponding historical data for wind speeds and loading conditions and generates a set of time-series power flows using fixed power factor controls and terminal voltage controls at the DFIG farms in the system. These power flows provide insight into the steady-state voltage performance of the electricity network and the impact of control strategy on the system's steady-state performance.

This study was completed on the 2013 Republic of Ireland (ROI) electricity network. The 2013 system was used, as this was the most complete model available regarding future transmission reinforcements. The ROI electricity network is well suited for large scale studies; its relatively compact size enables steady-state and dynamic studies to be completed on the full network model.

In Ireland, where wind generation and other sustainable resources will provide a significant percentage of the power produced in the country, 40% by 2020 [8], voltage performance in the rural areas of the network will become an increasingly important issue. The west of Ireland has a tremendous wind resource and most of the wind generation in the country is located along the west coast. However, the western region of the country is sparsely populated and does not contain the major load centers of the country. Most of the conventional generation along with the majority of the load, is located in the eastern half of the country, near Dublin. This presents a problem when more and more wind generation is brought online in the rural regions of the network; there is often a deficit of dynamic reactive generation and voltage performance suffers as a result. This will not only be an issue in Ireland but in many systems where new wind generation will be connected in regions of low population density, i.e. the mid-western United States.

This paper describes the methodology and results of a set of time-series power flow simulations and will be divided as follows: Section II will describe the methodology of the study process, Section III will present the results of the study, and Section IV is a summary of the study.

II. Study Methodology

This study used a detailed time-series power flow analysis in order to draw conclusions about the ROI electricity network's

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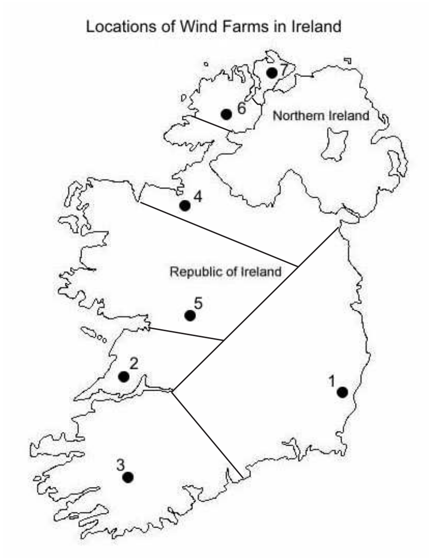

Fig. 1. Locations of the seven wind farms used in this study and the corresponding wind region divisions. Existing and future farms were mapped back to the nearest location.

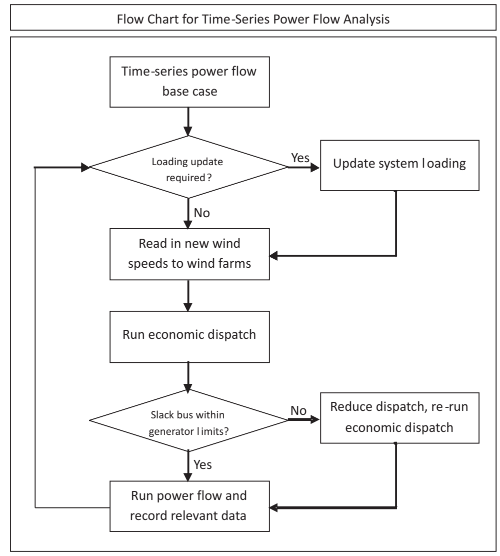

Fig. 2. Methodology used for time-series power flow analysis for one-week (672 power flows at 15-minute intervals) in SNV and WP loading scenarios.

steady state voltage performance. This was achieved using the following methodology:

A. Wind Speed and Loading Data

The wind speed and loading data used for this study were based on data collected from 2004. The wind speed data was collected in 15 minute intervals for the entire year across seven different farms. These farms can be seen in Fig. 1 and were used to divide the country into seven different regions. These seven regions were referred to as WR 1, WR 2, etc., and provided the wind speeds for the rest of the wind farms. Dublin is located in WR 1 and contains a majority of the country's load and conventional generation. Existing wind generation is interconnected predominately in WR 3, WR 4, WR 6 and WR 7.

