Volt-Var Curve Control Using Wind Turbine Generators and Photovoltaic Inverters for Voltage Regulation

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***Abstract* — With increasing interest in renewable energy sources, more distributed energy resources (DERs) such as solar photovoltaics (PVs) and wind turbine generators (WTGs) are being connected into the grid. PVs and WTGs may cause voltage deviations due to their dependency on variable and intermittent natural resources, e.g. solar irradiance, and wind speed. This creates a challenge for utilities and system operators in terms of maintaining voltage stability. New grid standards are requiring PV inverters to provide reactive power using Volt-Var Curve (VVC) control to ensure voltage regulation in distribution systems. VVC control is an autonomous grid support function for voltage regulation based on the relationship between voltage and reactive power. This paper demonstrates the ability of a WTG and a PV inverter to jointly provide voltage regulation in a distribution system using VVC control. A simulation model of a distribution system is used to evaluate the performance of the VVC control. For this simulation, the model considers three WTGs, a PV inverter, and a variable load that creates voltage variability.**

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

I. Introduction

As interest in renewable energy sources grows, integration of distributed energy resources (DERs) into the grid has become more common [1]. The variability from these renewable energy resources creates voltage challenges for distribution system [2]. It is critical for utilities to ensure system voltage is maintained within the required operational limits to prevent any adverse effects to the system. Although voltage variations have been traditionally mitigated using load tap changing transformers, capacitor banks, and other voltage regulation devices, advances in power electronics enable DERs such as photovoltaic (PV) inverters and wind turbine generators (WTG) to provide voltage regulation [3]. PV inverters must comply with grid interconnection standards that require grid support capabilities, including voltage regulation [4]. IEEE Standard 1547-2018 requires PV inverters to provide voltage regulation using Volt-Var Curve (VVC) control [5], [6]. VVC control is an autonomous grid support function based on the relationship between voltage and reactive power [7]. It is expected that WTGs, like PV inverters, comply with grid interconnection standards, enabling voltage regulation capabilities and ensuring voltage levels are within regulatory limits. Studies have investigated the effectiveness of WTGs using VVC control for voltage regulation [8]. Although this study explored the ability of a WTG to provide voltage regulation for low voltage events, this did not consider high voltage events created from high penetrations of DERs. Moreover, these simulations did not analyze VVC control interactions between DERs of different renewable energy resource types, mainly solar and wind.

Previous research has demonstrated that coordination between WTGs and PV inverters is effective in regulating voltage [9]. Other research has shown that an optimized distributed reactive power control for WTGs and PV inverters can maintain voltage levels within regulatory limits [10]. Reactive power control has also been proven to maintain system voltage within the allowable limits in distribution systems dominated by WTGs and PV at not only varying irradiance, wind speed, and load conditions [11]. In [12], the authors demonstrated how WTGs and PV inverters can mitigate voltage variations associated with the intermittent renewable power output and load variation using VVC control [13]. The use of innovative VVC control schemes that coordinates reactive power between WTGs and PV inverters has also proven to effectively regulate voltage in distribution systems.

In this paper, we demonstrate the ability of a WTG and a PV inverter to jointly provide voltage regulation in a distribution system using VVC control. The proposed WTG and PV inverter models with VVC control are connected to a large power distribution circuit model and simulated using *MATLAB/Simulink*. The simulations were conducted with variable wind speed and solar irradiance profiles to demonstrate the robustness of the approach under varying conditions. A variable load is used to create an event that will affect the voltage at the end of the feeder. Simulation results demonstrate that the WTGs and PV inverter are able to absorb and inject reactive power in order to regulate voltage.

