Dynamic Distribution Voltage Stability Control Using Distributed Energy Resources for Improved Resiliency

Kenan Hatipoglu
Department of Electrical and Computer Engineering
West Virginia University Institute of Technology
Beckley, West Virginia, USA 25801
Kenan.Hatipoglu@mail.wvu.edu

Yaosuo Xue
Electrical and Electronics Systems Research Division
Oak Ridge National Laboratory
Oak Ridge, TN USA 37831
xuey@ornl.gov

Abstract— **The main goal of this paper is to present the development and simulation of a new dynamic voltage stability control technique, with a focus on effective control and coordination of all available reactive power generation resources in a microgrid setting. Both power electronics and synchronous generator based distributed energy resources (DERs), and grid-supporting functions, are considered to accommodate a high penetration of diverse DERs and energy storage by using an enhanced microgrid voltage stabilizer. A systematic controller parameter synthesizing method is employed, and the overall dynamic voltage stability of the system is studied and evaluated with a time-domain dynamic simulation during emergency, hazard and disaster events. The results with the new approach show significant improvements and enhancements on the dynamic voltage profile of the distribution system, leading towards a more resilient grid system with high penetration of diverse DERs during emergency, hazard and disaster events.**

***Index Terms*-- Distributed energy resources, microgrid, volt/VAR control, voltage stability, voltage support.**

I. Introduction

Ever-increasing energy demands are stressing the generation and transmission capabilities of power systems. Due to the continuous growth and deregulation of the electric power grid, voltage stability has become one of the main problems concerning utilities. Utilization of distributed energy resources (DERs) has the ability to meet the growing demand, and high penetration of DERs with voltage-regulating capability is increasing rapidly on distribution systems. DERs are connected to power systems at distribution voltage levels, with the microgrid concept being used for interconnection. Having high penetration of DERs, especially with output power fluctuations, weakens the grid system from the voltage stability standpoint. Also, improving resiliency and voltage stability of the power grid/systems through local voltage regulation and control has drawn much attention, especially in light of past major cascading outages and natural disasters [1]. DERs with power electronics (PE) interfaces (such as solar panels and wind turbines) and/or synchronous generators (SGs) (used in micro turbines and diesel engine generators) and logic control using local measurements are capable of providing reactive power to tackle the voltage stability problem at distribution systems. But unfortunately, most of today's DERs with voltage-regulating capabilities disconnect, rather than support, the grid during disturbances such as emergency, hazard and disaster events like the one that recently occurred in Puerto Rico [1].

As devastating Hurricane Maria churned menacingly toward Puerto Rico on 19 September 2017, winds topping 280 kilometers per hour began to topple transmission towers and snap concrete power poles, entangling lines and battering power plants. Finally, at 2 a.m. on 20 September, the entire island went into total blackout. The Department of Energy's (DOE's) Grid Modernization Laboratory Consortium is looking at ways to make the grids of Puerto Rico more resilient against future storms. Those possibilities include modern relay protection of the key substations, predictive modeling with improved sensing capabilities, and hardened control devices. There are also opportunities for microgrids. Two hundred key locations on Puerto Rico for potential microgrids (plus another 400 under investigation) were identified, such as water treatment plants and hospitals. If fully implemented, the generating capacity would total 11 MW. Also, using simulations to identify better locations for wind and solar generation and integrating DERs were specifically mentioned in "How the Energy Department Is Helping to Restore Power in Puerto Rico and the U.S. Virgin Islands," an article by Bruce Walker, Assistant Secretary of the DOE Office of Electricity Delivery and Energy Reliability [1], [16].

In literature, the grid's dynamic voltage stability was enhanced with the voltage-regulating capabilities of SG-based DERs and electronically interfaced DERs individually. Dynamic voltage stability control of power systems [2]–[10] illustrated that DERs interconnected with the power grid using a PE interface are capable of supplying voltage regulation service dynamically, in particular with the application of PID controllers in [5]–[10], because of their simplicity and robustness. Similarly, a microgrid voltage stabilizer (MGVS) has been developed for controlling the excitation field voltage of the SGs, along with automatic voltage regulators to enhance the dynamic voltage stability of microgrids at simulation level [11] and hardware level [15]. However, the work focused on the control structure design with little effort on exploring how to set the PID controller parameters systematically. Furthermore, no single controller could control and coordinate all available SG-based DERs and PE-interfaced DERs altogether.

