Development of a Wind Turbine Generator Volt-Var Curve Control for Voltage Regulation Using Power Hardware-in-the-Loop

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***Abstract* – As interest in renewable energy increases, more distributed energy resources (DERs), including photovoltaics (PV) and wind turbine generators (WTGs), are being interconnected into the grid. Due to their dependence on natural resources, high penetrations of DERs may cause voltage deviations in distribution systems. Distribution feeders that include DERs must have the ability to regulate voltage. Advances in power converter technology has enabled DERs to regulate voltage. Autonomous controls such as Volt-Var Curve (VVC) control allow DERs to regulate voltage by generating or absorbing reactive power. Herein, this paper experimentally demonstrates the ability of a WTG to provide voltage regulation in a distribution feeder. Experimental results are obtained by deploying the VVC control in a wind turbine emulator connected to a real-time simulation model of a distribution feeder using a Power Hardware-in-the-Loop platform. The real-time simulation model of the distribution feeder along with simulation models of WTGs are simulated using an Opal-RT OP5600 real-time simulator. Experiments consider the wind turbine emulator operating simultaneously with two simulated WTGs in the real-time simulation environment, each one providing VVC to regulate voltage deviations caused by a variable load at the end of the distribution feeder.**

***Index Terms* – distributed wind, wind turbine generators, voltage regulation, controls, power hardware-in-the-loop.**

I. Introduction

The interest in renewable energy has increased the rate of installation of distributed energy resources (DERs) such as wind turbine generators (WTGs), photovoltaics (PV), and energy storage systems (ESS) [1]. Due to their dependence on varying natural resources, such as wind speed and solar irradiance, high integration of DERs may cause voltage deviations in distribution systems [2]. These voltage deviations not only limit higher adoption of wind and solar generation, but without sufficient regulation could result in system instability, voltage collapse, and could even lead to power outages. This creates challenges for utilities and system operators associated to maintaining system voltage within the operational limit [3]. It is evident that in order to ensure power system reliability and resilience, system voltage must be maintained within the required voltage limits. Although voltage variations were traditionally reduced by using capacitor banks, load tap changers, and other voltage regulation devices, advances in power converter technology have enabled DERs to provide voltage regulation [4]. Autonomous controls such as Volt-Var Curve (VVC) control allow DERs to regulate voltage by generating or absorbing reactive power. Although voltage regulation for WTGs is more common in transmission systems, there is an opportunity for WTGs to provide voltage regulation in distribution systems [5]. Previous research has demonstrated that WTGs can provide reactive power to regulate voltage through the use of VVC controls [6], adhering to grid interconnection standards such as IEEE Standard 1547-2018 [7]. Although studies have investigated that these controls are effective in simulation, there is a need to experimentally test the performance of these controls.

This paper experimentally demonstrates how a WTG can regulate voltage in a distribution feeder by replicating the simulation results obtained in [8], using a wind turbine emulator in a Power Hardware-in-the-Loop (PHIL) platform. This is achieved by implementing a VVC control in a wind turbine emulator's power converter connected to a real-time simulation model of a distribution feeder using a PHIL platform. The real-time simulation model of the distribution feeder along with simulation models of WTGs are simulated in an Opal-RT OP5600 real-time simulator and built using the RT-Labs toolbox. The simulated WTGs in the real-time environment aid in understanding the interactions that exist between simulated and hardware WTG power converters. Experimental results were obtained by utilizing variable wind speed profiles for both the hardware wind turbine emulator and the simulated WTGs. The VVC control performance is tested by subjecting the distribution feeder to varying load conditions in the real-time simulation environment, which causes the voltage to decrease at the end of the distribution feeder. Experimental results demonstrate that the wind turbine emulator can provide voltage regulation using VVC control.

