

The Effect of the Volt/Var Control of Photovoltaic Systems on the Time-Series Steady-State Analysis of a Distribution Network

Insu Kim, Ronald G. Harley, and Raee Regassa

Georgia Institute of Technology, Atlanta, GA USA

R. G. Harley is also a Professor Emeritus at the University of

KwaZulu-Natal, in Durban, South Africa.

iskim@gatech.edu, rharley@ece.gatech.edu, and

raey@gatech.edu

Yamille del Valle

National Electric Energy Testing Research and

Applications Center

Atlanta, GA USA

yamille.delvalle@neetrac.gatech.edu

Abstract—Grid-connected photovoltaic (PV) systems with relatively high capacity effectively reduce peak load, but because of their reverse power flow, they can cause overvoltage along a feeder that can exceed five percent of the rated voltage. Modern PV systems with the capability of Volt/Var control can mitigate overvoltage by either injecting or absorbing reactive power. Thus, the objectives of this study are to (1) model a distribution network (feeder J1 located in the northeastern United States and enhanced by thirteen PV systems) using OpenDSS; (2) use actual collected load profile data as input data to the simulation model and PV generation output data at 15-minute intervals; and (3) calculate the time-series steady-state power flow of the distribution network when PV systems generate or absorb reactive power. Finally, it addresses overvoltage resulting from the deployment of high-capacity grid-connected renewable PV systems and mitigation techniques for such overvoltage issues, particularly Volt/Var management and control.

Index Terms—Photovoltaic (PV) systems, time-series steady-state power flow, and Volt/Var.

I. INTRODUCTION

Grid-connected photovoltaic (PV) systems with relatively moderate to high capacity (hundreds of kW to tens of MW) have many benefits for electricity producers and distribution systems such as reductions in peak load and losses. However, because of their inverter's ability to produce or consume reactive power, they also have an ability for reactive power management and voltage management on the distribution feeder. There are, however, challenges associated with the connection of high capacity PV systems in the distribution network: approval from the local utility is required for the PV system to actively participate in the voltage regulation of the system. The changes in the active and reactive outputs have to be coordinated with the local utility in order to stay within the service voltage requirements of ANSI C84.1-2011 Range A and the other voltage regulation and reactive management equipment on the feeder. In addition, protection functions of the interconnection system have to respond to abnormal conditions in the distribution network in accordance with "Table 1" of IEEE Std 1547a-2014. Only under mutual agreement of the local utility and the PV operator can other static or dynamic voltage and clearing time trip settings be permitted [1].

A practical study on the integration of high capacity PV systems in a distribution network should include the new requirements of IEEE Std 1547a-2014 into the voltage and reactive power management scheme. However this study only focuses on the full potential of the PV Volt/Var application when these constraints are not included. A subsequent study will look into the practical aspects to assess the differences with respect to the cases presented below.

Many studies have examined the steady-state behavior of distribution networks enhanced by grid-connected PV systems (with unity power factor). In 2002, one study claimed that utility distribution systems would experience a substantial increase in distributed generation (DG) systems for the following few decades and addressed the issues on the changes in reliability, overcurrent protection, and transformer connections [2]. After that, another study modeled a distribution system, supplied by a transformer of 14 MVA and 70/10 kV, with a synchronous generator of 3 MW or 6 MW and an induction generator of 3 MW or 6 MW; added a PV system with a relatively low capacity of 50 kW, the power output of which is estimated from irradiance data in the Leuven area of Belgium in 5-sec intervals during one year; and concluded that voltage fluctuation caused from the PV system with relatively low capacity is limited [3]. Another study [4] proposed an analytical method based on voltage sensitivity analysis for a linearized power system model, modeled a 70-bus distribution network with a peak demand of 3,802.2 kW and 2,694.6 kVar, as a case study, and determined maximum limits of acceptable power such as 1,198 kW, 989 kW, and 706 kW that a DG could inject while not violating 5 percent of rated voltage at steady state. Using OpenDSS, a further study modeled a 12 kV and 10 MW distribution feeder; calculated the time-series steady-state power flow of the test feeder enhanced by PV systems with a capacity of 20 percent of peak demand with the capability of Volt/Var control; and concluded that PV inverters with the appropriate reactive power control could increase the hosting capacity (which means the allowable maximum capacity) of DG without leading to voltage fluctuations [5, 6]. Recently, a study modeled a conventional feeder with two PV systems with their total capacity of 2 MW as well as a feeder with a 6-MW PV plant; it examined reverse power flow, voltage rise and fluctuations, and reactive power fluctuations caused by PV systems; and addressed the issues of the impact of grid-