This paper intends to present a more effective control and coordination strategy for all available voltage-regulating capabilities of DERs to sustain the voltage stability phenomenon of the distribution system to increase overall grid resiliency. A systematic controller parameter calculation method was employed, and the overall dynamic voltage stability of the system was investigated and evaluated with a time-domain dynamic simulation during emergency, hazard and disaster events. Impacts of the high penetration of DERs on grid resiliency and power quality were also investigated. The expected results with the new approach are significant improvements and enhancements of the dynamic voltage profile of the distribution system, leading towards a more resilient grid system with high penetration of DERs during emergency, hazard and disaster events.

The main goal of this study is to develop a new dynamic voltage stability control technology, with a focus on effectively controlling and coordinating all available reactive power generation resources, both electronically interfaced and SG-based DERs, and grid-supporting functions, to accommodate a high penetration of DERs and energy storage by using distributed local control of DERs with an *enhanced* microgrid voltage stabilizer (EMGVS). Details of the EMGVS and the systematic parameter synthesizing method are covered in sections 2 and 3 respectively. Simulation results are provided for the IEEE 21-bus microgrid system to demonstrate the effectiveness of the new control strategy, followed by the conclusion and future work.

II. Enhanced Microgrid Voltage Stabilizer

The EMGVS works much like a power system stabilizer (PSS). The PSS provides an input to the excitation system of a generator to bring angle stability to a power system. The EMGVS gives an input to the excitation systems or reactive power loops of the DERs, which act to adjust reactive power into the microgrid to prevent any voltage collapse. The EMGVS model is shown in Figure 1.

The input to the EMGVS is a measure of the voltage deficiency of the microgrid. The per unit difference ($\Delta V_{i\,err}$) between the desired voltage ($V_{i\,des}$) and the dynamic voltage ($V_{i\,dyn}$) is calculated for all the load buses.

$$\Delta V_{i\,err} = \frac{V_{i\,des} - V_{i\,dyn}}{V_{i\,des}}, \qquad i = 1,2,..n \tag{1}$$

Weighting factors for all buses, based on the importance of the bus (i.e., induction motor loads are more sensitive to disturbances than the resistive loads), are defined. A weighted average of $\Delta V_{i\,err}$ is taken, to obtain an aggregate voltage deficiency (ΔV_{err}) for the system. ΔV_{err} is fed through a lead/lag block with a gain constant K and time constant T_1 and T_2. The output of this MGVS controller is V_{MGVS} , as shown in Figure 1.

The weighting factors for all the load buses, $i = 1$ to n are $\propto_1, \propto_2, \ldots.\propto_n$.

$$\Delta V_{err} = \frac{\propto_1 \Delta V_{1\,err} + \propto_2 \Delta V_{2\,err} + \ \ldots.\propto_n \Delta V_{n\,err}}{\propto_1 + \propto_2 + \cdots + \propto_n} \tag{2}$$

The following equations are the corresponding differential equations representing the EMGVS. It has additional lead-lag blocks added to the original MGVS control block. System output ΔV_{err} is taken as an input for the MGVS, and MGVS feeds the new block with V_{MGVS}. V_{EMGVS} is the new output of the EMGVS and changes the reference voltage of each reactive source as represented in Figure 1.

$$\dot{x}(t) = -\frac{1}{T_1}x(t) + \frac{K(T_1 - T_2)}{{T_1}^2}\Delta V_{err} \tag{3}$$

$$V_{MGVS}(t) = x(t) + K\frac{T_2}{T_1}\Delta V_{err} \tag{4}$$

$$\dot{x}_2(t) = -\frac{1}{T_3}x_2(t) + \frac{(T_3 - T_4)}{{T_3}^2}\, V_{MGVS} \tag{5}$$

$$V_{EMGVS}(t) = x_2(t) + \frac{T_4}{T_3}\, V_{MGVS} \tag{6}$$

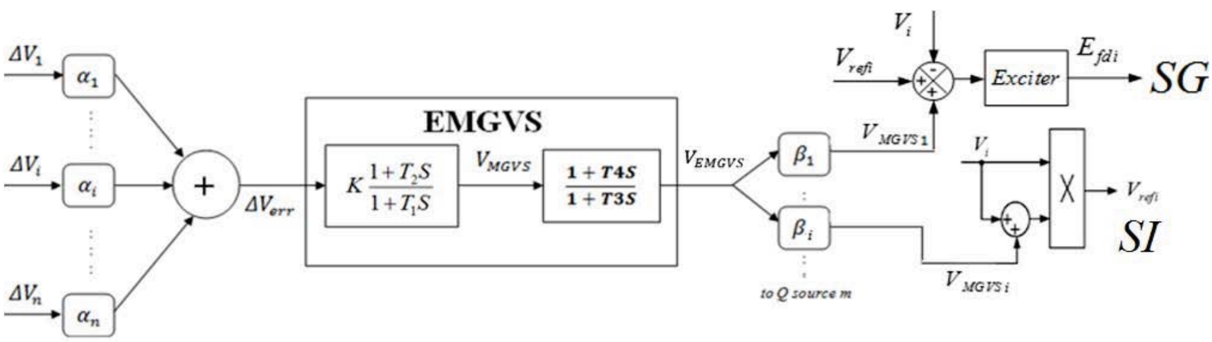

Figure 1. EMGVS model and its output signal to the SG excitation system and to the solar inverter (SI)

