Impact of Increasing Distributed Wind Power and Wind Turbine Siting on Rural Distribution Feeder Voltage Profiles

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Impact of Increasing Distributed Wind Power and Wind Turbine Siting on Rural Distribution Feeder Voltage Profiles

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Abstract—**Many favorable wind energy resources in North America are located in remote locations without direct access to the transmission grid. Building transmission lines to connect remotely-located wind power plants to large load centers has become a barrier to increasing wind power penetration in North America. By connecting utility-sized megawatt-scale wind turbines to the distribution system, wind power supplied to consumers could be increased greatly. However, the impact of including megawatt-scale wind turbines on distribution feeders needs to be studied. The work presented here examined the impact that siting and power output of megawatt-scale wind turbines have on distribution feeder voltage. Many possible siting locations and wind power output levels for wind turbines connected to the distribution system were studied. This is the start of work to present a general guide to megawatt-scale wind turbine impact on the distribution feeder and finding the amount of wind power that can be added without adversely impacting the distribution feeder operation, reliability, and power quality. Preliminary results indicate that inclusion of wind turbines near heavily-loaded feeders at farther distances from a substation increases per-unit bus voltages and could cause overvoltage conditions.**

Keywords-distributed generation; distributed wind; impact studies

I. INTRODUCTION

The need for transmission lines to connect remote wind power plants to major load centers is a barrier to increasing the wind power penetration level in North American interconnections. By adding utility-sized megawatt-scale wind turbines to existing distribution networks, the amount of wind power supplied to consumers can be increased without the associated political difficulties and additional cost of building transmission lines. The focus of this work is to assess the limitations on the amount of wind power that can be added to the distribution system without adversely impacting distribution system operations. Results are presented on one specific power quality issue: the impact of megawatt-scale wind turbines on distribution feeder bus voltages as a function of wind power production and of the electrical distance of wind turbine sites from a distribution substation.

Megawatt-scale wind turbines connected to the distribution circuit are generally located away from heavily-populated areas, therefore the impact megawatt-scale wind turbines will have on rural distribution feeders in particular was studied. Characteristics of rural distribution feeders differ from more-heavily-populated and -loaded urban and suburban areas. Rural distribution feeders tend to be radial, have longer feeder lengths, and are relatively lightly loaded. Also, rural feeders have a higher ratio of the number of overhead lines compared to underground distribution cables. Detailed models of rural distribution feeders are available from GridLab-D in SynerGEE format [1]. In the future, these models will be used to study the effects of wind power on the rural distribution circuit. The work presented here used a distribution circuit made available by the Electric Power Research Institute in OpenDSS script. The distribution circuit modeled in OpenDSS is radial and contains mostly residential load. A simple wind turbine model with power factor controls was used. This model is similar to the standard Western Electricity Coordinating Council Type 3 doubly-fed induction generator and Type 4 full-converter wind turbine models, both of which were used in the study because Type 3 and Type 4 wind turbines have the ability to maintain the desired power factor at the wind turbine terminals. The Institute of Electrical and Electronics Engineers Standard 1547 specifications and requirements for interconnection of distributed generation were applied [2].

Similar impact studies and distribution analyses have been performed but instead studied the impact of rooftop photovoltaic on feeder voltage profiles [3-5]. However, distributed wind differs from rooftop photovoltaic in terms of scale and distribution of the resource. Traditionally, the power available from a distribution-connected wind plant is fed in at one bus in the distribution circuit, as opposed to the many locations of distributed solar power. Wind and solar resource variability and uncertainty are also significantly different. The lack of solar generation at night is the most basic example of the many differences.

Section II provides a description of the distribution feeder and the megawatt-scale wind turbine model. Section III describes the analysis applied to the feeder model. Results from the analysis are presented in Section IV, and the findings summarized and future areas for research identified are presented in Section V.

II. Distribution Circuit and Wind Turbine Generator Models

Descriptions of the distribution circuit and wind turbine generator (WTG) models used in this work are provided in this section. Although the results shown are specific to this particular distribution feeder, the methodology developed and the issues examined are of interest for other distribution feeder models in which megawatt-scale wind turbines could potentially be connected.

