An Advanced Voltage Regulation Control for Distributed Wind Turbine Generators

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***Abstract* – Power grids that incorporate a variety of distributed energy generation must be capable of maintaining system voltage in the allowable range against potential disturbances caused by load variations and variable generation provided by renewable energy sources. Advances in grid support functions enable wind turbine generators (WTGs) to provide reactive power in order to regulate voltage. Herein, this paper investigates the ability of a WTG to provide voltage regulation in a distribution system. An advanced control is designed and tested by subjecting the system to a load step, which causes a low voltage event at the end of the distribution system. A stability analysis is performed in order to guarantee that the WTGs reactive power control is able to provide voltage support and improve the response of the distribution system. *MATLAB/Simulink* is used to carry out the advance control analysis method and to perform simulation.**

***Index Terms* – wind turbine generators, distributed wind, controls, voltage regulation, stability**

I. Introduction

With increasing interest in renewable energy generation, grid integration of Distributed Energy Resources (DERs), such as solar photovoltaics (PV), wind turbine generators (WTGs) and energy storage systems (ESS) have become more common. Distribution systems with high penetrations of DERs may experience voltage deviations due to variations in active power [1]. These voltage deviations can limit higher penetrations of wind power, causing wind farms to trip [2]. Moreover, without sufficient reactive power support, voltage instability may lead to voltage collapse. Traditionally, devices such as load tap-changers, capacitor banks, and voltage regulators are used to regulate voltage fluctuations [3].

Recent advancements in DER power electronics technology have enabled these devices to provide voltage regulation. DERs such as ESS and PV inverters have shown to stabilize system voltage [4]. In [5], ESS are used to improve transient system stability. In the work performed in [6], PV inverters with Volt-Var Curve (VVC) control provide the necessary mechanisms to ensure that system voltage magnitudes remain within acceptable limits. In [7] a coordination strategy based on the implementation of load tap-changers and PV inverters was proposed to provide voltage regulation. Previous research demonstrated that WTGs have the ability to provide reactive power to regulate system voltage [8]. VVC control has also been deployed in WTGs as shown in [9], but although results proved that VVC control is effective, the VVC regulated voltage within the VVCs deadband, allowing fluctuation around the desired voltage target.

To design a voltage regulation control, a stability analysis can be performed in order to understand the dynamic behavior of the power system. A system identification allows modulating the reactive power of the WTG to characterize dynamics of the system. Based on this system identification, a transfer function that represents the system can be used to design an advanced voltage regulation control. The transfer function of the system and the advanced control can be analyzed using bode plots to determine system stability. Based on these results, a compensator can be implemented into the control loop to improve system stability. In this paper, an advanced WTG control is designed and implemented in *MATLAB/Simulink* to perform voltage regulation. A system identification technique is employed to estimate the dynamic behavior of a power system. This is achieved by utilizing a probing signal that determines the effects that reactive power injection from a WTG has on a distribution system. The main contribution of this paper is using this identified system to design a WTG voltage regulation control. The control is tested by subjecting the system to variable load conditions which cause low voltage at the end of the distribution system. A stability analysis is performed to guarantee that the WTGs reactive power control can improve the response of the distribution system.

Simulation results for the advance controller demonstrated that the WTGs are able to regulate to the desired target voltage at varying wind speeds and varying load conditions. Moreover, when compared to traditional VVC control results in [9], the advance control was able to regulate to the desired target voltage with little to no voltage variations.

II. Distribution System Model

The power system used in this work represents the Scaled Wind Farm Technology (SWiFT) facility located in Lubbock, Texas [10]. Fig. 1 illustrates the one-line diagram of the SWiFT facility distribution system. The distribution system is connected to a transmission system through a transformer located at Bus 1. The main power source of the transmission system is modeled as a synchronous machine (SM). Table I summarizes the parameters for the SM model. The voltage level for the transmission system is 69 kV. The primary line voltage level of the distribution system is 12.47 kV. The secondary line voltage of the distribution system is 480 V. A variable load is connected at Bus 10. The wind farm, composed of three WTGs, is connected to Bus 5. Each WTG has a power rating of 200 kVA for a total generation of 600 kVA.