II. Distribution System Description

The distribution system is composed of the Scaled Wind Farm Technology (SWiFT) test site and the Global Laboratory for Energy Asset Management and Manufacturing (GLEAMM) microgrid, co-located on the Reese Technology Center Campus, in Lubbock, Texas. The SWiFT test site is the first public facility to use multiple WTGs to measure turbine performance in a wind farm environment [14], [15]. GLEAMM is a collaboration with Texas Tech University which manages a microgrid composed of a PV system, a diesel generator, a battery energy storage system, and variable loads. For this analysis, the SWiFT test site and the GLEAMM microgrid are connect to the utility via the Hurlwood substation. Fig. 1 illustrates the one-line diagram of the distribution system, including the SWiFT test site, GLEAMM microgrid, and the Hurlwood substation. The distribution system is composed of 6 transformers, 11 buses, and 8 distribution lines. For this analysis, the simulation model considers the three SWiFT WTGs, each rated at 200 kVA for a total of 600 kVA. The analysis also considers a variable load rated at 500 kW and a PV inverter rated at 150 kVA, both located at the GLEAMM microgrid.

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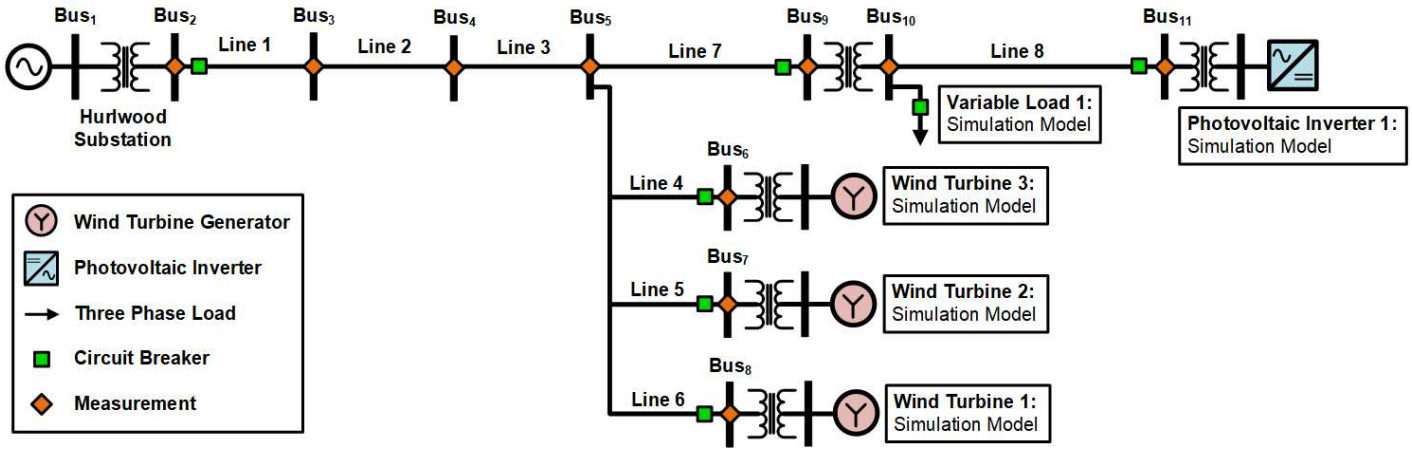

Fig. 1. One-Line diagram for the distribution system, including the GLEAMM microgrid and SWiFT test site.

A. Wind Turbine Generator Model

The SWiFT WTGs are represented using a Type-IV, WTG model [16]. Table I summarizes the WTG parameters. Fig. 2 illustrates the diagram of the WTG model 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.

TABLE I:
WIND TURBINE GENERATOR PARAMETERS

Parameter	*Variable*	*Value*	*Units*
Nominal Mechanical Power	P_m	200	kW
Nominal Generator Power	P_g	200	kVA
Converter Frequency	f_n	60	Hz
Converter Voltage	V_{AC}	575	V

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 control regulates the speed of the WTG and the reactive power from the grid-side converter. The voltage control of the DC-link capacitor is achieved by the DC/DC boost converter. The pitch control limits and controls the extracted active power.