connected PV systems on voltage rise and fluctuations during steady state [7]. More recently, a study modeled 12.47 kV distribution feeders using OpenDSS; it investigated the impacts of PV with penetration levels of 10, 30, and 50 percent on voltage, tap changes of regulators, and losses of the system; and claimed that existing control settings such as regulators and capacitor banks on the feeders enhanced by high-penetration PV (50 percent) failed to mitigate voltage rise [8]. In 2013, using OpenDSS, one study modeled grid-connected smart inverters for PV systems with the capability of Volt/Var, Volt/Watt, and dynamic reactive power control and analyzed their impact on the voltage of distribution feeders [9]. Then, another recent study modeled 16 radial distribution feeders using GridLAB-D; calculated the steady-state power flow of the feeders enhanced by either clustered or distributed PV systems; and claimed that the maximum penetration level of distributed PV systems (not violating the limits of voltage) could be 50 percent and that of clustered PV systems could be 30 percent [10].

However, these studies have not performed the steady-state analysis of distribution feeders enhanced by relatively high-capacity PV systems (e.g., 30 percent) with the capability of Volt/Var in high resolution (e.g., 15-min intervals). Therefore, this study (1) models feeder J1, which is located in the northeastern United States and is enhanced by thirteen PV systems with their total capacities of 15 and 30 percent of total peak generation [11], using OpenDSS, an open-source program useful for calculating steady-state power flow [12]; (2) uses, as input data to the simulation model, collected load profile data and the generation output data of thirteen PV systems installed on the feeder, at 15-minute intervals; and (3) examines the time-series steady-state behavior of the feeder when PV systems generate or absorb reactive power, which means Volt/Var control. Finally, it addresses the overvoltage issues caused by the deployment of grid-connected PV systems with the capability of Volt/Var control and management.

II. PROBLEM STATEMENT

Present regulations require that grid-connected DG systems, particularly PV systems in this study, maintain a terminal voltage within 0.95 to 1.05 PU of rated voltage and operate at or near unity power factor [13]. However, to maintain terminal voltage within the range, present PV systems can inject or absorb reactive power. In addition, since various DG systems, including PV systems, wind farms, and microturbines, with inverters able to control reactive power, are being connected to distribution networks, the objective of this study is to (1) calculate the time-series steady-state power flow of the distribution network enhanced by such PV systems either with or without the capability of Volt/Var control, (2) analyze an increase in overvoltage caused from active and reactive power injected by grid-connected PV systems, and (3) investigate the mitigation techniques on the overvoltage issues (e.g., the effect of Volt/Var control), from the perspective of time-series steady-state analysis.

III. REACTIVE POWER CONTROL

Nowadays, an inverter in a solar PV system can adjust the

reactive power to be injected to feeders, which is referred to as Volt/Var control. Figure 1 illustrates on how a PV inverter can control reactive power according to its bus voltage in steady-state. For example, between Q_2 and Q_3 in the range of 0.99 and 1.01 PU of voltage, the PV inverter injects only active power. However, if its bus voltage increases above V_3 (e.g., 1.01 PU), the inverter absorbs reactive power, thus operating as an inductive load; and if the bus voltage decreases below V_2 (e.g., 0.99 PU), the inverter provides reactive power like a capacitive load [14]. This study implements Volt/Var control on the inverter model used by OpenDSS [15], the set points of which are presented in TABLE I and the minimum and maximum reactive power values (Q_{min} and Q_{max}) are changed from ± 1.0 PU to ± 0.4 PU to avoid violating the maximum iteration constraint (for controllers) imposed by OpenDSS.