II. Distribution Feeder Model Description

The distribution feeder simulation model used in this analysis is based on the Scaled Wind Farm Technology (SWiFT) facility [9]. The distribution feeder is composed of 10 buses and 8 distribution lines. In this power system, the primary line voltage is 12.47 kV, while the secondary line voltage is 480 V. The variable load, rated at 500 kW, connects to Bus 10 which is located at the end of the distribution feeder. The SWiFT wind farm is composed of three 200 kVA WTGs for a total rating of 600 kVA and connects to Bus 5. A diagram of the distribution feeder representing the SWiFT facility is shown in Fig. 1 [10]. In this diagram, Wind Turbine 1 is a physical wind turbine emulator while, Wind Turbine 2 and Wind Turbine 3 are simulated WTG models.

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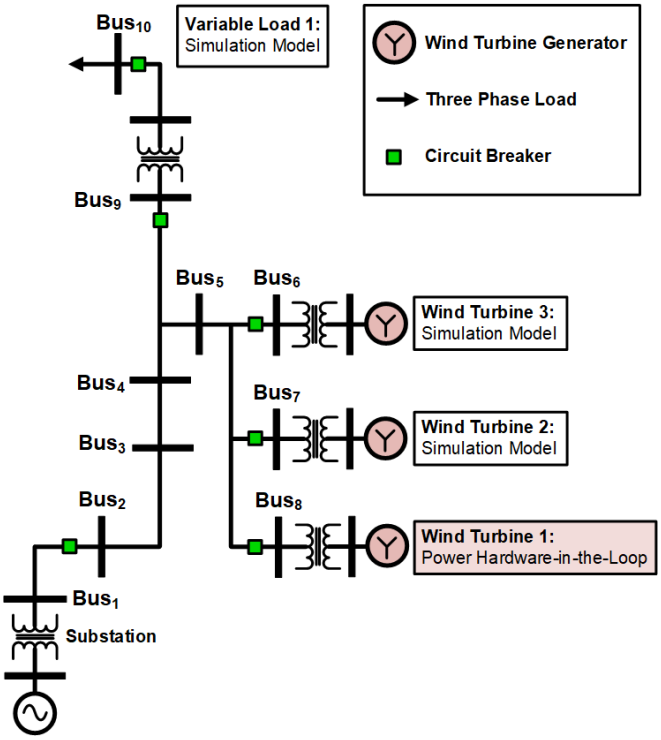

Fig. 1. Diagram of the SWiFT facility distribution feeder.

The simulated WTGs are modeled as a Type-IV, representing the aerodynamic and the electromechanical transient (EMT) components [11], [12], [13]. The aerodynamic model of the WTG emulates the drive train which generates the mechanical torque based on wind speed conditions. The EMT model of the WTG consists of a synchronous generator (SG), rectifier circuit, DC/DC converter (boost converter), inverter circuit, RLC circuit and transformer. The mechanical power that is captured by the EMT model of the WTG is converted to electrical power using the SG. The power generated by the SG is delivered to the rectifier circuit which transforms it into DC power, then it is regulated by the DC/DC converter and finally it is converted to AC power by the inverter circuit. The RLC circuit filters the output signal. The parameters used for the WTG models are summarized in Table I.

TABLE I: WTG PARAMETERS

Variable	Parameter	Value	Units
P_m	*Nominal Mechanical Power*	200	kW
P_g	*Nominal Electrical Power*	200	kVA
V_n	*Nominal Line to Line Voltage*	480	V
H_g	*Generator Inertia Constant*	0.41	s
H_w	*Wind Turbine Inertia Constant*	1.30	s
f_n	*Nominal Frequency*	60	Hz
v_{in}	*Cut-in Wind Speed*	3.5	m/s
v_n	*Nominal Wind Speed*	11.5	m/s
v_{out}	*Cut-out Wind Speed*	25.0	m/s

The WTG controls consist of an excitation control, speed regulator control (pitch control), and a grid-side converter controller. Reactive power is provided by utilizing the grid-side converter controller.

III. VOLT-VAR CURVE CONTROL DESCRIPTION

Autonomous controls, such as VVC control, are grid support functions that allow DERs to regulate voltage. This is achieved by generating or absorbing reactive power depending on the voltage measured at the point of interconnection or point of common coupling (PCC). Fig. 2 shows a default and an aggressive VVC. In Fig. 2, the slope of the VVC function is defined by the points along the curve, which determines the reactive power that can be generated or absorbed. For this analysis, an aggressive VVC is used [8].