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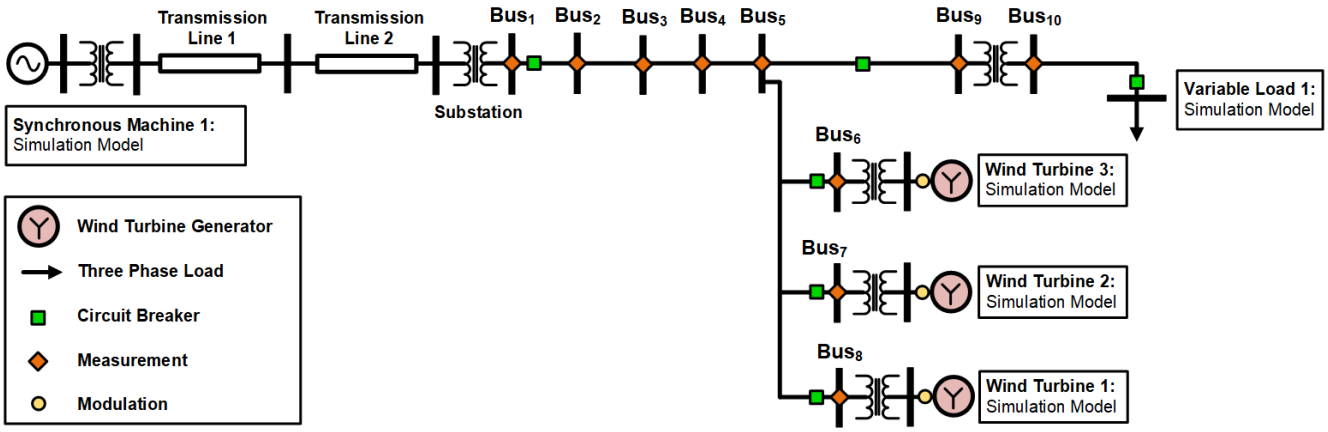

Fig. 1. One-Line Diagram for the SWiFT Facility Distribution System.

TABLE I: SYNCHRONOUS MACHINE PARAMETERS

Parameter	Variable	Value	Units
Nominal Electrical Power	P_g	600	kW
Nominal Voltage (Line to Line)	V_m	20	kV
Nominal Frequency	f_m	60	Hz
Generator Inertia Constant	H_g	3	s

III. WIND TURBINE GENERATOR MODEL

The WTGs are modelled as Type-IV. The WTG model combines an aerodynamic and an electromechanical transient (EMT) model [11]. The aerodynamic model emulates the WTGs drive train, generating a mechanical torque at different wind speeds. The WTGs EMT model converts the mechanical torque into electrical power. Table II summarizes the WTG model parameters.

TABLE II: WIND TURBINE GENERATOR PARAMETERS

Parameter	Variable	Value	Units
Nominal Mechanical Power	P_m	200	kW
Nominal Electrical Power	P_g	200	kW
Nominal Voltage (Line to Line)	V_n	480	V
Generator Inertia Constant	H_g	0.41	s
Wind Turbine Inertia Constant	H_w	1.30	s

Fig 2 illustrates a block diagram for the WTG model. The WTGs EMT model is composed of a synchronous generator, a rectifier, an average DC/DC boost converter, an inverter, an RLC filter, and a transformer.

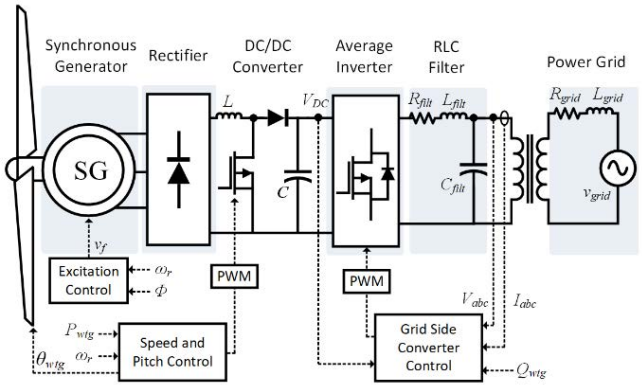

Fig. 2. Diagram of the Wind Turbine Generator Model.