A. Distribution Circuit Model

The distribution circuit model used in the study was made available by the Electric Power Research Institute in OpenDSS script [6]. This circuit was selected as an example of how to analyze some of the impacts megawatt-scale wind turbines have on the distribution system. The analysis methods developed are broadly applicable to other circuits, which is the intended focus of future work. The distribution circuit used in this paper has a rated system voltage of 12.47 kV, which is connected through a 16.3-MVA rated service transformer. The location of the substation in the distribution circuit is indicated in Fig. 1. The locations of switched capacitor banks with capacitor controls to determine when to switch capacitor banks on or off are indicated in Fig. 1. Three-phase and single- or two-phase lines in the circuit are also labeled in Fig. 1.

This radial distribution circuit serves mostly residential load. The load locations and relative sizes are shown in Fig. 2**.** The radius of each circle representing a single-phase load is proportional to the power of the load. All loads are single-phase loads; the phase of each load is labeled in the figure. The total three-phase load for the circuit is 7.01 MW.

B. WTG Model

Four typical WTG model types are used for power flow representations of wind power plants, as described in [7]. The Western Electricity Coordinating Council standard Type 1 and Type 2 models, also known as fixed-speed and variable-slip WTGs, respectively, represent WTGs with capacitor bank controls to supply reactive power to the WTG. Western Electricity Coordinating Council standard Type 3 and Type 4 WTGs, also known as doubly-fed asynchronous and full-power-converter generators, respectively, have power electronic controls that allow for power factor control or voltage control at the terminals. In this paper, a combined Type 3/Type 4 WTG model was used because most megawatt-scale modern WTGs are either Type 3 or Type 4. For the research presented here, the active power factor controls for the generator models representing the Type 3/Type 4 WTGs were set so that the power factor at the WTG terminals was held at unity (pf = 1.0). The ranges of the power output of the WTG models are described in Section III and Section IV.

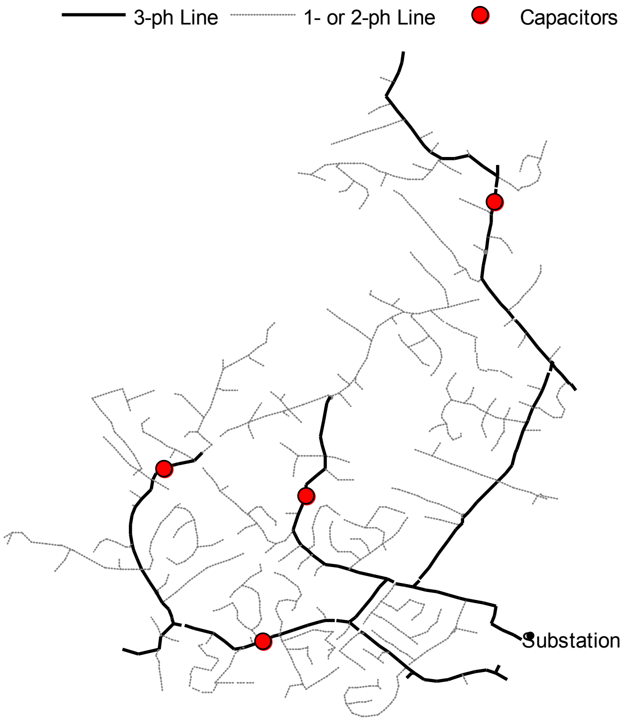

Figure 1. Distribution circuit model.