In this study, new wind generation was connected as follows; using the resource analysis from the All-Island Grid Study [9], new wind farms were added to the system and placed in the appropriate wind region. They were interconnected at the 110 kV bus designated in the All-Island Grid Study, and new wind speeds were fed into each individual farm based on its wind region. This allowed the power production from each wind farm to be based on its historical regional wind characteristics rather than from random wind speeds. Since the load data was from 2004, it was scaled to match the expected loading values for 2013 [10].

B. Power Flow Analysis and Automation

All of the power flow simulations were completed in PSS/E 30.3.2, from Siemens PTI, and the automated process for completing the power flows was written using the Python script language. The overall methodology used in the automation process is described in Fig. 2. By creating an automated process for the power flow, a large time-series analysis was completed where, rather than starting each power flow from a flat voltage set point, the voltage values from the previous power flow run were used. This allowed for the control implementation to be consistent from one run to the next and a more realistic and time dependent analysis to be completed.

C. Economic Dispatch

Economic dispatch needed to be included in order to achieve a balance between the variable wind generation, the conventional generation, and the system loading. This was also essential since wind generation is given priority in Ireland; wind generation is currently not curtailed and as a result, an economic dispatch was run using the automated process in PSS/E. The generation dispatch was based on the heat rate curves of the conventional generating units in the ROI system, while the merit order of the machines was based on fuel prices [10]. As such, machines with lower prices were the first to ramp up and those with higher prices were the first to ramp down. By controlling the conventional generation units in the system, the appropriate generation-load balance was maintained.

D. Loading Profiles and System Characteristics

Loading data was used from 2004 and represented two distinct loading periods: the Summer Night Valley (SNV) and the Winter Peak (WP). The SNV and WP represent the two operating points of the system loading when the system is the most severely stressed. These points correspond to a single 15 minute interval, and as such, the time-series power flows were built with one half week along each side of these two points. This means, that the SNV and WP correspond with the mid-week point in each run.

In the 2013 ROI case, the SNV loading was 2268 MW, and is when system loading is at a minimum. The WP is the interval when the ROI network sees its maximum load. At the WP, the loading is 6211 MW. Using these two loading periods, one week time series power flows were run using the two loading values to scale the load for each set of simulations.

The base case, i.e. the case before any new wind generation was added consisted of 664 MW of existing wind generation. This was a combination of DFIG and fixed speed generator (FSG) wind turbines, all operated at a fixed power factor; FSGs were compensated with capacitor banks to achieve a 0.95 inductive power factor. An additional 1222 MW of wind generation was added to the ROI system, bringing the total penetration in each loading scenario to a capacity 1886 MW of wind generation capacity or a 33.35% penetration level in the SNV and a 21.95% penetration level in the WP.

By observing the voltage performance within the seven wind regions, (Fig. 1), a series of probability density functions (PDF) were generated for several buses within these regions using different control strategies in the DFIG wind turbines. The loading scenarios and the control strategy implemented for each case can be seen in Table I.

TABLE I
CONTROL DISTRIBUTION IN CASES

Case	Loading Scenario	Terminal Voltage Controlled DFIGs	Fixed P.F. Wind Turbines
A	SNV	50%	50%
B	SNV	80%	20% (existing FSGs)
C	WP	50%	50%
D	WP	80%	20% (existing FSGs)

Using these four cases, critical bus voltages were recorded in each of the seven wind regions. Along with the bus voltages, the sum of the active and reactive power produced/consumed in each of the wind regions was also recorded. This allowed for a comparison of voltage performance in relation to the reactive capabilities of a region. This will be further discussed in the results section.

III. RESULTS

This section will provide a detailed results and analysis of each of the four study cases. It will also examine the impact of control on the distribution level and any effect it has on the transmission system.

