SAND2022-9629C

Development of a Wind Turbine Generator Volt-Var Curve Control for Voltage Regulation in Grid Connected Systems

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Abstract — **Growing interest in renewable energy sources has led to an increased installation rate of distributed energy resources (DERs) such as solar photovoltaics (PVs) and wind turbine generators (WTGs). The variable nature of DERs has created several challenges for utilities and system operators related to maintaining voltage and frequency. New grid standards are requiring DERs to provide voltage regulation across distribution networks. Volt-Var Curve (VVC) control is an autonomous grid-support function that provides voltage regulation based on the relationship between voltage and reactive power. This paper evaluates the performance of a WTG operating with VVC control. The evaluation involves a *MATLAB/Simulink* simulation of a distribution system is performed. For this simulation the model considers three WTGs and a variable load that creates a voltage event.**

Index Terms — **wind turbine generator, voltage regulation, distributed generation, renewable energy**

I. Introduction

With increasing interest in renewable energy sources, more distributed energy resource (DERs) are being connected into the grid [1]. This creates challenges associated with distribution circuit's voltage regulation [2]. Maintaining the voltage within the operational limit is considered to be a critical issue for utilities. It is critical to support system voltage by maintaining it within the required limits of the grid to prevent any adverse effects to the system. Traditionally, voltage swings were mitigated by implementing load tap changing transformers, capacitor banks, and other voltage regulation devices. With new advances in power electronics, DERs such as photovoltaic (PV) inverters and wind turbine generators (WTG) can also provide reactive power within their rated capacity limits to help mitigate voltage deviations [3], [4].

WTGs can provide voltage regulation through the process of generating and absorbing reactive power during voltage fluctuations [5]. However, the ability of the wind power plants to produce or absorb reactive power depends on the strength of the grid and the length of the transmission lines [6]. Offshore wind farms can provide reactive power to stabilize transmission networks [7]. Several studies have explored the reactive power control capabilities of these inverter-based resources in terms of system strength evaluation [8], [9], [10]. The reactive power absorbed by a transmission line changes significantly as the power being transmitted through it changes [11]. Moreover, since wind farms are usually far away, massive amounts of power are frequently delivered to remote loads via long transmission lines. The impedance between the point of connection between the WTG and the grid is another fundamental factor that contributes to voltage fluctuations [12].

Previous research demonstrated that the use of reactive power capabilities in WTGs can cause voltage instability at a transmission level [13]. Although WTGs have a more predominant presence at a transmission level, WTGs with reactive power control capabilities presents a research opportunity for distributed wind applications. New grid standards require DERs to provide voltage regulation using advanced grid support functions [14]. IEEE Standard 1547-2018 requires DERs to provide grid support functions for voltage regulation such as Volt-Var Curve (VVC) control [15], [16]. VVC is an autonomous control technique based on the relationship between voltage and reactive power [17]. It is expected that WTGs adhere to these grid standards to provide voltage regulation capabilities and ensure adequate voltage operating conditions [18]. Many countries have already implemented standards for wind farms, specifying technical requirements for WTGs with VVC capabilities [19], [20]. Although, studies have investigated issues related to WTGs using VVC [21], [22], there is a need for understanding the interactions of WTGs with VVC capabilities in distributed wind applications when operating under varying voltage conditions.

In this paper, we demonstrate the ability of a WTG to provide voltage regulation using reactive power control. The proposed WTG model with VVC control is connected to a large power distribution circuit model and simulated in *MATLAB/Simulink*. The simulations were conducted with variable wind speed to demonstrate the robustness of the approach.

II. Distribution System Description

The Scaled Wind Farm Technology Facility (SWiFT) test site is the first public facility to use multiple WTGs to measure turbine performance in a wind farm environment [23]. The control parameters of these WTGs are summarized in [24]. The SWiFT facility is co-located on the Reese Technology Center Campus along with the Global Laboratory for Energy Asset Management and Manufacturing (GLEAMM) microgrid located in Lubbock, Texas.