IV. SYSTEM IDENTIFICATION OF THE DISTRIBUTION SYSTEM

To develop a voltage control strategy for the distribution system, it is important to understand the dynamics of the system and understand the relationship between the WTG reactive power and the voltage. System identification is a classical problem in signal processing, which can be applied to power system applications. Equation (1) illustrates an output signal.

$$y[n] = \sum_{k} h[n-k] \cdot x[k] \tag{1}$$

In this equation, the variable *x[k]* is the transmitted signal or input signal to a system and *h[n]* is the impulse response of the system. The objective is to identify the linear time invariant transfer function *H(ω)* of *h[n]* given the input *x[n]* and the output signal *y[n]*. In this work, the system identification technique relies on using an exponential chirp signal as a probing input signal. The time-domain function for a sinusoidal exponential chirp signal *q(t)* is given by equation (2).

$$q(t) = A \cdot sin \frac{2 \cdot \pi \cdot f_0 \cdot (r^t - 1)}{ln(r)} \tag{2}$$

In this equation, the variable *r* is the exponentially increasing frequency rate of change, as shown in equation (3).

$$r = \left(\frac{f_1}{f_0}\right)^{1/T} \tag{3}$$

In this equation, the variable A is the amplitude of the signal, f_0 and f_1 are the starting and ending frequencies of the exponential chirp signal and T is the duration of the signal. The starting frequency f_0 and ending frequency f_1 are selected to be 0.1 Hz and 30 Hz, respectively. These frequencies were selected in order to excite the electromechanical modes of the system. Variable A is 0.25 pu and T is 200 s. The variable A was selected to be small enough of a value such that the system remains in a linear region, but large enough that the dynamics of the system are perturbed. The objective is to estimate how the system's voltage varies when the reactive power is injected by the WTGs. Using the chirp signal *q(t)* as the input reactive power

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from the WTG and measuring the corresponding voltage at any bus of interest, a system identification technique can be used to obtain a transfer function of the system. The system identification technique used in this work is based on MATLAB system identification routine [12]. The output signal is the measured voltage at Bus 5, the point of interconnection of the three WTGs. The SWiFT distribution system has three WTGs. However, to simplify the system identification analysis, an aggregated model that represents all three WTGs is used, and the chirp signal is used as the input reactive power Q_c. Fig. 3 shows the dominant poles obtained from the system identification for four different transfer functions. In this analysis the 11th order transfer function is used.

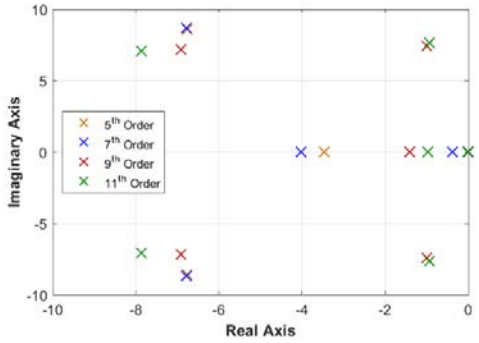

Fig. 3. Eigenvalues for Four Different Transfer Functions Obtained with the System Identification Technique.

V. Control Analysis and Design

The control analysis was performed on an aggregated WTG model connected to the distribution system. The objective is to control the reactive power injection of the WTG based on a voltage deviation. The voltage at the point of common coupling (PCC), V_{pcc} of the WTG is compared to a reference voltage, V_{ref}. For this tests, the reference voltage is set to 1.03 pu. The voltage error is fed into a control, $H(s)$ to determine the amount of reactive power Q_C that will be injected into the system. $H(s)$ represent any control and can be a simple proportional gain (K_g). The control is designed to operate with active power priority, which allows the WTG to provide reactive power depending on the active power that is being generated. This will limit reactive power based on the relationship between active and reactive power, as well as the power rating of the WTG.

A. Proportional Gain Control

This section shows the result when $H(s)$ is selected to be a proportional control with a gain of K_g. The unit of the gain is in pu of the WTG base power. The performance of the proportional control for different values of K_g is tested by setting the control to regulate to 1.03 pu at approximately t = 0.1 s. Increasing the value of the gain, K_g results in an increase in the controls output signal, Q_C. Fig. 4 and Fig. 5 shows the reactive power and voltage at the WTG with no control (Baseline) as well as with the proportional gain control (Control) when the gain K_g = 20 and K_g = 40. In the Baseline scenario, there is no reactive power from the WTG, and the voltage at the PCC remains the same. With K_g = 20, the controller is not able to regulate to the target voltage. When K_g = 40, it is observed that the system becomes unstable.

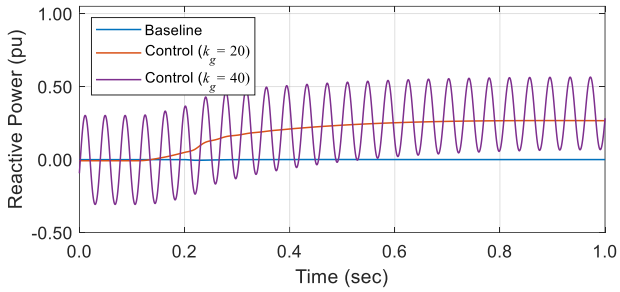

Fig. 4. Results for the Wind Turbine Generator Reactive Power.