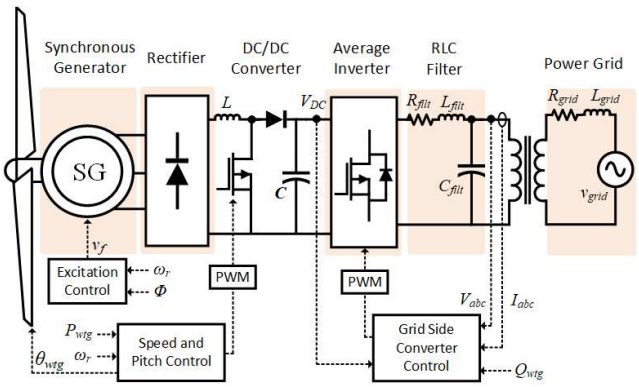

Fig. 2. Block Diagram of the Wind Turbine Generator Model.

B. Photovoltaic Inverter Model

The GLEAMM PV inverter is represented using an average current controlled, grid following inverter model. Table II summarizes the PV inverter parameters. Fig. 2 illustrates the diagram of the PV inverter model consisting of a PV module model, a DC/DC converter, an average three-phase inverter, an RLC filter, and a three-phase transformer [17]. The PV module power is regulated using a DC/DC converter, then an inverter converts this DC power to AC power. Finally, an RLC circuit is used to filter the output signal.

TABLE II:
PHOTOVOLTAIC INVERTER PARAMETERS

Parameter	*Variable*	*Value*	*Units*
Nominal Photovoltaic Power	P_{pv}	200	kW
Nominal Inverter Power	P_{inv}	150	kVA
Nominal DC Voltage	V_{DC}	500	V
Converter Frequency	f_n	60	Hz
Converter Voltage	V_{AC}	277	V

The control of the PV inverter consists of a DC/DC converter control as well as a grid-side converter control. The DC/DC converter control tasked with executing the maximum power point tracking algorithm to extract the utmost available power from the PV module as well as with performing active power curtailment algorithm to extract a power value from the PV modules less than the maximum power. The grid-side converter control is based on the *dq*-current-control and allows regulating active and reactive power.

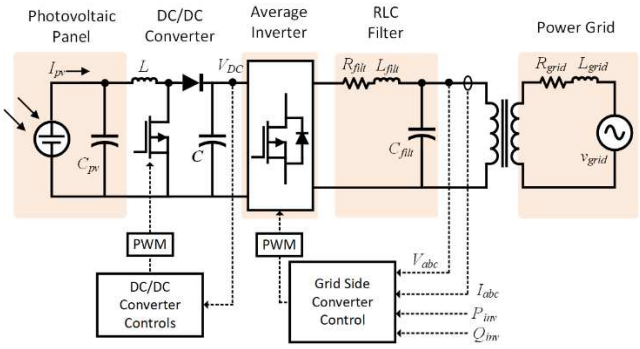

Fig. 3. Block Diagram of the Photovoltaic Inverter Model.

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III. Reactive Power Control

VVC control is an autonomous grid support function for voltage regulation based on the relationship between voltage and reactive power. DERs that employ VVC control are able to provide reactive power, within their nameplate power rating, based on their measured point of common coupling (PCC) voltage. Fig. 4 illustrates an example of a default (solid blue line) VVC and a most aggressive (dashed red line) VVC. Notice that the points along the VVC define the slope of the function and determine how much reactive power can be delivered or absorbed by the DER at any given voltage. The aggressiveness of the VVC depends on the amount of allowed reactive power generation or absorption as well as on the deadband of the VVC.