GLEAMM is a collaboration with Texas Tech University, managing a microgrid composed of PV system, a diesel generator, a battery energy storage system, and variable loads. Both the SWiFT and the GLEAMM microgrids can connect or disconnect from the utility via the Hurlwood substation. Fig. 1 illustrates the one-line diagram of the system, including the GLEAMM microgrid, SWiFT test site, and the Hurlwood substation. The system is composed of 5 transformers, 10 buses, 8 distribution lines. For this analysis, the model considers the three SWiFT WTGs, each rated at 200 kVA, and the GLEAMM microgrid variable load rated at 500 kW.

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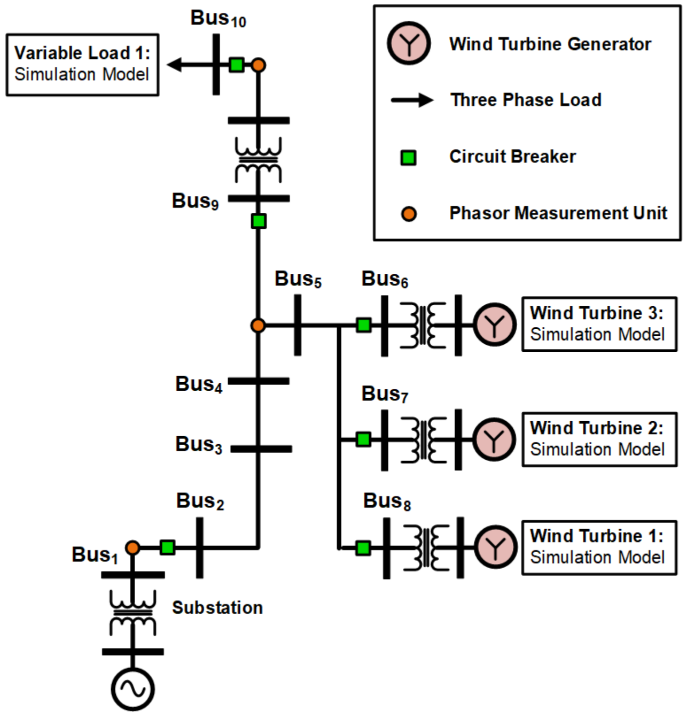

Fig. 1. One-Line diagram for the distribution system, including the GLEAMM microgrid and SWiFT test site.

III. Wind Turbine Generator Model

This SWiFT WTGs are represented using a Type-IV, WTG model [25], [26]. Fig. 2 illustrates the WTG model diagram consisting of a synchronous generator (SG), a three-phase rectifier circuit, an average DC/DC boost converter, an average three-phase inverter, an RLC filter, and a three-phase transformer. The mechanical power captured by the WTG is converted to electrical power by the SG. The power produced by the SG goes through the three-phase rectifier circuit, a DC/DC boost converter and then through a three-phase inverter. Finally, an RLC circuit is used to filter the output signal. The control is implemented through a speed regulator, excitation, and pitch control as well as a grid-side converter control. Fig. 3 illustrates a comparison of the experimental and simulation results obtained for the SWiFT WTGs power curve.

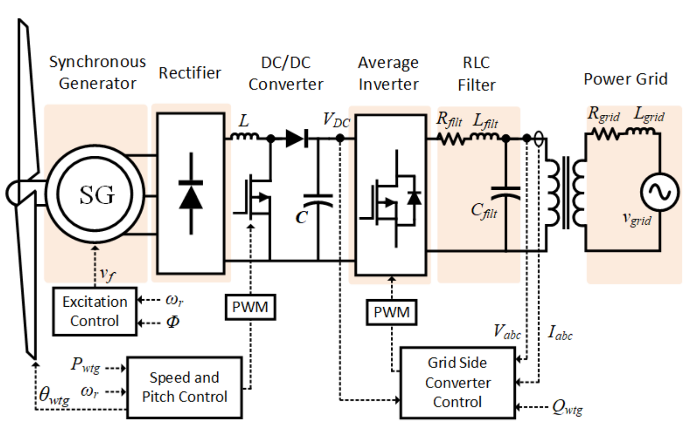

Fig 2. Block Diagram of the Wind Turbine Generator Model.