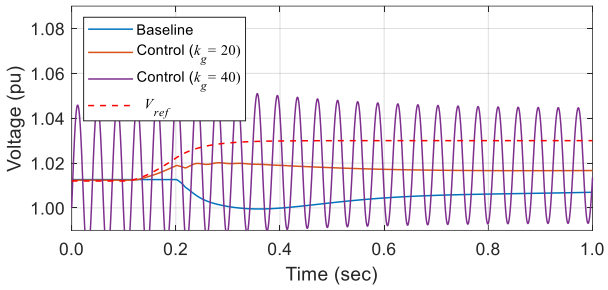

Fig. 5. Results for the Wind Turbine Generator Voltage at Bus 5.

The distribution system is a nonlinear system and the oscillations shown in Fig 4 and Fig. 5 are a result of nonlinear dynamics. The result of the system identification yields a linear transfer function which approximates the nonlinear dynamics of the distribution system. Fig. 6 shows the Bode plot of the identified system. It has a gain margin, G_m of 28 dB at 25.3 Hz, equivalent to a gain of 25. At, K_g = 40, when $K_g > G_m$, the frequency of the oscillation of the voltage and power signals is approximately 25 Hz. Using the identified systems linear transfer function, an advanced control is designed to increase the systems gain margin, increasing the reactive power of the WTG.

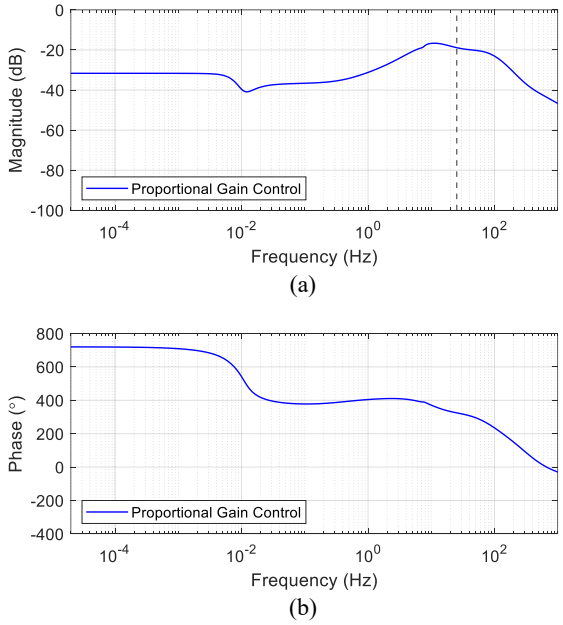

Fig. 6. Bode Plot of the Identified System. (a) Magnitude. (b) Phase.

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B. *Advanced Control*

The compensator *H(s)* of the advanced control is designed to allow higher gain values while maintaining stability. Increasing this gain results in higher reactive power injection, Q_C. The diagram of the advanced control is shown in Fig. 7.

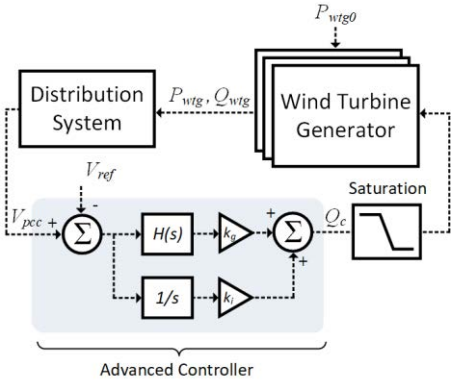
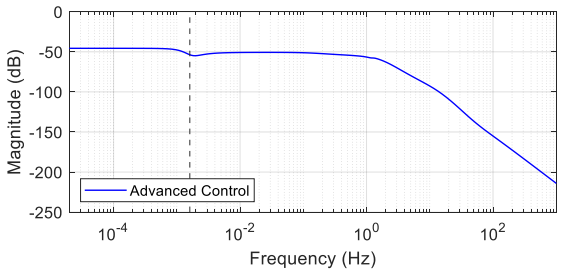


Fig. 7. Block Diagram of the Advanced Control.