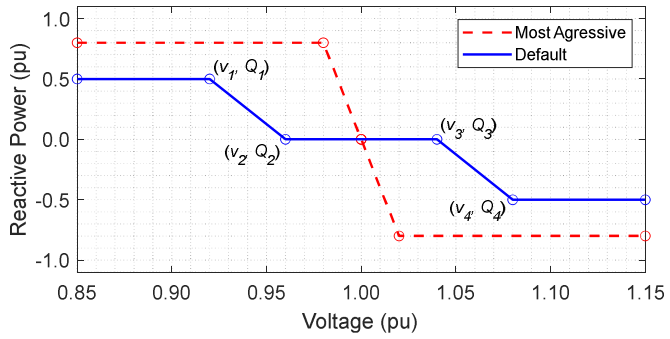

Fig. 4. Diagram of a VVC Illustrating a Default (Solid Blue Line) and Most Aggressive (Dashed Red Line) Curves.

In this diagram 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. Table III summarizes the VVC parameters used for the simulation performed for the WTG. The VVC of the WTG is designed to regulate to 1.04 pu. Table IV summarizes the VVC parameters used for the simulation performed for the PV inverter. The PV inverter VVC is designed to regulate to 1.00 pu. The values of the VVC are selected to provide the maximum allowable absorption of reactive power at both ends of the VVC. The voltage points of the are selected to allow 0.5 % voltage deviation at the deadband.

TABLE III:
WIND TURBINE GENERATOR
VOLT-VAR CURVE CONTROL PARAMETERS

Parameter	*Value (kVar)*	*Parameter*	*Value (pu)*
Q_1	200	v_1	1.025
Q_2	0	v_2	1.035
Q_3	0	v_3	1.045
Q_4	-200	v_4	1.055

TABLE IV:
PHOTOVOLTAIC INVERTER
VOLT-VAR CURVE CONTROL PARAMETERS

Parameter	*Value (kVar)*	*Parameter*	*Value (pu)*
Q_1	150	v_1	0.985
Q_2	0	v_2	0.995
Q_3	0	v_3	1.005
Q_4	-150	v_4	1.015

IV. Simulation Description

A model of the SWiFT facility and the GLEAMM microgrid is simulated using *MATLAB/Simulink*. This simulation model considers the three SWiFT WTGs. The model also considers a PV inverter and 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. Fig. 6 illustrates the irradiance profile used for the simulation. The data is calculated using measurements from the GLEAMM PV system. 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. 7 shows the variable load profile used to create a voltage event.

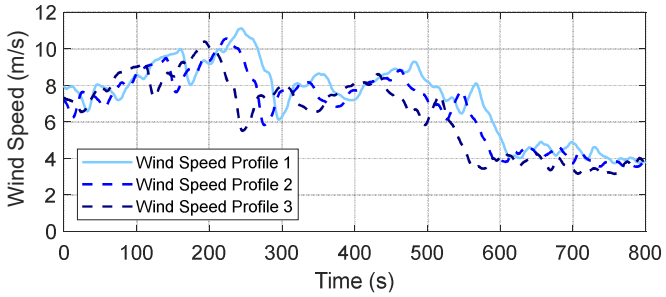

Fig. 5. Wind Speed Profiles for the SWiFT Wind Turbine Generators.

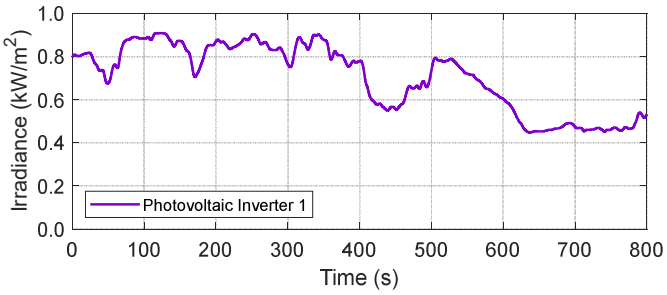

Fig. 6. Irradiance Profile for the GLEAMM Microgrid PV Inverter.