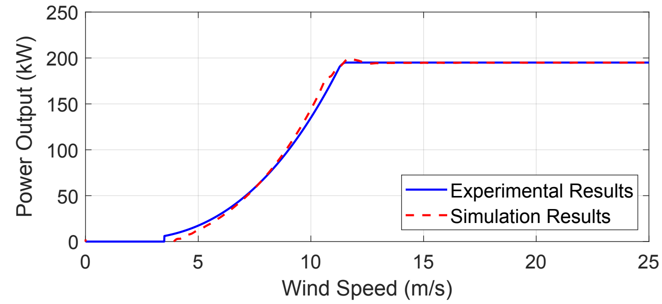

Fig 3. Comparison of the experimental and simulation results obtained for the SWiFT WTGs power curve.

The WTG model uses wind speed as an input variable. The model also includes active and reactive power setpoints. The control of the WTG consists of a speed regulator, excitation, and pitch control as well as a grid-side converter control. The grid-side converter regulates the speed of the WTG and the reactive power of the grid side converter. Reactive power is adjusted by modifying the parameter Q_{ref}. The voltage control of the DC-link capacitor is achieved by the DC/DC boost converter. The pitch control limits the extracted power to its rated value. By adjusting the parameter P_{ref}, the WTGs pitch angle β is adjusted and active power is curtailed. Table I summarizes the WTG parameters. Table II summarizes the WTG control parameters.

TABLE I:
WIND TURBINE GENERATOR PARAMETERS

Parameter	Variable	Value	Units
Nominal Mechanical Power	P_m	200	kW
Nominal Generator Power	P_g	200	kW
Nominal Voltage	V_n	730	V
Nominal Frequency	f_n	60	Hz
Cut-in Wind Speed	C_{in}	3.5	m/s
Nominal Wind Speed	C_n	11.5	m/s
Cut-out Wind Speed	C_{out}	25.0	m/s
Generator Inertia Constant	H_g	0.41	s
Wind Turbine Inertia Constant	H_w	1.3	s
Converter Voltage	V_{AC}	575	V
Coupling Inductance	L_{coup}	0.15	pu
Coupling Resistance	R_{coup}	0.003	pu
Filter Capacitance	C_{filt}	50	VARs
Converter Resistance	R_{DC}	5	mΩ
Converter Capacitor	C_{DC}	90	nF
Converter Inductance	L_{DC}	1.2	mH
Converter Voltage	V_{DC}	1.1	kV

TABLE II:
WIND TURBINE GENERATOR CONTROL PARAMETERS

Parameter	Variable	Value	Units
Proportional Pitch Compensation	$k_{p,pitch}$	5.5	–
Integral Pitch Compensation	$k_{i,pitch}$	25	–
Proportional Pitch Controller	G_{pitch}	55	–
Maximum Pitch Angle	β_{max}	27	°
Maximum Pitch Rate of Change	$d\beta/dt$	20	°/s
Proportional Speed Regulator	$k_{p,speed}$	5	–
Integral Speed Regulator	$k_{i,speed}$	1	–
Proportional Field Excitation	$k_{p,exc}$	10	–
Integral Field Excitation	$k_{i,exc}$	20	–

IV. Reactive Power Control

VVC control is an autonomous grid support function that provides voltage regulation based on the relationship between voltage and reactive power. The VVC is generated by interpolating between the voltage measured at the point of common coupling (PCC), V_{pcc}, and available reactive power as shown in equations (1).