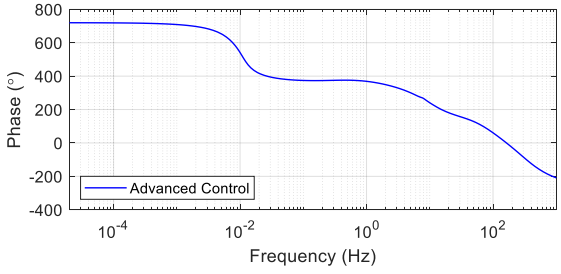
The compensator *H(s)* for the advanced control is described in equation (4).

$$H(s) = \frac{1}{s^2 + 10 \cdot s + 5} \tag{4}$$

Fig. 8 illustrates the Bode plot of the system with the advance control. With the advanced control, the gain margin G_m of the system increases to 63 dB, which is equivalent to a gain of K_g = 1,425. This allows the WTG to provide more reactive power while at the same time maintaining system stability. The performance of the advanced control for different gain values, K_g is tested on the distribution system. Fig. 9 and Fig. 10 illustrate the reactive power and voltage (V_{ref} is shown in the dashed red line) at the WTG for the advanced control cases when the gain K_g = 40, K_g = 400 and K_g = 800, K_i =600.



(a)



(b)

Fig. 8. Bode Plot of the Identified System. (a) Magnitude. (b) Phase.

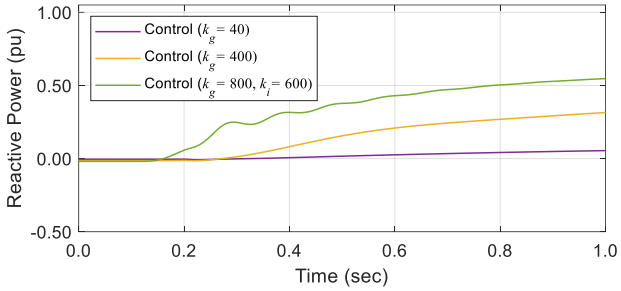


Fig. 9. Results for the Wind Turbine Generator Reactive Power.

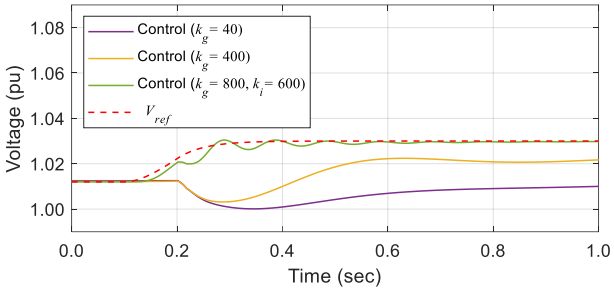


Fig. 10. Results for the Wind Turbine Generator Voltage at Bus 5.

VI. Simulation Results

Simulation results are obtained by testing the WTGs operating with no control (Baseline), and advanced control (Control) on the distribution system shown in Fig. 1. The designed control is implemented on all three WTGs, allowing them to inject reactive power. For each WTG, V_{ref} is selected to be 1.04 pu, and the feedback voltage, V_{PCC} for each control is their respective PCC voltage. In section V, the control analysis is performed on an aggregated WTG model representing three WTGs, yielding K_g =800, and K_i =600. However, in this section, the gain values are distributed to three WTGs, yielding K_g =800/3, and K_i =600/3. Fig. 11 shows the active power from the WTGs. For the Baseline and Control cases, the WTGs provide the same active power, and the results overlap. Fig. 12 shows the reactive power from the WTGs. Notice that as active power increases, each WTG provides reactive power depending on active power generated. Fig. 13 shows the voltage at the WTGs PCC. In this results since the WTGs regulate for the same V_{ref}, the Baseline and Control voltage measurement are the same for all three WTGs. The advance control regulates voltage to the desired V_{ref} of 1.04 pu. Fig. 14 shows the voltages at the PCC at the variable load. Notice that for the Baseline case the voltage falls under 0.95 pu, but for the Control case, the advance control is able to maintain the voltage at 0.97 pu.

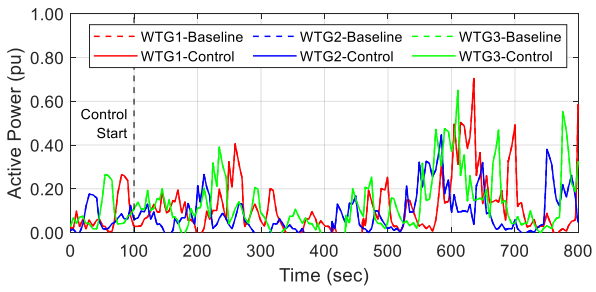


Fig. 11. Results for the Wind Turbine Generators Active Power.