V_{EMGVS} represents the total EMGVS correcting signal, which is the output of a lead/lag block with time constants T_3 and T_4, which is divided between the DERs depending on the generation reserve, proximity to inductive loads, etc. The weighting factors for all generator buses (1 to m) are $\beta_1, \dots, \beta_i, \dots, \beta_m$. $V_{MGVS\,i}$ is the input to the i^{th} SG's excitation system or i^{th} voltage reference for generating pulse width modulation signal to drive the solar inverter (SI) as shown in Figure 1.

$$V_{MGVS\,i} = \beta_i \, V_{EMGVS}, \quad i = 1,2, \dots .m \qquad (7)$$

III. SYSTEMATIC SYNTHESIZING METHOD

Previous work [12], [13] has shown that the controller parameters greatly affect the DER dynamic response for voltage regulation. Incorrect parameter settings may cause inefficient (slow), oscillatory, or (worse) an unstable response that can lead to system instability. Logically this raises an interesting issue, especially when diverse DERs with voltage-regulating capabilities and high penetration are deployed. It is not feasible for utility engineers to perform trial-and-error to find suitable parameters when a new DER is connected. Hence, an autonomous approach is needed to eliminate the manual process. An autonomous approach is much more advantageous for adjusting control parameters to regulate voltage with minimal communications (such as a voltage schedule provided with low-cost communications).

To calculate the parameters of the EMGVS blocks, a systematic synthesizing method based on pole placement methodology (PPM) was used in this study. PPM uses the EMGVS to obtain the characteristic equation with unknown parameters of the overall system. The idea of pole placement is to make an existing system's poles further away from the $(j\omega)$ axis in the negative half complex plane by introducing new poles with new control blocks. With EMGVS, two new poles can be introduced, and three pole locations can be determined.

The transfer function of the system is used to calculate the parameters of the EMGVS blocks with PPM. To obtain the transfer function of the system, the overall system has to be linearized at an operation point. The linearization process is fully described in [14].

After linearization of the system, the transfer function of the system can be obtained with the help of A, B, C and D matrixes of the system. The characteristic equation of the overall system, including the original MGVS, can be formulated as

$$1 + G(s) * C(s) = 0 \qquad (8)$$

$G(s)$ is the system transfer function and $C(s)$ is the transfer function of the MGVS.

$$G(s) = \frac{N(s)}{D(s)} \qquad (9)$$

$N(s)$ is the numerator of the system transfer function, and $D(s)$ is the denominator of the system transfer function.

$$C(s) = \frac{n(s)}{d(s)} \qquad (10)$$

$n(s)$ and $d(s)$ are the numerator and denominator of the MGVS's transfer function respectively.

$$n(s) = K * T2\,s + K \qquad (11)$$

$$d(s) = T1\,s + 1 \qquad (12)$$

$$1 + \frac{N(s)}{D(s)} * \frac{n(s)}{d(s)} = 0 \qquad (13)$$

$$\frac{D(s) * d(s) + N(s) * n(s)}{D(s) * d(s)} = 0 \qquad (14)$$

After expanding the characteristic equation, (16) can be obtained from (15).

$$\Longrightarrow \quad D(s) * d(s) + N(s) * n(s) = 0 \qquad (15)$$

$$D(s) * (T1\,s + 1) + N(s) * (K * T2\,s + K) = 0 \qquad (16)$$

MGVS itself has three parameters: gain constant K, and time constants T1 and T2. Equation (16) contains three unknowns. To find these three unknowns, three more equations are needed. To obtain these three equations, values for the three poles of the overall system can be selected based on the idea of making the system's poles further away from the $(j\omega)$ axis inside the negative half complex plane. Once the values of the three poles of the overall system are chosen as $s_1, s_2,$ and s_3, we can solve the three equations with three unknowns.