$$\left.\begin{array}{ll} Q_{ref} = Q_1 = Q_{max} & v_{pcc} \leq v_1 \\ Q_{ref} = \dfrac{(Q_2 - Q_1)}{(v_2 - v_1)} \cdot (v_{pcc} - v_1) + Q_1 & v_1 < v_{pcc} < v_2 \\ Q_{ref} = 0 & v_2 \leq v_{pcc} \leq v_3 \\ Q_{ref} = \dfrac{(Q_4 - Q_3)}{(v_4 - v_3)} \cdot (v_{pcc} - v_3) + Q_3 & v_3 < v_{pcc} < v_4 \\ Q_{ref} = Q_4 = Q_{min} & v_{pcc} \geq v_4 \end{array}\right\} \#(1)$$

In this equation, variables Q_{max} and Q_{min} are the maximum and minimum reactive power values of the VVC, respectively. The variable Q_{ref} is the reference reactive power value and represents the operating point in the VVC. The variables Q_1, Q_2, Q_3, and Q_4 represent different reactive power points in the VVCs reactive power axis. The variables v_1, v_2, v_3, and v_4 represent different voltage points in the VVCs voltage axis. The values of the VVC are selected to provide the maximum allowable absorption of reactive power at both ends of the VVC. Table III summarizes the VVC parameters.

Table III:
Volt-VAR Curve Control Parameters

Parameter	Value (kVAR)	Parameter	Value (pu)
Q_1	200	v_1	0.985
Q_2	0	v_2	0.995
Q_3	0	v_3	1.005
Q_4	-200	v_4	1.015

Fig. 4 illustrates an example of two VVCs. Notice that the points along the VVC define the slope of the function and determine the aggressiveness of the reactive power that can be delivered and absorbed by the WTG.

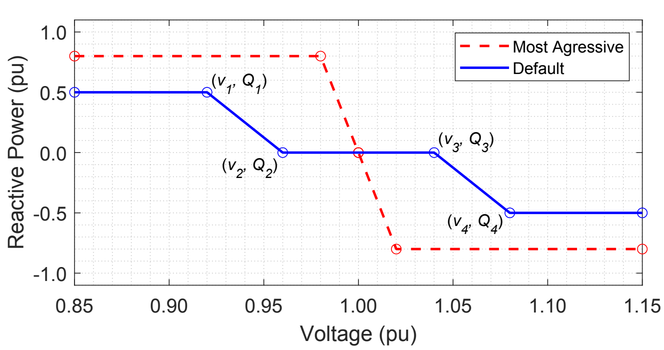

Fig. 4. Diagram of a VVC Illustrating a Default (Blue) and Most Aggressive (Red) Curves.

In order to dampen abrupt changes in the VVC dynamics that might lead to system instability, a low pass filter is implemented at the output of the VVC control, as shown in equation (2).

$$H(s) = \frac{1}{T_s \cdot s + 1} \#(2)$$

In this equation, the variable T_s is the response time, which was set to 0.5 s. The model is implemented with active power priority, which allows the WTG to provide a certain degree of reactive power, while prioritizing active power generation. This is achieved adhering to the relationship between active, reactive, and apparent power as shown in equation (3).

$$S_{wtg} = \sqrt{\left(P_{wtg}\right)^2 + \left(Q_{wtg}\right)^2} \#(3)$$

In this equation, the variables P_{wtg} and Q_{wtg}, are the reference active and reactive powers commanded by the grid support function, respectively. Solving for the reactive power yields the active power priority relationship, shown in equation (4).

$$Q_{lim} = Q_{wtg} = \pm \sqrt{\left(S_{wtg}\right)^2 - \left(P_{wtg}\right)^2} \#(4)$$

The instantaneous three-phase voltage V_{abc} is measured at the PCC of the WTG and used to calculate the RMS value. This is used to obtain the average of the phases, V_{pcc}. This serves as the input variable for the VVC, shown in equation (1). A low pass filter, shown in equation (2), dampens any abrupt changes in reactive power that could lead to instability. Finally, the active power priority function, shown in equation (4), is used to determine the reactive power limits $\pm Q_{lim}$, that prioritize the WTGs active power.