A. Cases A and B: Summer Night Valley

Cases A and B both occur during the SNV, and represent a worst case analysis. At the peak, wind accounted for 58% of the generation in the SNV. Fig. 3 is a PDF of the voltage distribution at a 110kV bus in WR 4 for Cases A and B. This bus is located in a rural region, where there is little dynamic reactive support from conventional generation and control must be maintained locally.

In Case A, 50% of the turbines were operated at a fixed power factor and the remaining 50% of the were operated using the terminal voltage control capability of the DFIG. As observed from Fig. 3, in Case A the bus operates over a range of 0.977 pu to 1.015 pu, and does not have a dominant voltage, i.e. the voltage is spread across the range of operating points.

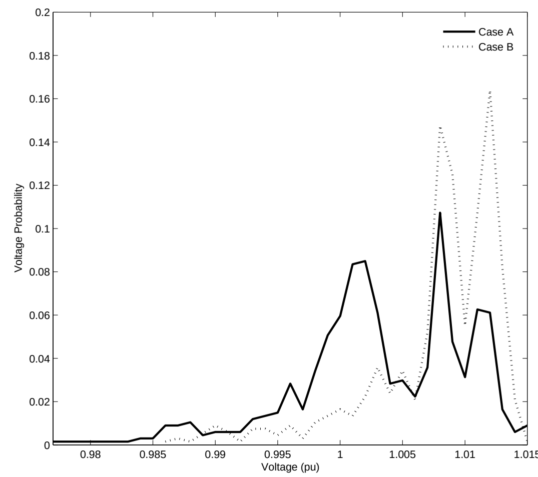

Fig. 3. Voltage PDF of rurally located 110kV bus in WR 4 for both Cases A and B. The PDF for Case B is shifted and contains more voltages operating at higher levels.

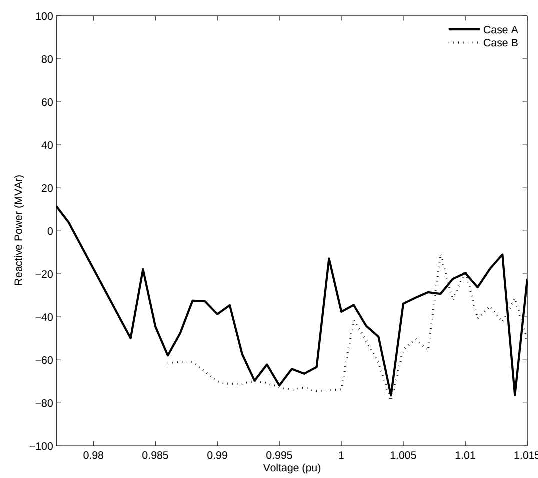

Fig. 4. Reactive power production of the wind turbines in Case A and B. Case B is more random indicating less dependence on wind power.

TABLE II
SNV VOLTAGE PROBABILITY

Case	Voltage Range (pu)	Probability
WR 4 Case A	1.005 $\leq$ V$_{bus}$ $\leq$1.015	0.42
WR 4 Case B	1.005 $\leq$ V$_{bus}$ $\leq$1.015	0.55

Along with the voltage PDF from Case A the results for the same bus in Case B can be seen in the same plot. In Case B all the DFIGs added to the ROI system were operated using terminal voltage control and the minimum voltage observed at the bus is now 0.986 pu while the voltage density is concentrated at values above 1.005 pu. In comparison to Case A, the voltage is more tightly controlled and allows for improved system operation. Along with controlling the voltage between a smaller range of values, the overall voltage is shifted with a larger probability of the voltages occurring at higher values. This shift in probability is seen in Table II.