$$D(s_1) * (T1\,s_1 + 1) + N(s_1) * (K * T2\,s_1 + K) = 0 \qquad (17)$$

$$D(s_2) * (T1\,s_2 + 1) + N(s_2) * (K * T2\,s_2 + K) = 0 \qquad (18)$$

$$D(s_3) * (T1\,s_3 + 1) + N(s_3) * (K * T2\,s_3 + K) = 0 \qquad (19)$$

After obtaining the unknown parameters of MGVS, now it is time to find the new block's unknown parameters. Let's define the additional new block as $p(s)$.

$$p(s) = \frac{1 + T4s}{1 + T3s} \qquad (20)$$

The new block has two unknown parameters, T3 and T4. To find these two parameters, two equations are needed. The unknown values of the MGVS block have been calculated previously. Now K, T1 and T2 are known. Only T3 and T4 values are unknown. Equations (21) and (22) can be derived after adding $p(s)$ into (16).

$$D(s_4) * (T1\,s_4 + 1) * (T3s_4 + 1) + N(s_4) * (K * T2\,s_4 + K) * (T4s_4 + 1) = 0 \qquad (21)$$

$$D(s_5) * (T1\,s_5 + 1) * (T3s_5 + 1) + N(s_5) * (K * T2\,s_5 + K) * (T4s_5 + 1) = 0 \qquad (22)$$

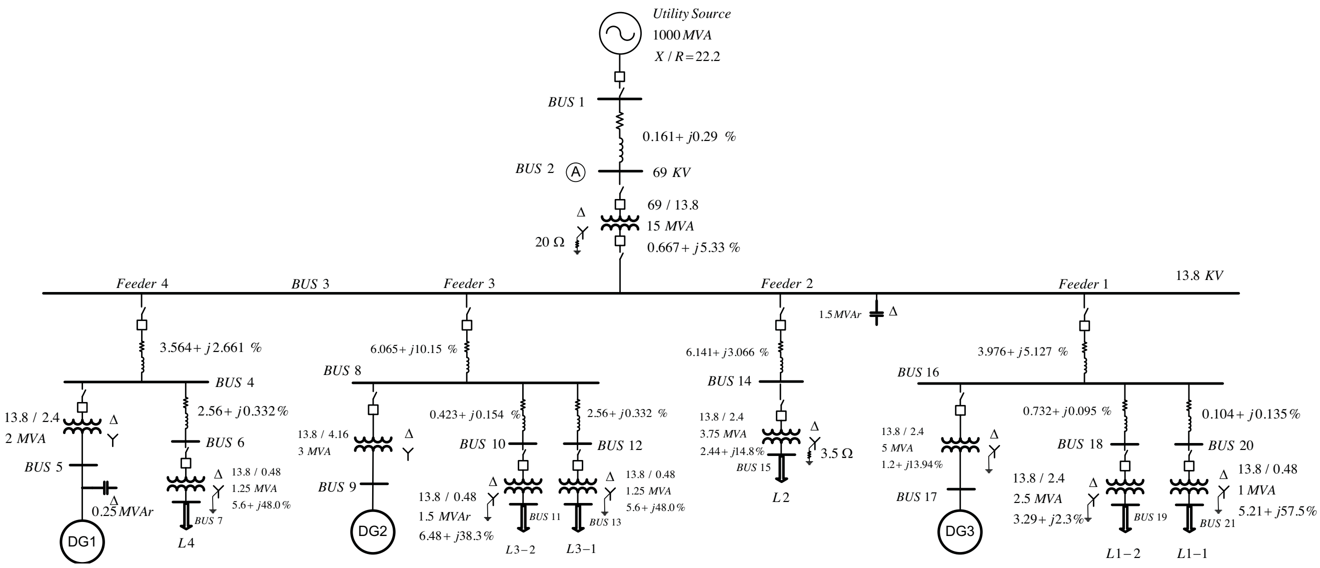

Figure 2. IEEE 21-bus microgrid system

This is a simple two equations, two unknowns problem. After solving these equations, values of T3 and T4 can be obtained. The new poles to be selected are s_4 and s_5. After finalizing the entire process, the parameters needed for the EMGVS, which are K, T1, T2, T3 and T4, are now obtained.

IV. Simulation Results

The IEEE 21-bus microgrid system as shown in Figure 2 is used as a test system for implementing the DER-based EMGVS control strategy. Different combinations of PE- and SG-based DERs were used during the study. To imitate emergency, hazard and disaster conditions, three-phase fault, line outages and drastic load change (load loss or generator loss) scenarios were simulated, and the effectiveness of the control method was evaluated and significant improvements on the system's dynamic voltage stability and grid resiliency were observed.