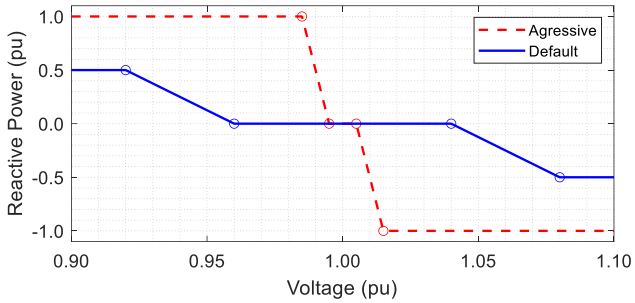

Fig. 2. Diagram of a default (shown in Blue) and an aggressive (shown in Red) VVC.

For this analysis, the setpoint for the VVC reference voltage is selected to help regulate the PCC voltage closer to 1.04 pu, withing the limits of IEEE Standard 1547-2018. This reference voltage value is closer to the substation's nominal voltage value and helps ensure that the voltage at the end of the distribution feeder is within acceptable limits.

IV. POWER HARDWARE-IN-THE-LOOP PLATFORM

PHIL enables a physical device to be connected into a simulated environment in order to test the performance of a specific hardware device operating in real conditions before it is deployed to the field [14]. Fig. 3 illustrates a block diagram of the PHIL platform used in these experiments, including, the Opal-RT OP5600 real-time simulator, wind turbine emulator and wind turbine controller.

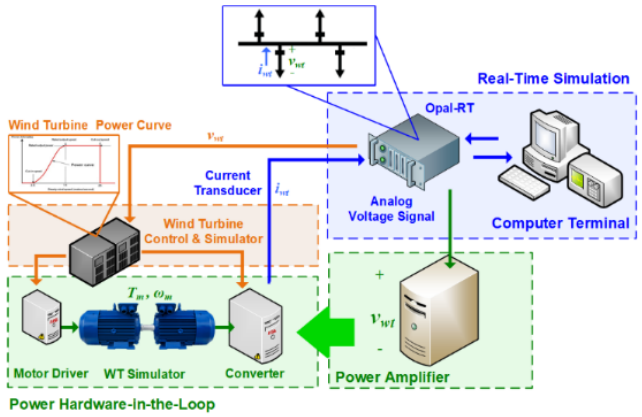

Fig. 3. Diagram of the real-time PHIL setup, including the wind turbine emulator.

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A real-time simulation model representing the SWiFT facility is simulated in *MATLAB/Simulink,* using the Opal-RT RT-Lab toolbox. This real-time simulation model considers two simulated SWiFT WTGs (Wind Turbine 2 and Wind Turbine 3 in Fig. 1) and a variable load located at the end of the distribution feeder. Fig. 4 illustrates wind speed measurements collected at the SWiFT facility. This wind speed data is used as the input to the WTG models. *Wind Speed Profile 1* was acquired by a SWiFT facility met tower while the rest of the wind speed profiles were obtained by modifying *Wind Speed Profile 1*. *Wind Speed Profile 2* and *Wind Speed Profile 3* are used for the simulation models of the WTGs (Wind Turbine 2 and Wind Turbine 3 in Fig. 1*)*, respectively. At 400 s, a load step is introduced using the variable load to create an event that will cause a voltage reduction throughout the distribution feeder. Fig. 5 illustrates the profile for the variable load.

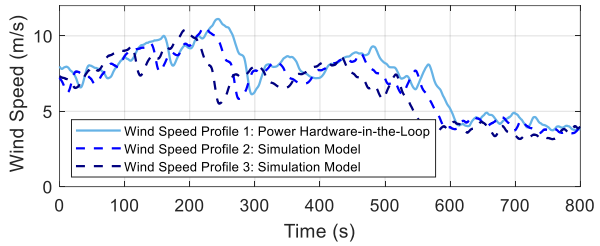

Fig. 4. Wind speed profiles for the SWiFT WTGs.