V. Simulation Description

A model of the SWiFT facility and the GLEAMM microgrid is simulated using *MATLAB/Simulink*. Three PMUs distributed throughout the SWiFT facility were used to validate the simulation model. These are located at the Hurlwood substation, SWiFT WTGs intertie, and at the GLEAMM microgrid, as shown in Fig. 1. This simulation model considers the three SWiFT WTGs and a variable load located at the GLEAMM microgrid. Wind speed data collected from the SWiFT facility is used as the input to the WTG models as shown in Fig. 5. The wind speed profile 1 is collected from a met tower located in the SWiFT facility. All other wind speed profiles are generated by shifting and scaling wind speed profile 1. Simulation results are obtained by comparing two scenarios: a baseline (BL) scenario, which considers the WTG operating with no control and a second scenario that implements a VVC to allow the WTG to provide reactive power. To create an event that will affect the SWiFT facility voltage, a load step using the GLEAMM microgrids variable load is introduced at 400 s. This load step creates a voltage reduction throughout the system, primarily affecting the bus voltage where the variable load is connected.

Fig. 6 shows the variable load profile used to create a voltage event.

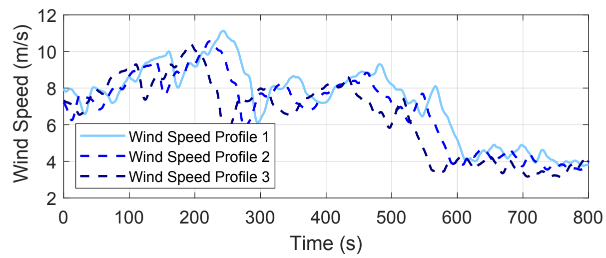

Fig. 5. Wind Speed Profile for the SWiFT Wind Turbine Generators.

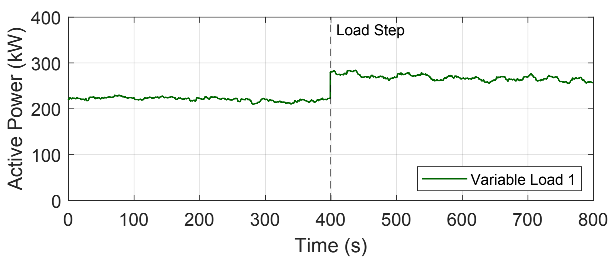

Fig. 6. Load Profile for the GLEAMM Microgrid Variable Load.

VI. Simulation Results

The SWiFT facilities PMU measurements show that the nominal voltage at the Hurlwood substation is 1.04 pu. Grid code standards such as IEEE 1547-2018 require DERs to continuously operate at a voltage range between 0.88 pu and 1.10 pu. Although DERs must adhere to IEEE 1547-2018, utilities are required to adhere to ANSI standards, maintaining loads at a voltage range of 0.95 pu and 1.05 pu [27], [28]. The VVC voltage set point is programmed to regulate voltage at 1.04 pu, which is withing the IEEE 1547-2018 limits. This was done to maintain a voltage closer to the Hurlwood substations nominal voltage as well as to maintain the appropriate voltage levels at the end of the feeder.

Fig. 7 through Fig. 9 illustrate the simulation results of the three WTGs RMS voltage and current for the BL and VVC scenarios. Fig. 10 illustrates the simulation results obtained for the voltage at the variable load for the BL and VVC scenarios. Fig. 11 illustrates the simulation results obtained for maximum, minimum, and average bus voltage comparing BL and VVC scenarios.