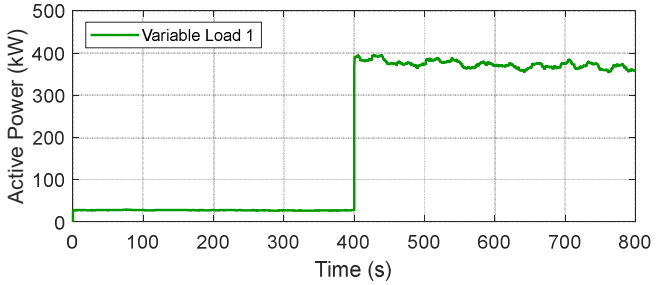

Fig. 7. Load Profile for the GLEAMM Microgrids Variable Load.

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V. Simulation Results

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, while utilities are required to maintain load voltage at a range of 0.95 pu and 1.05 pu, adhering to ANSI standards [18]. The VVC voltage set point for the WTGs were programmed to regulate voltage to 1.04 pu, which is within the IEEE 1547-2018 limits to ensure a voltage closer to the Hurlwood substations nominal voltage. The VVC voltage set point for the PV inverter was programmed to regulate voltage to 1.00 pu, within ANSI standards for load voltage requirements.

Fig. 8 through Fig. 10 shows the results obtained from the active, reactive, and apparent power of the WTGs and PV, respectively. Fig. 8 shows 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. The PV provides active power based on the irradiance profile with active power ranging between 100 kW and 140 kW, never reaching its maximum rated capacity of 150 kW. After 400 s, the power produced by the PV is reduced to approximately 60 kW. Fig. 9 shows that the WTGs as well as the PV provide reactive power at varying wind speed and irradiance conditions within their nameplate power rating. During the simulation period, the PV is operating at its maximum apparent power rating. These results show that for the WTGs there is initially reactive power absorption between 50 s and 300 s. Once the load event is introduced, the WTGs provide reactive power at 500 s. Results from the reactive power of the PV shows that initially the PV absorbs the maximum available reactive power to reduce its voltage at its PCC, until the load event is introduced, lowering the PV PCC voltage which causes the PV to provide reactive power, increasing its PCC voltage.

Fig. 11 shows the results for the RMS voltage and RMS current of the variable load obtained for the BL and VVC scenarios. Results for the BL scenario show that before the load event is introduced, the RMS voltage at the variable load is 293 V, above the ANSI upper limit of 290.85 V. Results for the VVC scenario show that the WTGs and the PV inverter are able to reduce the average RMS voltage from 293 V to 286 V, below the ANSI upper limit. Results for the BL scenario show that after the load event is introduced, the average RMS voltage at the variable load is 258 V, exceeding the ANSI lower limit of 263.15 V. Results for the VVC scenario demonstrate that the WTGs and the PV inverter can increase the average RMS voltage from 258 V to 266 V, below the ANSI upper limit.

Fig. 11 shows the simulation results for the variable load RMS voltage and current for the BL and VVC scenarios. Fig. 12 through Fig. 14 shows the simulation results of the three WTGs RMS voltage and current for the BL and VVC scenarios. Fig. 15 illustrates the simulation results of the PV inverters RMS voltage and current for the BL and VVC scenarios.

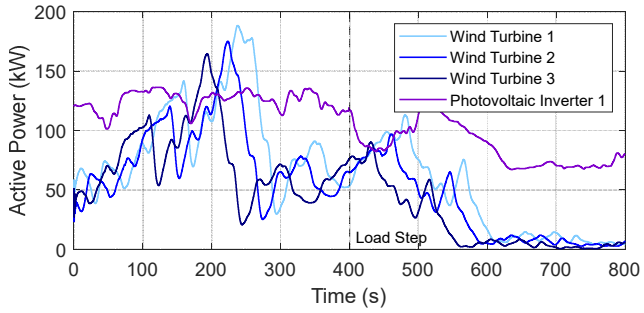

Fig. 8. Simulation Results for the SWiFT Wind Turbine Generators and GLEAMM Photovoltaic Inverters Active Power.