Fig. 4 shows the trends of the reactive power for each of the cases as well. From Fig. 4 there is less of an indicative

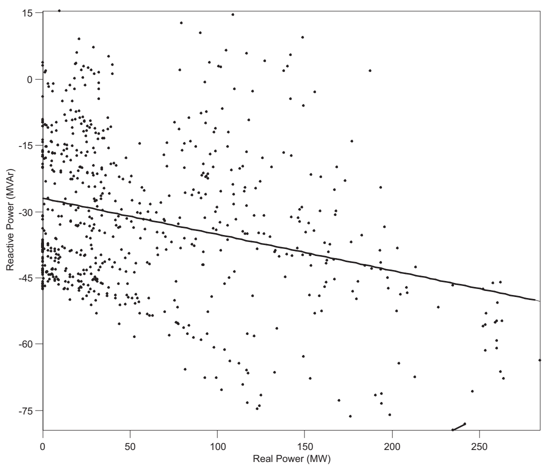

Fig. 5. The real power production from wind farms in WR 4 versus the reactive power production/consumption from the farms in the region for Case A.

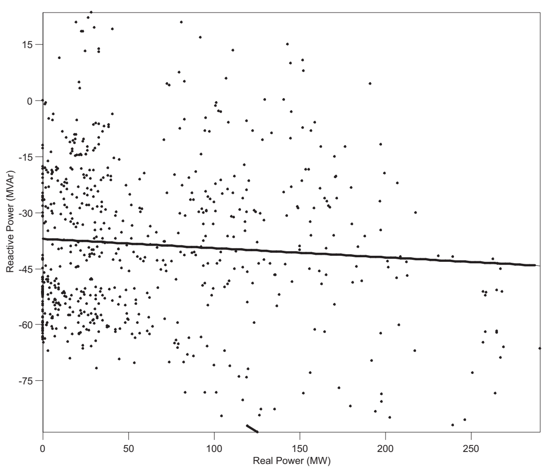

Fig. 6. The same P vs. Q plot except for Case B. Less slope in the linear regression indicates less dependence on real power.

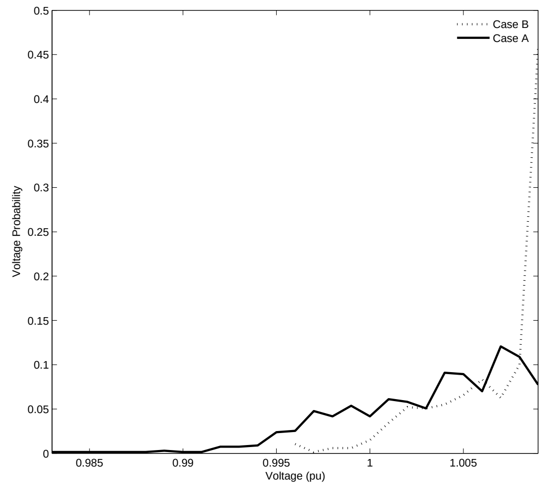

Fig. 7. Probability density function of the voltage of a 110kV bus in WR 1 plotted for Cases A and B. Case B shows a higher probability of increased voltages.

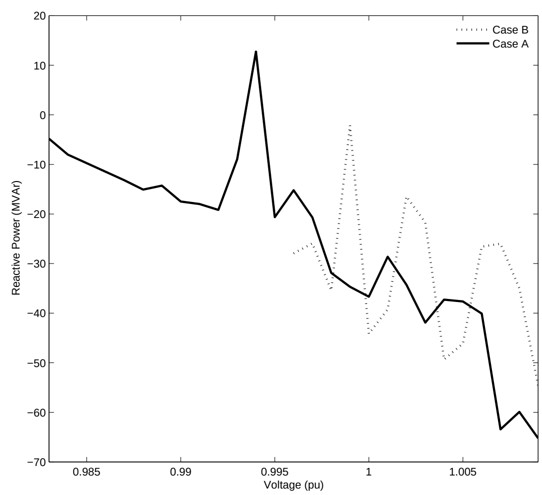

Fig. 8. The reactive power production for Cases A and B. Lower voltages are eliminated in Case B and the reactive power is not driven by wind power production.

relationship between voltage and reactive power production. However, there is a very pronounced relationship between reactive power and real power within WR 4 that is not seen clearly in the plots. Since the wind turbines are evenly distributed between fixed PF control and terminal voltage control in Case A, as the real power increases, the consumption of reactive power increases. Due to the improved voltage control, the reactive power production in Case B does not follow the same trend seen in Case A. Rather it is increasingly random and is trying to control the voltage rather than reacting to it.