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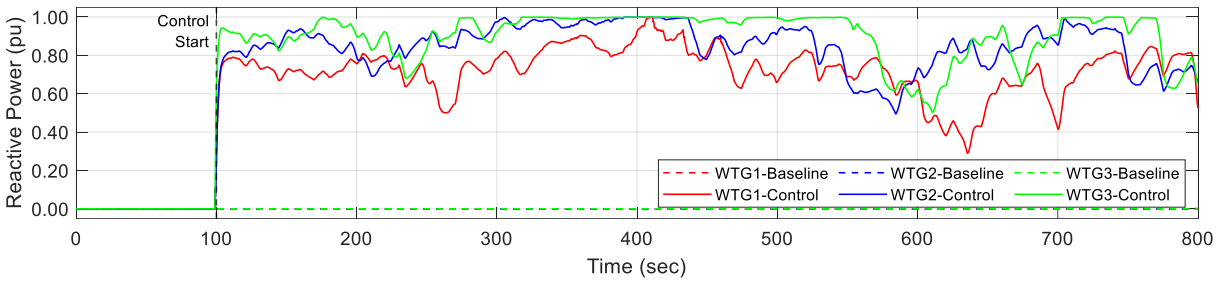

Fig. 12. Results for Wind Turbine Generators Reactive Power.

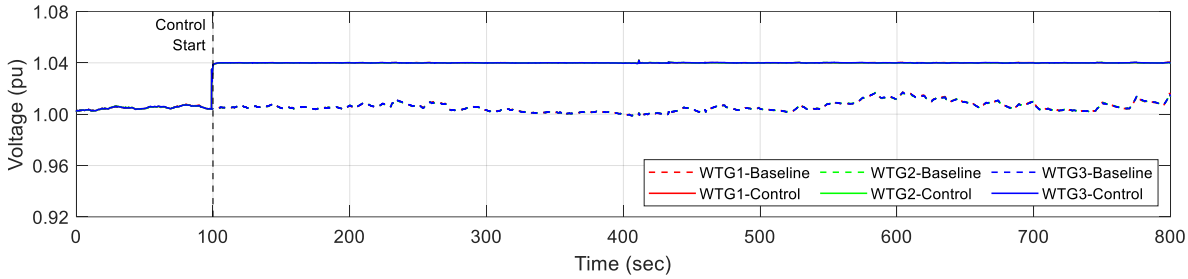

Fig. 13. Results for the Wind Turbine Generators Voltage at the Point of Common Coupling.

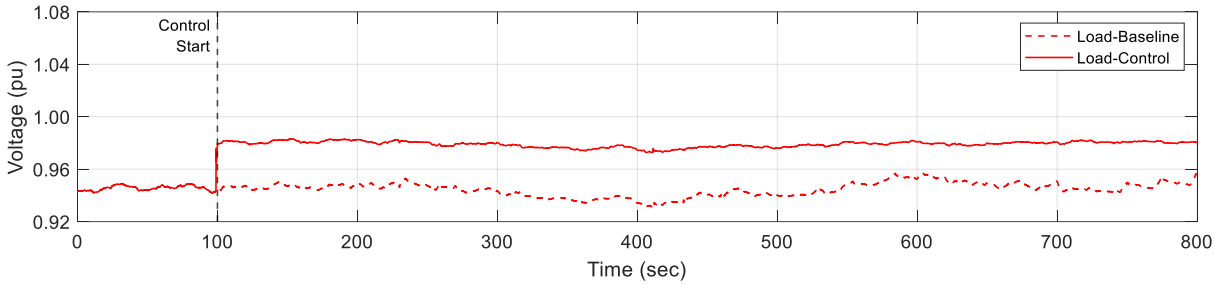

Fig. 14. Results for the Variable Load Voltage at the Point of Common Coupling.

VII. Conclusion

This work explores how WTGs can provide voltage regulation in a distribution power system by injecting reactive power. Simulation results are presented using *MATLAB/Simulink*. With a simple proportional control, the distribution system goes unstable when high gain values are introduced. An exponential chirp signal is used as a probing signal to identify the system. The resulting transfer function of the system identification is used to design an advance control for voltage regulation. The advanced control allows the WTGs to provide reactive power in order to regulate the voltage at their PCC at the desired voltage reference.

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