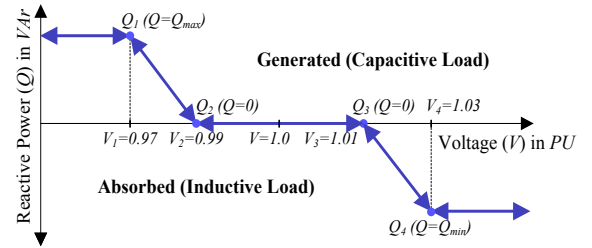


Figure 1. Example of Volt/Var control [14].

TABLE I. SET POINTS OF INVERTERS FOR VOLT/VAR CONTROL [5]

PV Bus Voltage (V)		Reactive Power (Q)
Base Voltage of 120 V	PU	PU
114	0.9500	$Q_{max} = +0.4$ ($= Q_1$ in Figure 1)
119	0.9917	$Q_2 = 0$
121	1.0083	$Q_3 = 0$
126	1.0500	$Q_{min} = -0.4$ ($= Q_4$ in Figure 1)

IV. CASE STUDY

EPRI has published distribution feeder models, including “J1, K1, and M1,” on their public domain website for research studies on the analysis of the effect of PV systems on distribution feeders [11]. This particular study uses feeder J1 in Figure 2 as a distribution network, which is located in the northeastern United States and enhanced by thirteen PV systems [11]. TABLE II shows the detailed specification of feeder J1 and the PV systems. The feeder operates at a nominal line-to-line voltage of 12.47 kV. The total capacity of the highly unbalanced local loads (which consist of 1,384 individual residential, commercial, and light industrial loads at a nominal line-to-neutral voltage of 0.24 kV) is 9.39 MW and the total power consumption of the feeder at such peak load is 11.86 MW because of distribution losses. To analyze the effect of PV systems on an increase in overvoltage, EPRI has installed four three-phase PV systems with a total capacity of 1,882 kVA and nine single-phase PV systems with a total capacity of 114 kVA and measured their generation output in 1-second, 1-minute, 15-minute, and 1-hour intervals from June 17, 2012 to June 25, 2012. This study collects the generation output of the thirteen PV systems and uses them as input data to time-series steady-state power-flow analysis.

V. SIMULATION RESULTS

A. Overvoltage Caused by Grid-Connected PV Systems

Grid-connected PV systems can reduce peak load but they may cause an increase in overvoltage along a feeder because of their reverse power flow. Figure 3 shows the line-to-neutral voltage profile of feeder J1 at a peak load of 9.39 MW for the distance of each bus from the substation (in Figure 2), which is enhanced by thirteen PV systems with their assumed total generation output of 2 MVA. In both the figures, the voltages decrease as the distance from the substation increases, but they dramatically increase at distances of 5 km, 8 km, and 13 km because of operations of voltage regulators. In addition, the assumed maximum generation of PV systems presented in Figure 3 (b) increases the feeder voltages along the distance of feeder J1 at a peak load of 9.39 MW.

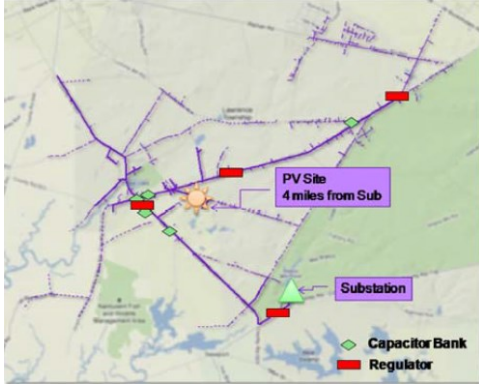


Figure 2. Feeder J1 in the northeastern United States [11, 16].

TABLE II. DETAILED SPECIFICATION OF FEEDER J1 AND PV SYSTEMS

Feeder	Name	J1
	The Number of Buses(Nodes)	3,434(4,245)
	Total Peak Generation (Total Peak Demand)	11.86 MW(9.39 MW)
	Nominal Voltages (kV _{LL})	12.47 and 0.416
	Location	Northeastern United States
	The Number of Customers	1,384
	Customer Type	Residential, Commercial, Light Industrial
PV	Length	58 Miles of Primary Lines
	Total Capacity	2.0 MVA($\approx 1,996$ kVA= $1,882+114$ kVA)
	The Total Number of PV Sites	2
	The Total Number of PV Systems	13