This coupling between real and reactive power is demonstrated in Fig. 5 and 6. Here, the power generated by the wind turbines in WR 4 is plotted against the reactive power produced, these points are essentially the operating points of the wind turbine complex power in the region. As observed from Fig. 5, the reactive power responds to the wind production in Case A, meaning the real power is in proportion to the reactive power in the system. This relationship is expected since half of the turbines in the region are operating at a fixed inductive power factor and as such linear regression of the operating points demonstrates a negative slope.

In Fig. 6 the operating points of Case B are plotted. Here the slope of the linear regression is significantly decreased in comparison to Fig. 5. This indicates that the real power and reactive power have become more decoupled, and that the voltage is the predominant factor in determining the reactive power production in the region. Once again, this relationship is expected since more of the turbines are operating using terminal voltage control. This demonstrates the significant impact that a particular control strategy can have on the reactive power production and voltage performance in a region.

The bus in Fig. 7 and Fig. 8 was located in an urban area near large levels of conventional generation where dynamic reactive support was present, WR 1. Fig. 7 shows the voltage PDF obtained for the bus. Similar to Fig. 3, the PDF of Case B shows an improvement in the voltage performance of the bus. In Case A, the bus voltage ranged from 0.983 pu to 1.009 pu, without a dominant voltage value. In Case B, the operating range is reduced from 0.996 pu to 1.009 pu, with the majority of the voltages concentrated at 1.009 pu. This value is very near the control set point of 1.01 pu and demonstrates the impact that control strategy can have on bus voltage. This improvement can be seen in the probability shifts in Table III.

TABLE III
SNV VOLTAGE PROBABILITY

Case	Voltage Range (pu)	Probability
WR 1 Case A	$1.005 \leq V_{bus} \leq 1.009$	0.46
WR 1 Case B	$1.005 \leq V_{bus} \leq 1.009$	0.76

Fig. 8 contains the plots of the reactive power production for the wind farms in WR 1. Here there is a pronounced trend in reactive power in Case A, as the voltage increases the reactive power consumption in the region increases. Essentially, the conventional generation units are providing increased reactive support to keep bus voltages at appropriate values. In Case B, the relationship between voltage and reactive power is not as prevalent. This is due to the decoupling of real and reactive power in the wind turbines and as a result in Case A, the reactive power responds to the voltage, while in Case B, the reactive power is attempting to control the voltage.

B. Cases C and D: Winter Peak

The WP scenario has significantly higher loading in comparison to the SNV scenario that results in an increased presence of conventional generation units. At the peak in the WP, wind accounted for only 40% of the generation. This allows for increased dynamic reactive power compensation and voltages across the system are more robust. As in the SNV scenario, PDFs were generated for buses in both in rural and urban locations.

Fig. 9 represents the same bus in WR 4 from the SNV scenario. Here the PDF from Cases C and D are plotted against each other. The voltage ranges from 1.025 pu to 1.061 pu in Case C. The voltages improve in Case D, where more of the turbines are operated using terminal voltage control. The voltage range shifts to include higher operating points: from 1.028 pu to 1.066 pu. As in the previous cases, improved control capability allows for improved voltage probability.