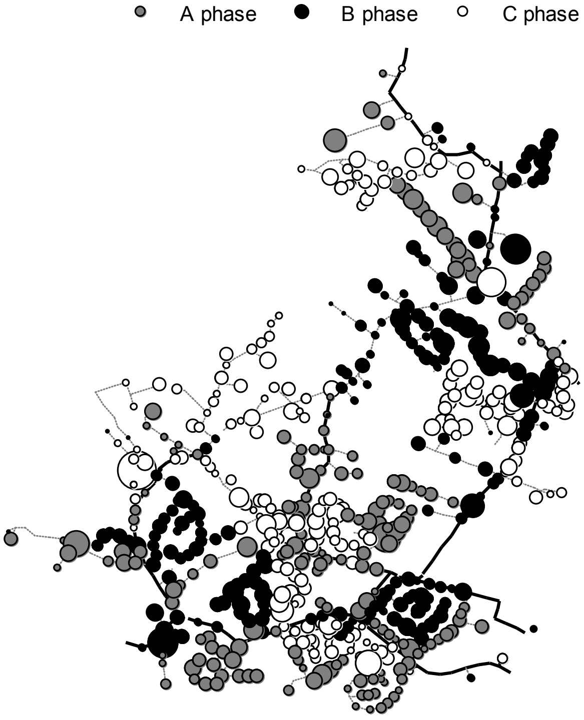

Figure 2. Distribution circuit single-phase loads.

III. METHODOLOGY

In most of the previous literature on megawatt-scale distributed-connected wind turbines, the site of the WTG was known and the impacts on the distribution system indices were studied to determine if the location, power output, and connections were acceptable [8] [9] [10]. In this work, however, to establish general guidelines for integrating megawatt-scale turbines in distribution circuits, all possible WTG locations, with varying levels of installed wind power capacity, were examined to determine the maximum acceptable wind power for the system without a significant decrease in power quality

A. Software

The analysis was performed in the MATLAB and OpenDSS programs. As mentioned in Section II, the distribution circuit model was provided in OpenDSS. MATLAB is used to drive OpenDSS through the COM interface, which allows for easy parameter changes in the circuit between runs, and advanced analysis of simulation results. Results were taken from steady-state solutions.

B. Analysis

For the research presented in this paper, the changes in bus voltages were examined for the steady-state analysis. First, bus voltage baselines were established in the distribution feeder model by running a simulation without any WTGs connected. The simulation was conducted and the per-unit voltages at each bus were recorded as baseline voltages. Next, the change in bus voltages when a WTG was interconnected at each possible location was examined. Possible WTG locations were all buses connected to three-phase lines and locations that had an electrical distance of at least 0.1 km from the substation. Two aspects of the change in bus voltage were examined when a WTG was connected at each of the possible locations. The first was the change in voltage at each bus, and the second was the sum of changes in bus voltages as a reflection of feeder-wide voltage change. The WTG locations that caused the maximum amount of change and the minimum amount of change were identified and are discussed in Section IV. For these cases, the capacitor bank controls were turned off to determine how sudden changes in WTG power output may affect the system bus voltages before the capacitor banks have time to react.

For the work presented here, only single WTG locations were studied, rather than having multiple WTGs located throughout the distribution circuit. Multiple, simultaneously-connected WTGs and the impact they have on the distribution feeder will be considered in future work. The WTG model was rated at 1.5 MW and included multiples of 1.5 MW depending on the case studied.

IV. ANALYSIS RESULTS

The first step was to find all possible buses within the distribution feeder that fulfilled the requirements for WTG placement previously mentioned. At this time, only the electrical characteristics of the distribution circuit were taken into account. Future work will consider the geographical location of the distribution feeder and detailed wind resource information when the data is available. To illustrate the impact different WTG bus locations have on bus voltages, the voltages at the buses indicated in Fig. 3 were examined. Phase A of the monitored bus voltages for all possible WTG bus locations is shown in Fig. 4. In Fig. 4, the x-axis is the WTG bus location represented as the distance along the feeder from the substation (in kilometers). The solid line in each plot represents the per-unit baseline voltage at the monitored bus before a WTG was added to the circuit.