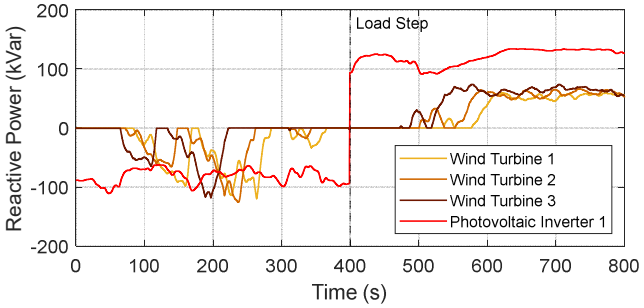

Fig. 9. Simulation Results for the SWiFT Wind Turbine Generators and GLEAMM Photovoltaic Inverters Reactive Power.

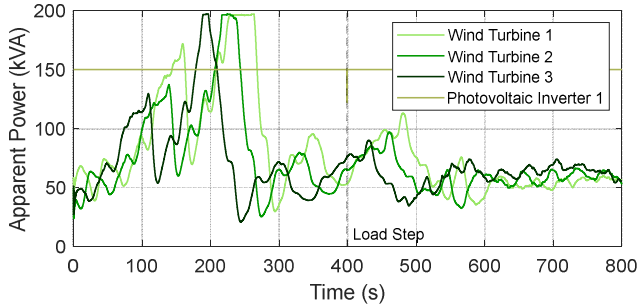

Fig. 10. Simulation Results for the SWiFT Wind Turbine Generators and GLEAMM Photovoltaic Inverters Apparent Power.

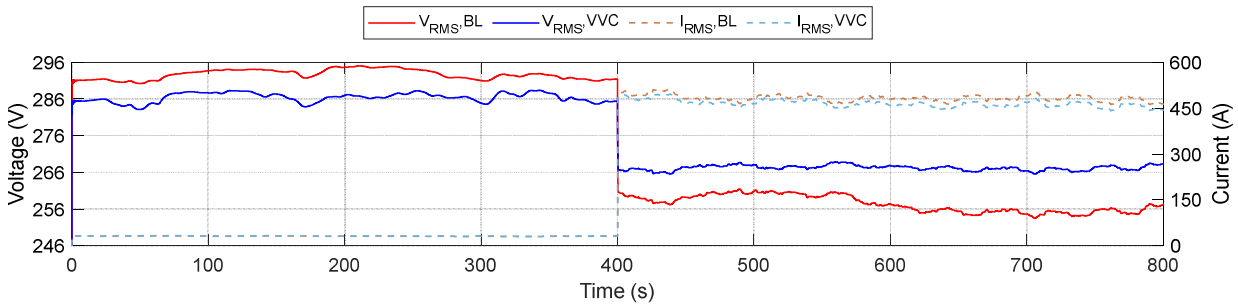

Fig. 11. Simulation Results for the Variable Load Voltage Comparing Baseline and Volt-Var Curve Scenarios.

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Results from Fig. 11 show that during the 400 s period, the VVC control is able to decrease the load voltage from approximately 295 V, above ANSI standards to 286 V. After the load step event is introduced at 400 s, results show that the VVC control is able to increase the load voltage from approximately 256 V, below ANSI standards to 266 V. Results from Fig. 12 through Fig. 14 for the BL scenario show that the RMS voltage of the WTGs vary between 278 V and 294 V. Results of the VVC scenario show that the WTGs can regulate the voltage at their PCC to the target 288.08 V. Results from Fig. 15 shows that the PV inverters RMS current is at its maximum value when operating with VVC control, due to providing the majority of reactive power. Fig. 16. shows the average, maximum and minimum bus voltage of the system. These results show that the WTGs and PV inverter operating with VVC control 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.