Fig. 10 shows the voltages for the same bus near Dublin in WR 1, and confirms the trends seen in the SNV scenario. In comparison to Cases A and B the voltages are greatly improved, however this can largely be attributed to the increased levels of conventional generation. As in the previous cases, allowing for increased flexibility in the control scheme of the DFIG turbines improves the voltage performance of the buses in urban locations without sacrificing power production. The range of voltages for Case C is from 1.036 pu to 1.052 pu, while the range in Case D is from 1.043 pu to 1.055 pu. Along with increasing the minimum voltage, Case D is able to control the voltage at nearly 1.05 pu for a majority of the time. As with the SNV cases, the probabilities associated with each case in the WP can be seen in Table IV

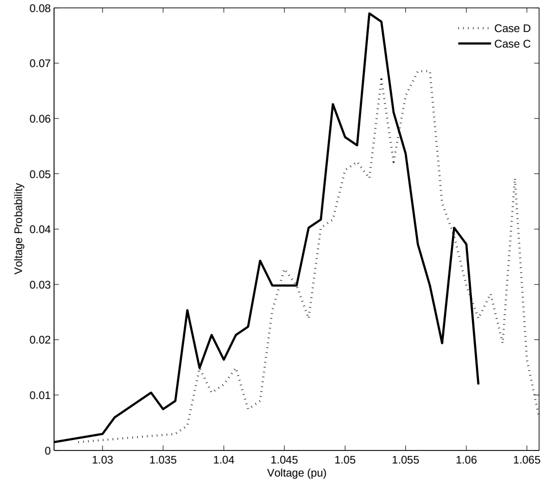

Fig. 9. The voltage PDF of the rurally located bus in WR 4 plotted for the two control cases. Voltages shift toward higher values as more terminal voltage control is enabled.

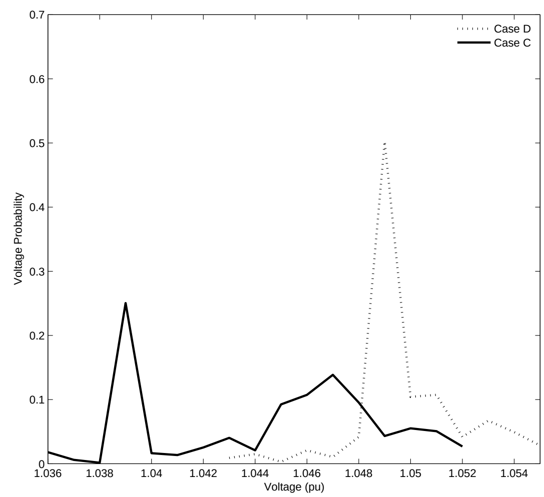

Fig. 10. The voltage PDF of a bus near Dublin for Cases C and D in WR 1. The probability of higher voltages increases in Case D, and show that a majority of the voltages lie at 1.049 pu.

TABLE IV
WP VOLTAGE PROBABILITY

Case	Voltage Range (pu)	Probability
WR 4 Case C	$1.050 \leq V_{bus} \leq 1.065$	0.27
WR 4 Case D	$1.050 \leq V_{bus} \leq 1.065$	0.80
WR 1 Case C	$1.048 \leq V_{bus} \leq 1.052$	0.56
WR 1 Case D	$1.048 \leq V_{bus} \leq 1.052$	0.74

C. Impact of Distribution Level Control

In Ireland wind farms are being interconnected at both distribution level, 6.6 kV to 38 kV, and transmission level, 110 kV and above. Farms as large as 30 MW are connected in the distribution level network and operate at a fixed PF. In this section, the impact of changing the operation of the distribution level connected wind farm from fixed PF to terminal voltage control was analyzed. In the ROI network, there is approximately 200 MW of distribution level connected

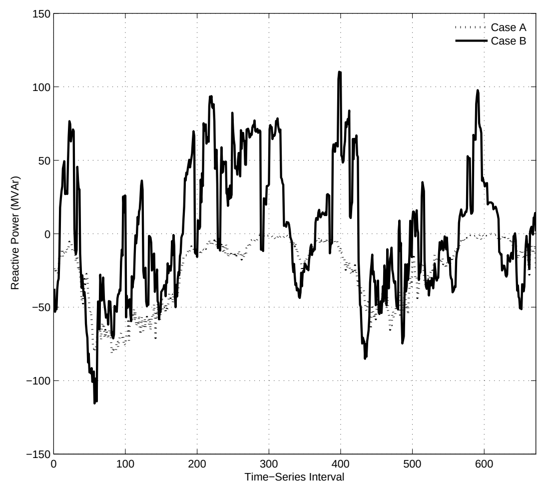

Fig. 11. The change in reactive power consumption over a one week period in the SNV between Case A and Case B.