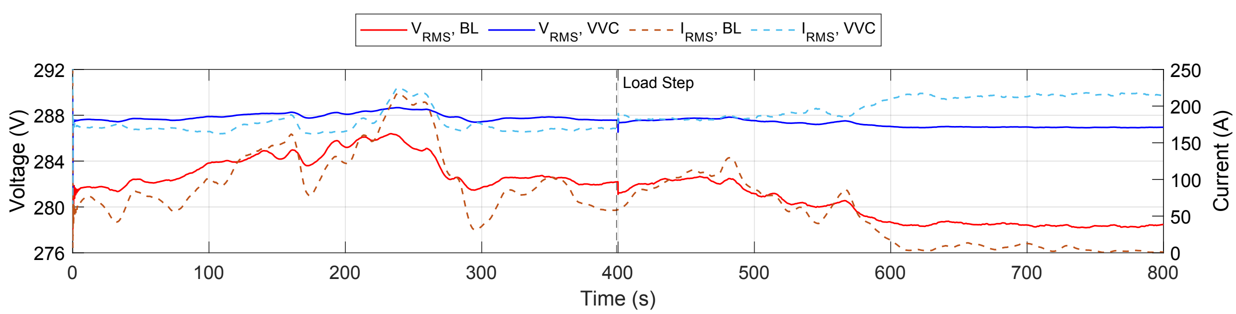

Fig. 7. Simulation Results for the SWiFT Wind Turbine Generator 1 Comparing Baseline and Volt-Var Curve Scenarios.

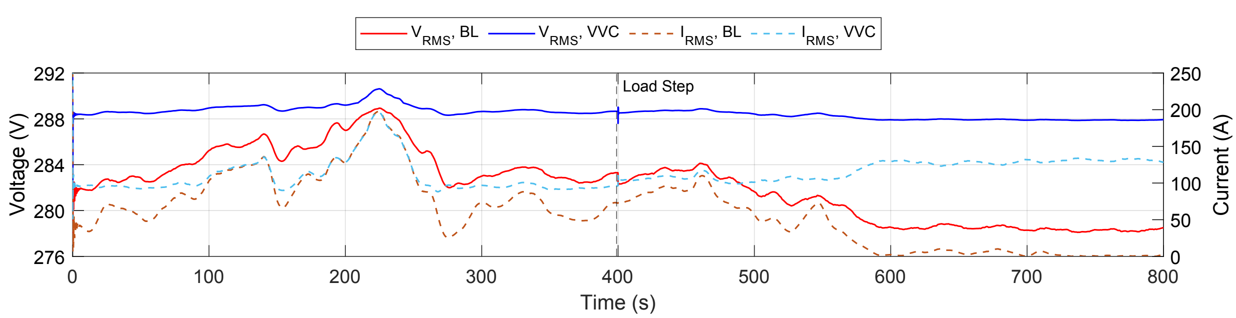

Fig. 8. Simulation Results for the SWiFT Wind Turbine Generator 2 Comparing Baseline and Volt-Var Curve Scenarios.

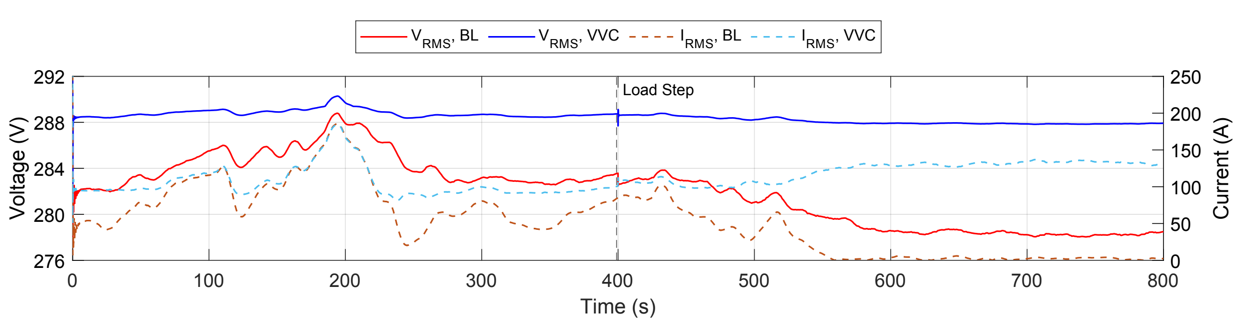

Fig. 9. Simulation Results for the SWiFT Wind Turbine Generator 3 Comparing Baseline and Volt-Var Curve Scenarios.