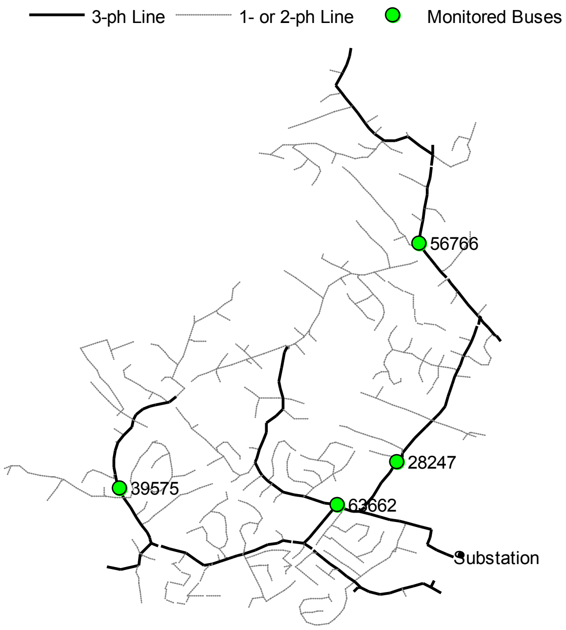

Fig. 3. Location of monitored buses to study the impact that the distance of a WTG from the substation has on bus voltages.

From the results shown in Fig. 4, we concluded that the change in voltage is not solely a function of the distance between the WTG bus and the substation. For WTG distances greater than 1 km, the per-unit bus voltages at Bus 63662, Bus 28247, and Bus 39575 began to diverge. Similar results were seen for Phase B and Phase C. Further analysis indicated that other factors may influence changes in feeder-wide bus voltage.

The next step in the analysis was to find the WTG locations that caused the most change in bus voltages. The heat map in Fig. 7 shows the change in feeder-wide bus voltages caused by the placement of WTGs at different buses. The buses in darker green represent WTG locations that caused the most change in bus voltages across the entire feeder. The buses in a lighter shade of yellow represent WTG locations that caused the least change in voltage across the entire feeder.

The WTG bus locations that experienced the most change (red) and the least change (green) in feeder-wide bus voltages are identified in Fig. 8. These buses were used in the following analysis. All buses in green were located near the substation, as was expected. The red buses were located farther from the substation. However, there were buses along the right branch of the feeder, located farther from the substation, that did not cause as much change to the bus voltages. Therefore, we concluded that distances of WTGs alone do not impact feeder-wide bus voltages. The total load for each of the braches was different—the load along the leftmost branch was higher than that along the rightmost branch (in which WTGs caused more change in bus voltages). Therefore, we concluded that the loading of the feeder where the WTG is located and the distance from the substation influences the change in voltages.

To illustrate the larger percentage change in feeder-wide bus voltages experienced by the buses identified in red, a WTG was placed at Bus 28288 and the change in voltage was calculated at each bus, as shown in Fig. 7. The WTG bus in blue is indicated in Fig. 7. The wind power output for the case presented here was 1,500 kW. The maximum change in voltage was 1.7%. Fig. 8 is a heat map of the change in voltage for a WTG located at Bus 74439 (shown in blue). This bus was along the rightmost branch, where the total load was less than the WTG branch location shown Fig. 7. The wind power output was also 1,500 kW for this case. Even though the WTG is located farther from the substation, the change in bus voltage was not as high as compared to the previous case. For this case, the maximum percent change in bus voltage was 1.1%.

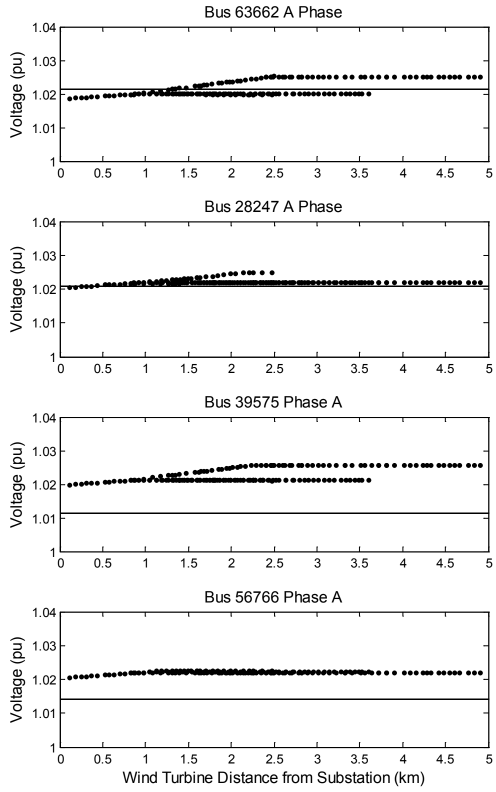

Figure 4. Phase A bus voltages at monitored buses without wind power and with wind power and WTG location as a function of distance (*).