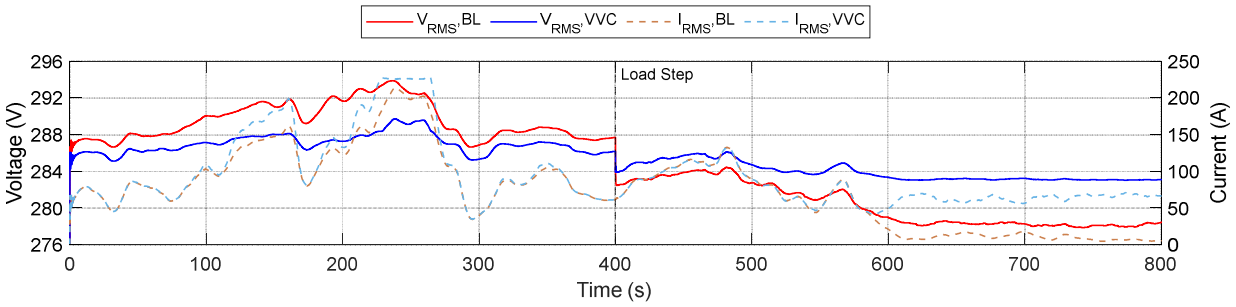

Fig. 12. Simulation Results for the SWiFT Wind Turbine Generator 1 Comparing Baseline and Volt-Var Curve Scenarios.

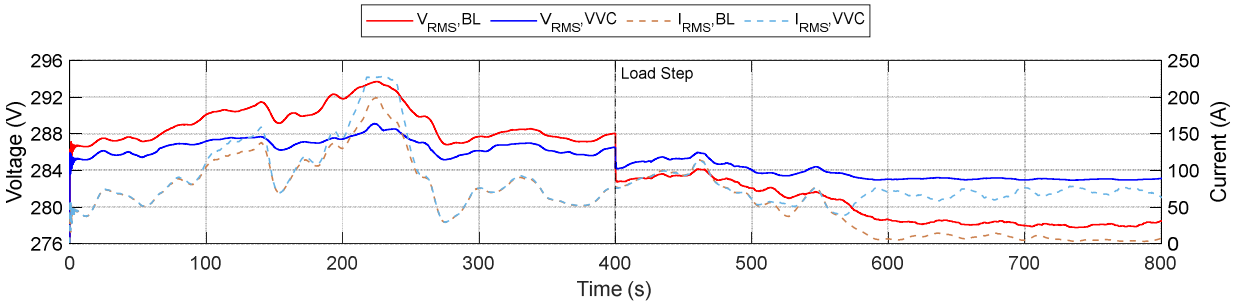

Fig. 13. Simulation Results for the SWiFT Wind Turbine Generator 2 Comparing Baseline and Volt-Var Curve Scenarios.

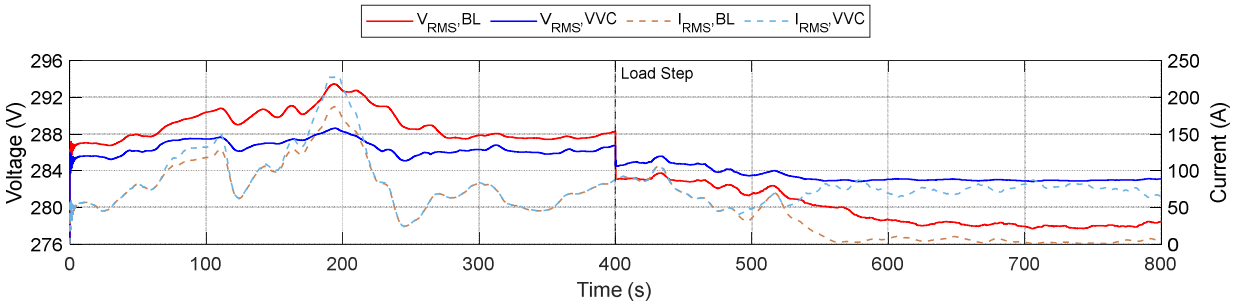

Fig. 14. Simulation Results for the SWiFT Wind Turbine Generator 3 Comparing Baseline and Volt-Var Curve Scenarios.