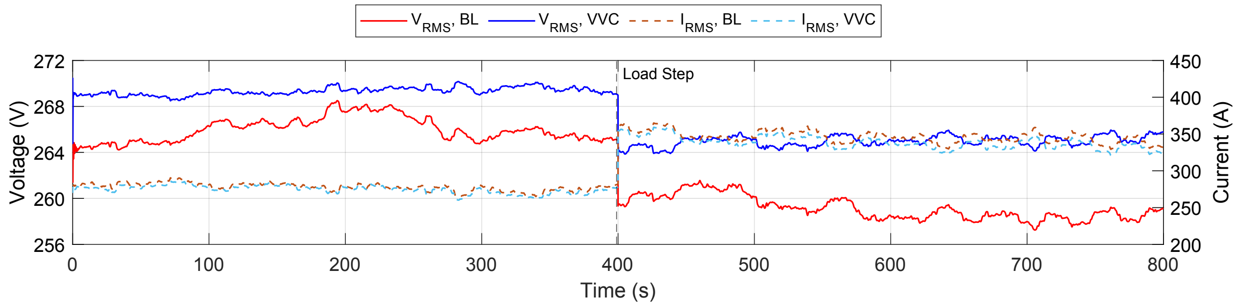

Fig. 10. Simulation Results for the Variable Load Voltage Comparing Baseline and Volt-Var Curve Scenarios.

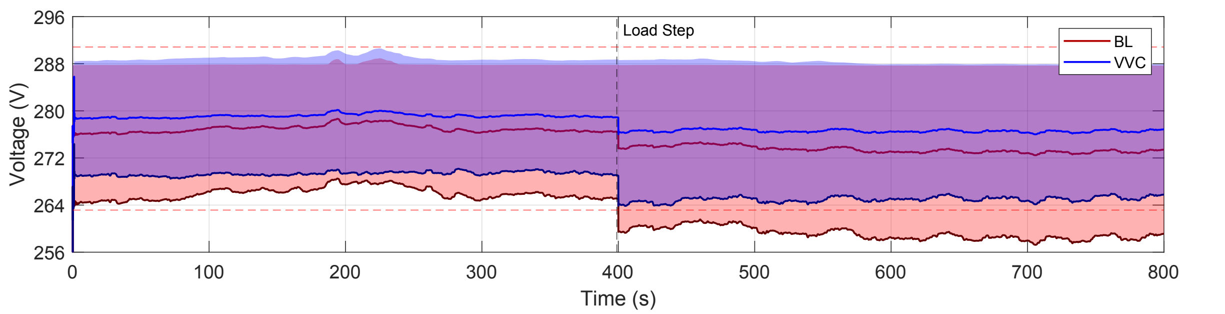

Fig. 11. Simulation Results for the Average, Maximum, and Minimum Bus Voltage Comparing Baseline and Volt-Var Curve Scenarios.

Simulation results from Fig. 7 through Fig. 9 for the BL scenario show that the RMS voltage of the WTGs varies between 278 V and 289 V. Results of the VVC scenario show that the WTGs can regulate the voltage at their PCC to the target 288.08 V.

Simulation results from Fig. 10 illustrate that for the BL scenario, the voltage at the variable load ranges between 264 V and 268 V. When the voltage event is introduced, the voltage at the variable load is reduced to 260 V, below the 263.15 V ANSI standard. Results for the VVC scenario show that the WTGs regulating their PCC voltage has an effect on the variable load voltage, regulating the voltage to 269 V before the voltage event. When the voltage event is introduced, the variable load voltage is reduced to approximately 264 V, above the ANSI standards minimum voltage requirement.