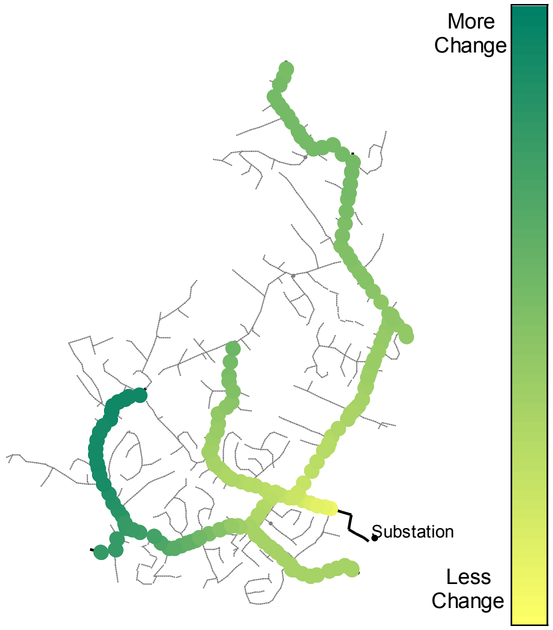

Figure 5. WTG locations and the resulting change in feeder-wide bus voltages.

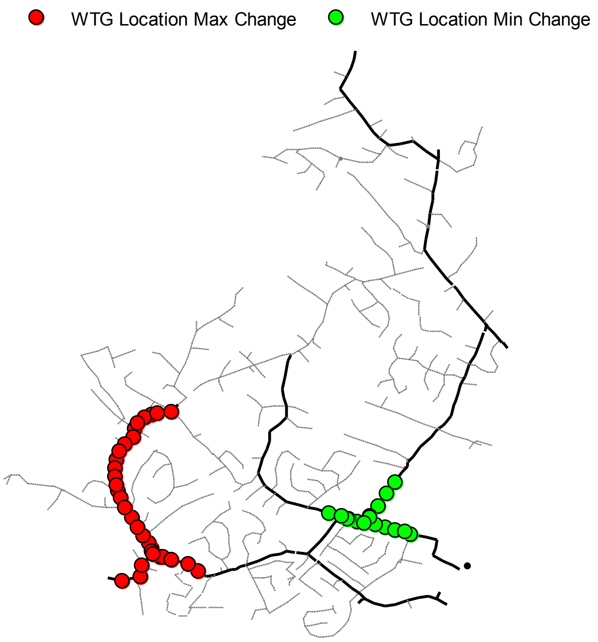

Figure 6. Phase B per-unit voltage change (red) maximum and (green) mininum for 1,500-kW WTG power output.

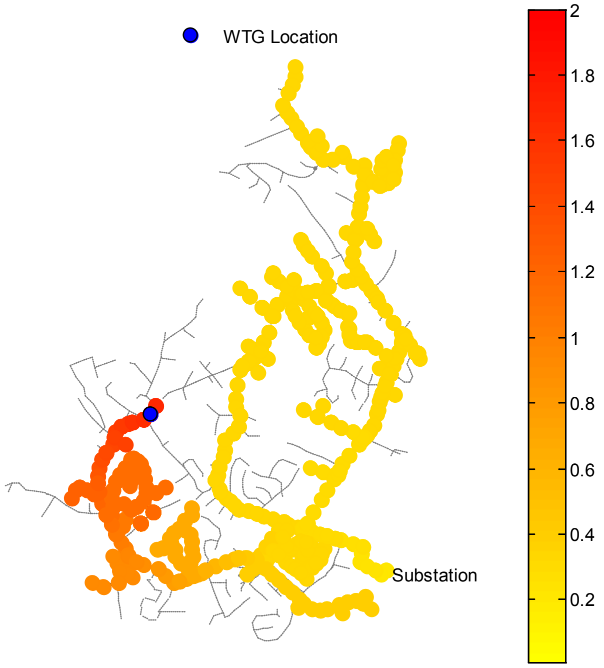

Figure 7. Maximum change in per-unit bus voltage seen at WTG location for Phase B with WTG power output of 1,500 kW at Bus 28288.