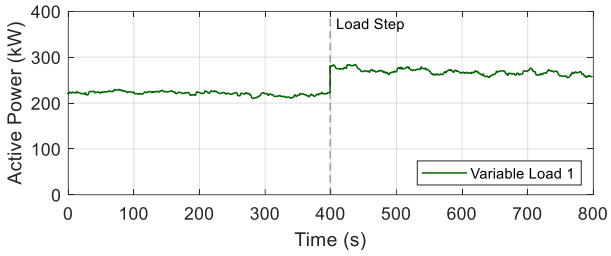

Fig. 5. Load profile for the variable load.

PHIL experimental results compare two different scenarios: a baseline (BL) scenario (WTGs operating with no control) and a VVC scenario (WTGs operating with VVC control). PHIL experiments are performed by programming the VVC controls in a wind turbine emulator [15]. The wind turbine emulator replicates a SWiFT facility WTG (Wind Turbine 1 in Fig. 1). *Wind Speed Profile 1,* shown in Fig. 4, is used for the wind turbine emulator. The wind turbine emulator incorporates the same controller hardware and software as an actual WTG, so the system behaves similar to the controllers used in the SWiFT facility. Fig. 6 shows wind turbine emulator used in the PHIL platform. The wind turbine emulator has a coupled motor ① and generator ②. The motor is driven by an ABB *ACS880-01-034A-5* ③. The ABB *ACS800-U11-0020-5* ④ is a regenerative power converter used to convert power for the grid and is the same model as the ones used for the WTGs in the SWiFT facility.

Fig. 6. Wind turbine emulator PHIL platform.

V. Experimental Results

Fig. 7 shows the experimental results for the WTGs active power. Fig. 8 shows the experimental results for the WTGs reactive power. Fig. 9 illustrates the experimental results for the WTGs apparent power.

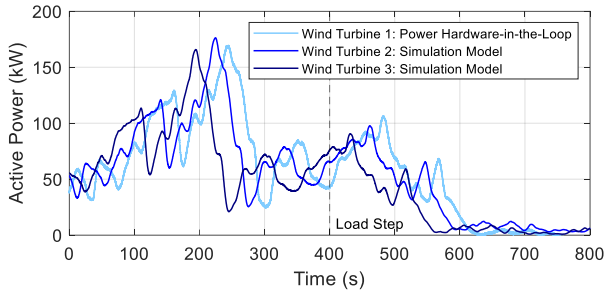

Fig. 7. Experimental results for the WTGs active power.

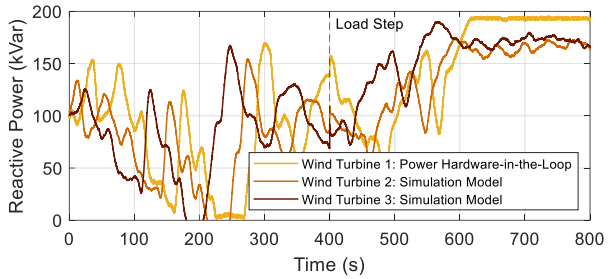

Fig. 8. Experimental results for the WTGs reactive power.

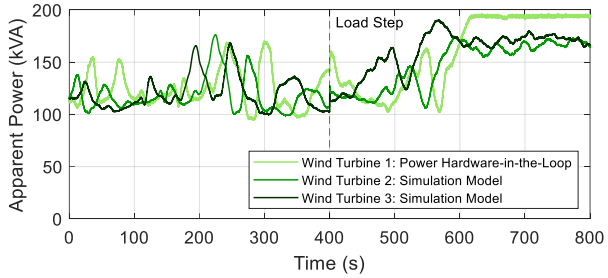

Fig. 9. Experimental results for the WTGs apparent power.

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Experimental results show that between 190 s and 250 s, the active power of the WTGs reach nominal power. After 500 s, the wind speed is reduced to 4 m/s and active power decreases until reaching 600 s, at which the WTGs stop producing active power. Experimental results show that the reactive power of the simulated WTGs 2 and 3 do not generate reactive power between 180 s and 280 s since the voltage at their PCC is at the target voltage. Experimental results show that the WTGs provide active and reactive power without exceeding their power rating limits. Fig. 10 through Fig. 12 show the experimental results of the WTGs voltage and current for the BL and VVC scenarios. Fig. 13 shows the experimental results of the variable load voltage and current for the BL and VVC scenarios. Fig. 14 shows the experimental results for the maximum, minimum, and average bus voltage comparing BL and VVC scenarios.