As an illustrative example, a microgrid system with two PE-based DERs with a solar inverter at Buses 5 and 9 and one SG at Bus 17 were used. Effectiveness of the EMGVS control method was investigated/compared against the no-control case and the random control parameter case under a three-phase fault at Bus 15, imitating a tree branch fall on utility lines. Overall power system operation was simulated for 10 seconds; the fault occurred at 2 seconds of the simulation and lasted 4 seconds. A 10% load loss on the entire system's loads occurred at 6 seconds. As can be observed from the simulation results in Figure 3, the EMGVS with the systematic controller parameter synthesizing method gives the best results on load voltages while effectively controlling and coordinating the reactive power generation among the DERs. The no-control case shows that SIs do not contribute enough to reactive power generation if the inverter voltage reference is not changed by the EMGVS. Also, random assignment of control parameters (Ps) does not ensure the best operating conditions, as can be visualized as the black line in Figure 3.

V. Conclusion and Future Work

This paper successfully presents a dynamic voltage stability control technique developed to more effectively control and coordinate all available voltage-regulating capabilities of diverse DERs together in a microgrid setting. The technique sustains the voltage stability phenomenon of the distribution system to increase overall grid resiliency on the simulation level. The results with the new approach employing EMGVS show significant improvements and enhancements on the dynamic voltage profile of the distribution system, leading toward a more resilient grid system with high penetration of diverse DERs during emergency, hazard and disaster events. Investigating possible field testing opportunities and hardware in the loop platforms with Real Time Digital Power System Simulation capabilities would be considered as future extension activities of this project. Hardware implementation of the EMGVS and optimization studies on the developed method are also intended to be achieved in the near future.

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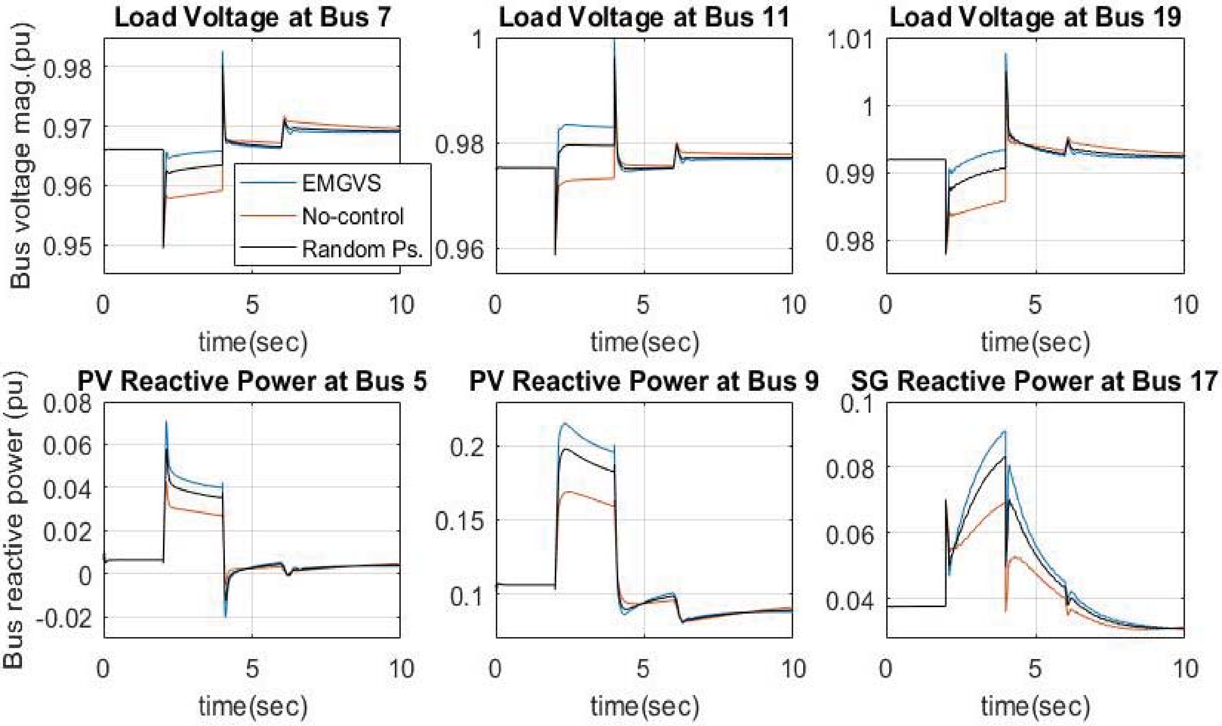

Figure. 3. Load voltages and reactive power generation of the DERs under three-phase fault at Bus 15

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