However, the effect of PV systems presented in Figure 3 fails to examine not only solar variability conditions such as sunny, overcast, highly variable, and rainy days but also medium or low demand that varies continuously according to customer power consumption. Therefore, to analyze the impact of grid-connected PV systems on the voltage profile, this study proposes following scenarios:

- 1) Thirteen PV systems with their total capacity of 2 MVA (a peak power of 1,813.6 kW and about 15.3 percent of a total peak generation of 11.86 MW at peak load) are installed on feeder J1 with load profile data varying in 15-minute intervals during a week.
- 2) Additional PV systems with their total capacity of 2 MVA are also added on the feeder, thus with a total capacity of 4

MVA (30.6 percent), as an example of high-capacity PV systems.

- 3) These PV systems operate in 15-minute intervals during a week, from June 17 to June 25, 2012, to reflect solar variability. The locations of the PV systems are presented in Figure 2.

Figure 4 shows the total generation output of thirteen PV systems with a capacity of 2 MVA installed on feeder J1 in 15-minute intervals on June 17, 2012. This study calculates the time-series steady-state power flow of feeder J1 enhanced by the PV systems in 15-minute intervals during a week, using OpenDSS. Figure 5 indicates the daily generation profile of feeder J1 on June 17 when the feeder is enhanced by PV systems with their total capacities of 2 MVA followed by an additional 2 MVA. In Figure 5, this study assumes that PV systems generate only active power at unity power factor [13]. Figure 6 depicts the weekly generation profile of feeder J1. Since the main objective of PV systems is to reduce the consumption of electricity generated by non-solar plants, from the perspective of their daily and weekly operations, low- and high-capacity PV systems effectively reduce peak demand, which can be identified in days 2-6 in Figure 6.

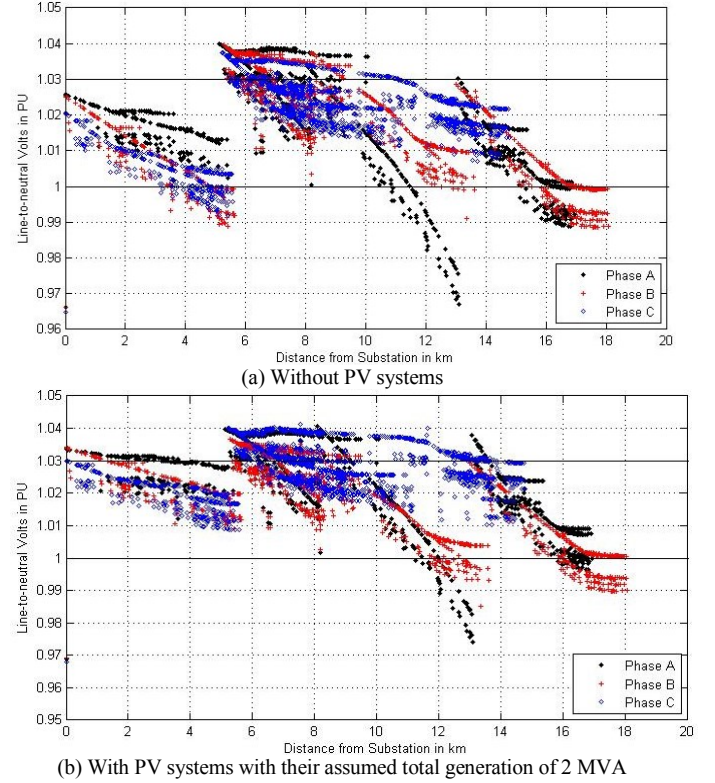


Figure 3. Feeder voltage profile for the distance of each bus from the substation at a peak demand of 9.39 MW.