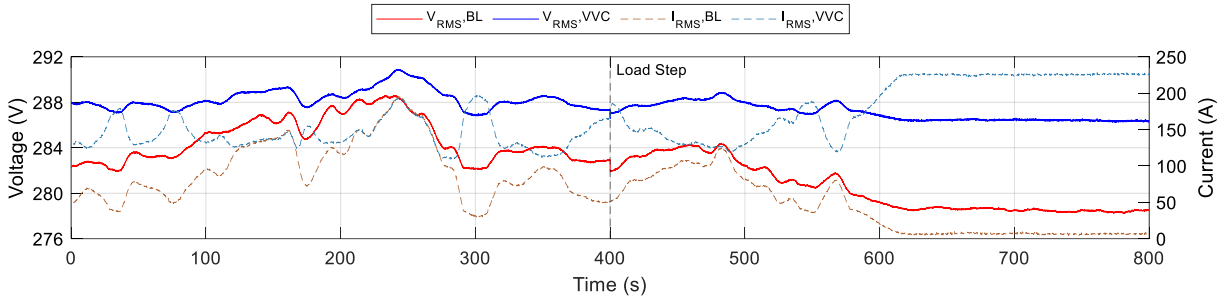

Fig. 10. Experimental results for the SWiFT WTG 1 comparing BL and VVC scenarios.

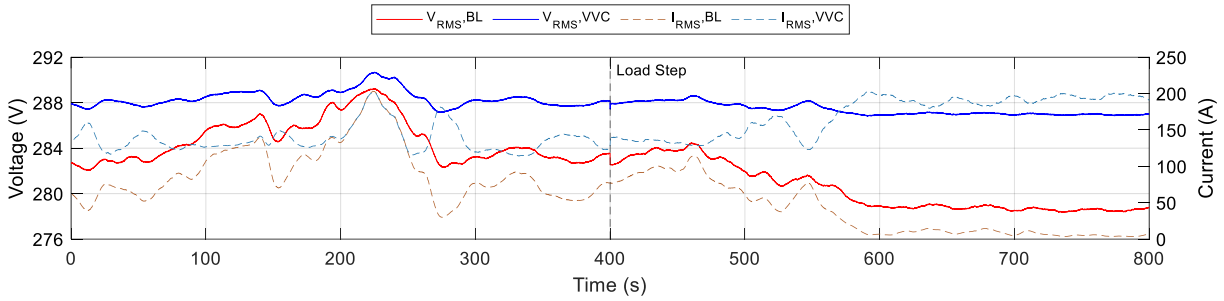

Fig. 11. Experimental results for the SWiFT WTG 2 comparing BL and VVC scenarios.

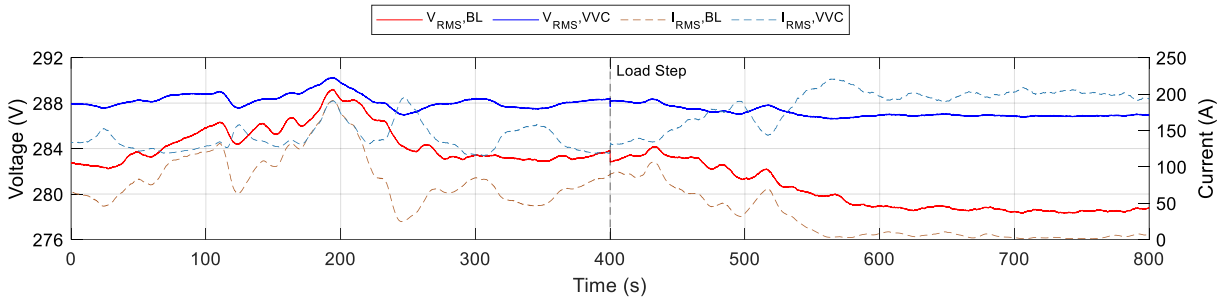

Fig. 12. Experimental results for the SWiFT WTG 3 comparing BL and VVC scenarios.