TABLE V
AVERAGE VOLTAGE PERFORMANCE OF DISTRIBUTION LEVEL CONNECTED WIND FARMS

	Average Voltage (pu)		
Bus (kV)	**Case A**	**Case B**	**Improvement**
A (20kV)	1.0143	1.0270	0.0127
B (20kV)	1.0132	1.0267	0.0135
C (20kV)	1.0114	1.0100	1.0100 target
D (20kV)	0.9793	1.0000	0.0207
E (20kV)	1.0048	1.0090	0.0042
F (6.6kV)	1.0269	1.0328	0.0059
G (20kV)	1.0092	1.0090	1.0090 target
H (20kV)	1.0035	1.0090	0.0055

wind generation all operated at a fixed PF.

For these simulations, the terminal voltage control was applied at the next highest voltage buses connected to the distribution level wind farm. The plot in Fig. 11 shows the change in reactive power at the distribution connected buses. As seen in the figure, the change in reactive power is quite significant.

In Case A, the average reactive power production from the distribution level connected wind farms is -25 MVAr. This consumption of reactive power is expected since the wind farms are operating at an inductive power factor is proportional to the real power production. In Case B, the net reactive power production is 1.68 MVAr. The reactive power moves from net consumption to production. The reactive power from the DFIGs provide support based on the system's current conditions and can now provide positive reactive power to increase the voltage values in the system. Table V shows the average voltage increase for the next highest voltage bus connected to the distribution level farm as a result of the increased reactive support.

Table V demonstrates how influential voltage can be at the distribution level. From Fig. 11, there is an additional 26.68 MVAr average available and this allows for either improved voltages at the bus (buses A, B, D, E, F, and H) or improved control to the target voltage (buses C and G). This is significant since by achieving higher voltages at the lower voltage levels in the network, the voltages at the transmission level can be positively impacted.

IV. CONCLUSION

This paper provides an in-depth voltage analysis for the ROI network. In comparing the two control strategies available in most DFIG machines today there is a clear positive impact in providing increased voltage control from both transmission level and distribution level connected wind farms in the system. In low load, high wind situations, where there is a lack of conventional generation and additional reactive power is necessary to maintain voltages at appropriate levels, DFIGs with terminal voltage control can be used as mitigation devices.

The power electronics in DFIG wind turbines allow for the implementation of reactive power control and should be utilized when necessary to improve the voltage performance of electricity networks. This is especially true in regards to the distribution level. By controlling the larger distribution level connected wind farms, voltage performance can be improved for voltages at the lower levels in the system. This will allow for increased performance at the higher voltage levels and improved performance across the system. Eventually, by optimizing their control strategies, a system operator can incorporate larger penetrations of wind generation without sacrificing the voltage performance of their system.

As well as demonstrating the impact of voltage control, this study was able to realistically assess the performance of the ROI network by incorporating historical data, i.e. wind speeds and loading patterns. This methodology accounted for the variability of the wind and accurately demonstrated the influence of control in mitigating negative voltage performance. A system operator can provide increased reactive support and improve voltage performance without sacrificing the viability of the wind resource. That is, by improving the reactive support locally, the system operator can improve voltages across the system and is not required to site wind farms in locations that may have increased voltage stability but a less desirable wind resource.

This work provides a foundation for examining the small-signal stability of the ROI system in future studies. In particular, the viability of strategically locating wind generation within a common resource as a means of improving voltage stability. By identifying particular modes of influence and examining the participation factors of the DFIG wind turbines, it is hoped that buses can be identified as candidates to accommodate large levels of wind generation.

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