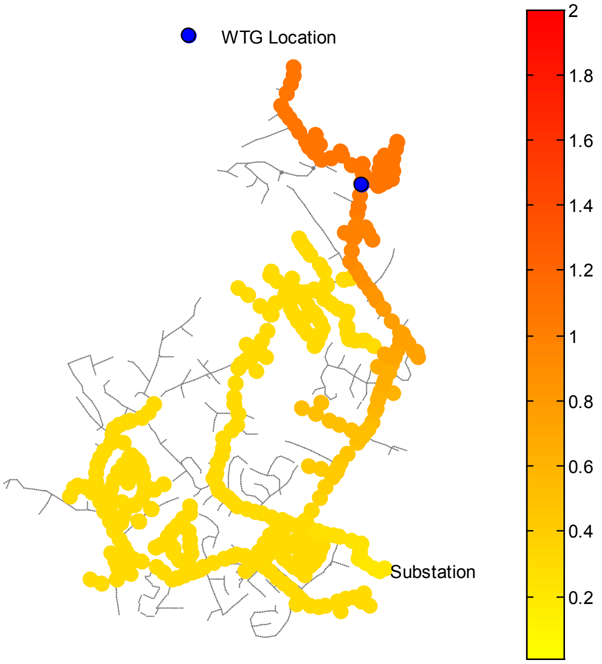

Figure 8. Increased distance of a WTG from the substation on a different branch experienced less per-unit bus voltage change for Phase B with WTG power output of 1,500 kW at Bus 74439.

To illustrate how placing the WTG near the substation has minimal impact on bus voltages, a case in which the WTG was placed at one of the buses indicated in green in Fig. 6 was simulated. The heat map with the WTG located at Bus 63657 (indicated in blue) indicating the change in per-unit voltage at each bus is shown in Fig. 9. The maximum percent change in bus voltage was 0.3% when the WTG was located near the substation. Fig. 7, Fig. 8, and Fig. 9 show results only for Phase B. Similar results were seen for Phase A and Phase C.

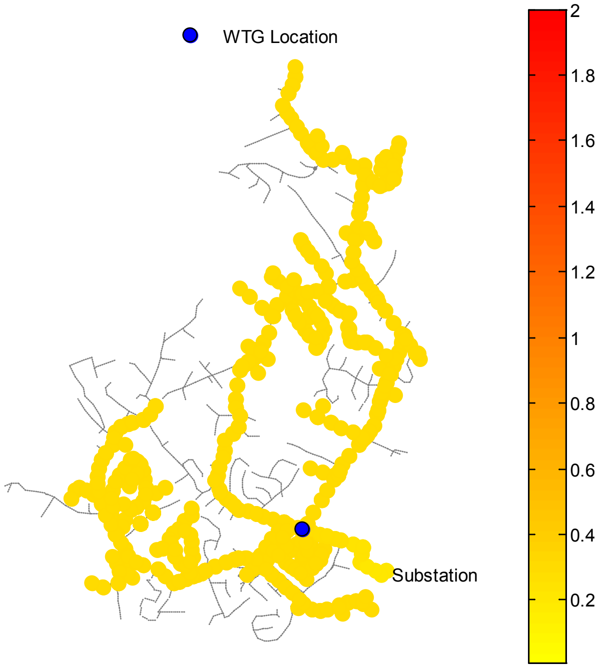

Figure 9. The WTG located near the substations experienced minimum change in per-unit bus voltages for Phase B with WTG power output of 1,500 kW at Bus 63657.

Next, the change in bus voltages when the WTG power output was changed to 15,000 kW was simulated. As expected, larger changes in the per-unit bus voltages were seen when the WTG power output was increased to 15,000 kW. The heat maps for the change in per-unit bus voltages are shown for Bus 28288 and Bus 63657 in Fig. 10 and Fig. 11**,** respectively. The scale of the color map increased in these figures with respect to the previous figures, and the maximum change in voltage was 5.9% for the case in Fig. 10 and 0.9% for the case in Fig. 11**.** In both cases when the WTG power output was 15,000 kW, some buses began to experience a negative change in bus voltage. For these high wind power output cases, it was important to check for undervoltage conditions at these buses.