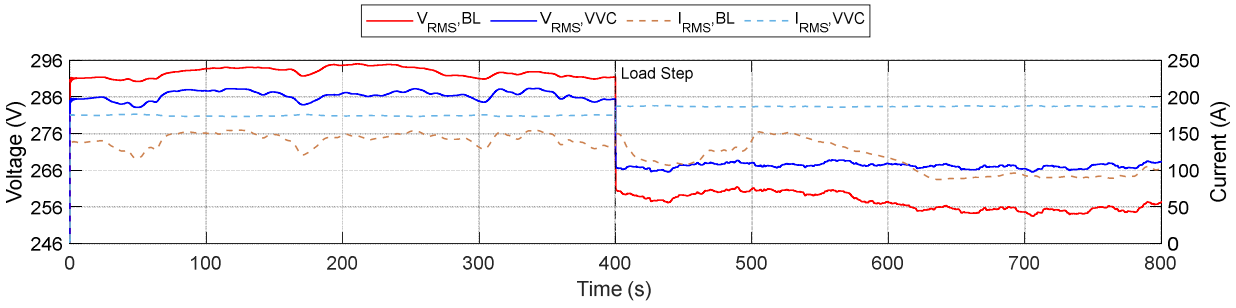

Fig. 15. Simulation Results for the GLEAMM Photovoltaic Inverter 1 Comparing Baseline and Volt-Var Curve Scenarios.

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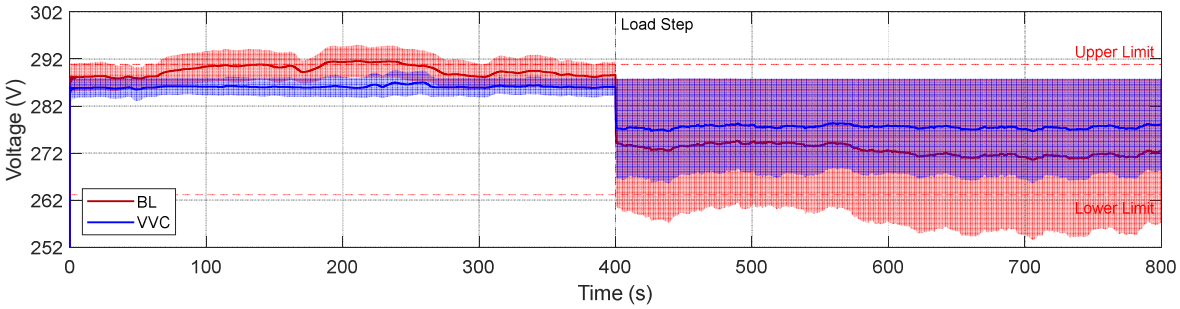

Fig. 16. Simulation Results for the Average, Maximum, and Minimum Bus Voltage Comparing Baseline and Volt-Var Curve Scenarios.

VI. Conclusion

In this paper, we demonstrate the ability of a WTG and a PV inverter to provide voltage regulation using VVC control. Simulation models for three WTGs and a PV inverter with VVC control capabilities are connected to a power distribution system and simulated in *MATLAB/Simulink*. To test the performance of the VVC control, the active power provided by the PV inverter creates a high voltage event, while the variable load creates a low voltage event. Simulation results are obtained by comparing two scenarios: a BL scenario, which considers the WTGs and PV inverter operating with no control and a second scenario that implements a VVC control to allow the WTGs and PV inverter to provide reactive power. Simulation results demonstrate that the WTGs and the PV inverter are able to provide reactive power to regulate the voltage at their PCC at varying wind speed and irradiance conditions, within their nameplate power rating. Results for the BL scenario show that the voltage at the variable load exceeds both upper and lower ANSI limits, but when the WTGs and PV inverter are providing VVC control, the voltage is regulated within the ANSI limits. Results show that the WTGs and PV inverter are able to maintain the system voltage within ANSI limits.

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