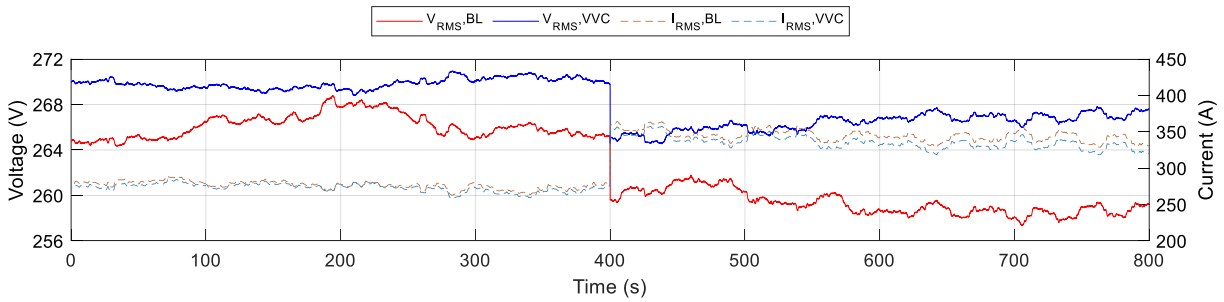

Fig. 13. Experimental results for the variable load bus voltage comparing BL and VVC scenarios.

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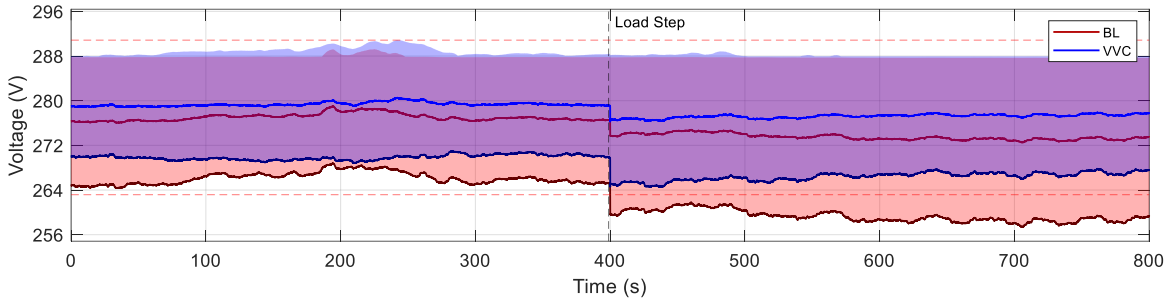

Fig. 14. Experimental results for the maximum, minimum, and average bus voltage comparing BL and VVC scenarios.

Results presented in Fig. 10 through Fig. 12 show that in the BL scenario the voltage at the WTGs vary, but for the VVC the WTGs can regulate their PCC voltage. Results in Fig. 13 show that when the WTGs operate with no control, the variable load ranges between 265 V and 269 V. When the low voltage event occurs, the variable load voltage is reduced to 258 V. When operating with VVC control, before the low voltage event is introduced, the WTGs are able to regulate their PCC voltage, increasing the voltage at the variable load to 270 V. When the low voltage event occurs, the WTGs are able to regulate their PCC voltage and maintain the voltage at the variable load to approximately 266 V. Results show that when the WTGs are operating with VVC control they can ensure that the average voltage is within an acceptable limit.

VI. Conclusion

This paper presents experimental results demonstrating how a WTG is able to regulate voltage in a distribution feeder. This is achieved by implementing a VVC control in a wind turbine emulator's power converter connected to a real-time simulation model of a distribution feeder using a PHIL platform. The simulation model used for these experiments represents the SWiFT facility, composed of three WTGs and a variable load connected at the end of the distribution feeder. The VVC control is tested by subjecting the system to a load step in the real-time simulation environment, causing a reduction in voltage at the end of the distribution feeder. The results demonstrate that the wind turbine emulator is able to provide voltage regulation using VVC control ensuring that the average system voltage is within the desired limits.

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