The work presented shows the percentage change in bus voltage to provide general guidelines and indicate that it is possible that including a WTG to a distribution system can cause overvoltage and sometimes undervoltage conditions. The overvoltage conditions depend on the distance of the WTG from the substation and the load along the feeder where the WTG is placed. Increasing the wind power output also increases the change in bus voltages.

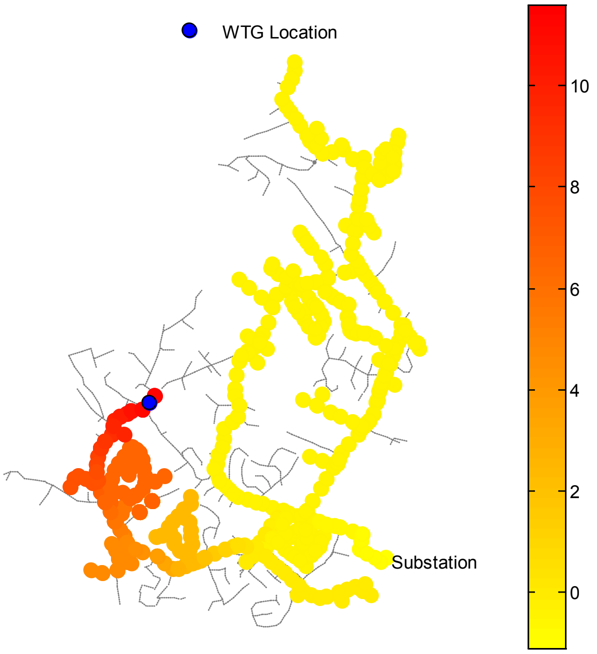

Figure 10. The per-unit bus voltage seen at the WTG location for Phase B with WTG power output of 15,000 kW at Bus 28288 saw an increase in change in voltage compared to Fig. 4.

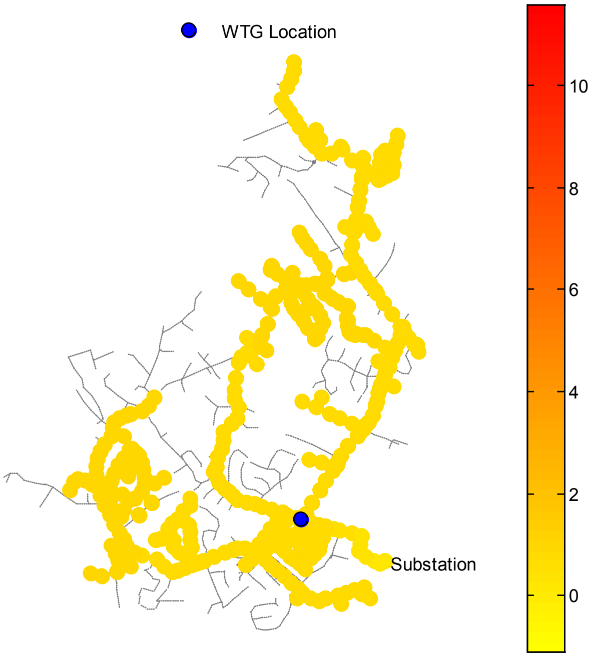

Figure 11. The WTG located near the substation experienced minimum change in per-unit bus voltages for Phase B with WTG power output of 15,000 kW at Bus 63657.

V. CONCLUSION

The impact megawatt-scale wind turbines have on distribution feeder bus voltages was studied. WTGs with power factor control were used in the study. The distance of the WTG from the substation influenced the amount of change in feeder-wide bus voltages as well as the amount of load on the feeder to which the WTG is connected. The percent change in bus voltages was used to represent general results. Large changes in bus voltages could result in overvoltage and, in the case of high wind power output, undervoltage conditions for specific feeders. Future work will apply the methodology used here to other distribution circuits, including actual distribution models provided by utilities. The coordination of wind turbines and voltage control devices will also be studied. A variety of scenarios for different voltage control devices (switched capacitor banks, load tap changers, and voltage regulators) and different load and wind power profiles will be studied.

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