Simulation results from Fig 11 illustrate that the WTGs VVC can maintain the average system voltage within the desired limits. In these results, the minimum voltage is caused by the variable load and the maximum voltage from the WTGs.

Fig. 12 through Fig. 13 illustrate the simulation results obtained from the active, reactive, and apparent power of the WTGs, respectively. Simulation results from the WTGs active power illustrate that at 200 s, the WTGs operate close to nominal power. At approximately 550 s, the WTGs are operating at 4 m/s (below cut-in wind speed) and active power slowly ramps down. After 600 s, the WTGs cease to provide active power. Simulation results from the reactive power for the WTGs show that at 200 s, the WTGs 2 and 3 did not provide reactive power due to their PCC voltage already operating at the VVC target voltage. After the voltage event is introduced, all WTGs provide reactive power in order to regulate voltage at their PCC. WTG 1 produces the largest reactive power due to its location being furthest from the substation and with the most voltage drop. Finally, Fig. 14 illustrates that the WTGs provide reactive power at varying active power within their nameplate power rating.

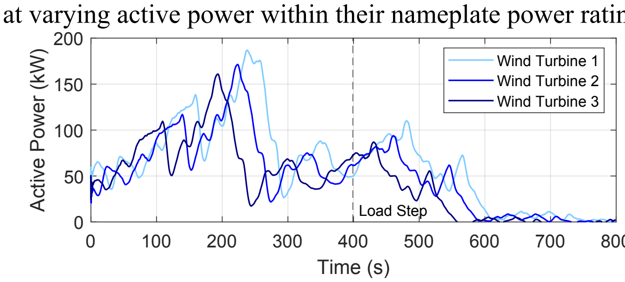

Fig. 12. Simulation Results for the SWiFT Wind Turbine Generators Active Power.

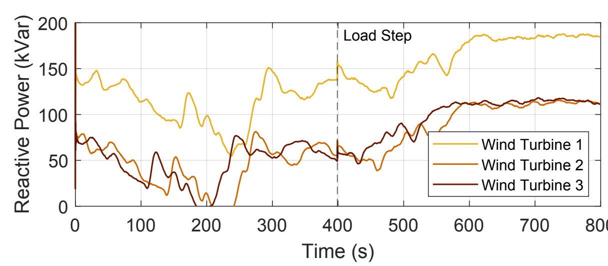

Fig. 13. Simulation Results for the SWiFT Wind Turbine Generators Reactive Power.

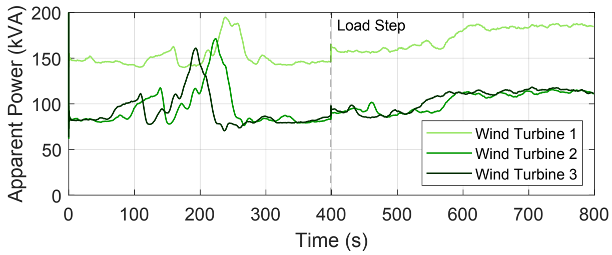

Fig. 14. Simulation Results for the SWiFT Wind Turbine Generators Apparent Power.

VII. Conclusion

In this paper, we demonstrate the ability of a WTG to provide voltage regulation using a VVC control approach. Three WTG models with VVC control capabilities are connected to a power distribution system and simulated in *MATLAB/Simulink*. A load step is introduced to create a voltage reduction throughout the distribution system. Simulation results are obtained by comparing two scenarios: a BL scenario, which considers the WTG operating with no control and a second scenario that implements a VVC to allow the WTG to provide reactive power. Simulation results demonstrate that the WTGs are able to provide reactive power to regulate the voltage at their PCC at varying active power within their nameplate power rating. Results for the BL scenario illustrate that when the load step is introduced, the voltage at the variable load falls below the ANSI limits, but when the WTGs are providing VVC, the voltage is regulated above the minimum ANSI voltage. Finally, simulation results illustrate that the WTGs are able to maintain the overall system voltage withing the desired ANSI voltage limits.

Acknowledgment

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

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