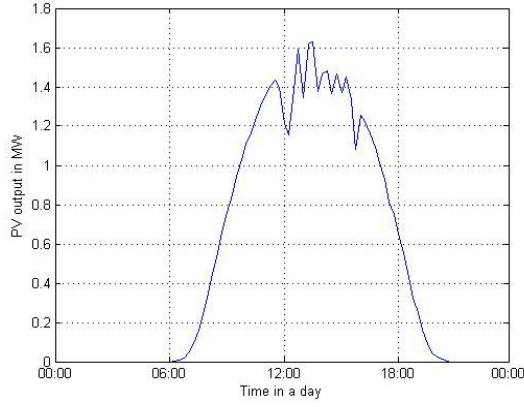


Figure 4. Total generation output of thirteen PV systems with a capacity of 2 MVA installed on feeder J1 in 15-minute intervals on June 17, 2012.

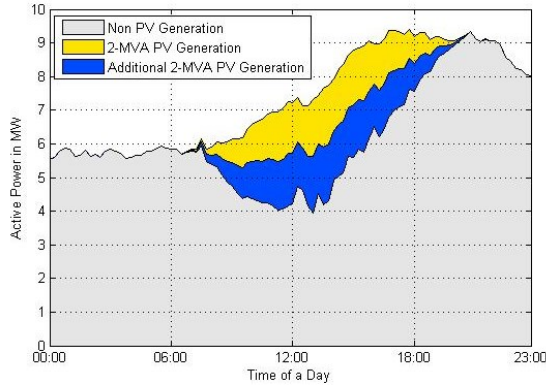


Figure 5. Daily generation profile of feeder J1 in 15-minute intervals on June 17, 2012.

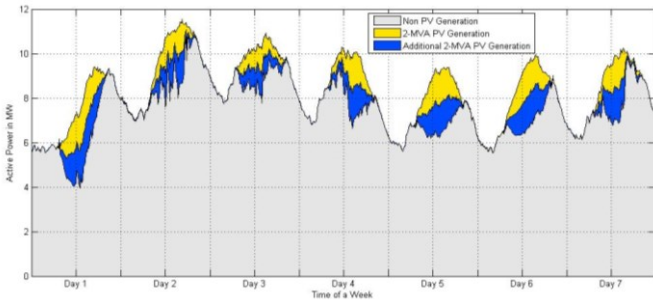
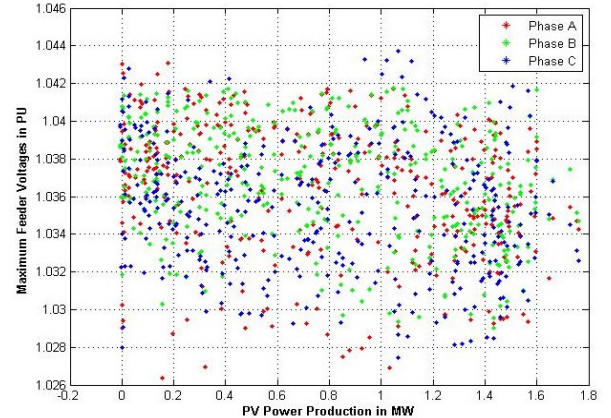


Figure 6. Weekly generation profile of feeder J1 in 15-minute intervals.

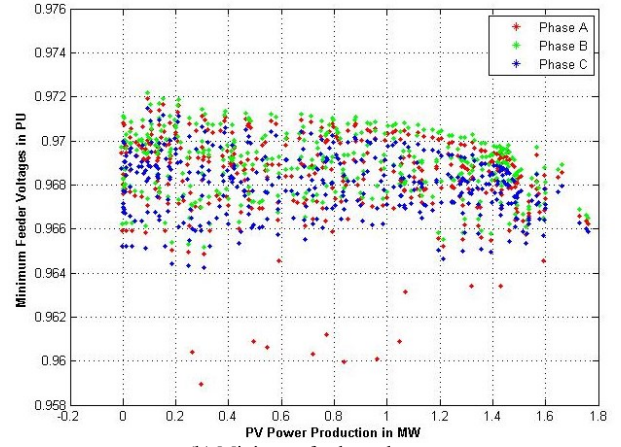
B. High Penetration of PV and the Effect of Volt/Var

Figure 7 plots maximum and minimum feeder voltages for the generation output of PV systems with a capacity of only 2 MVA in 15-minute intervals during a week. It indicates that no voltages of the feeder enhanced by PV systems with relatively low capacity (15.3 percent) violate the limits of 0.95 PU and 1.05 PU. Since high-capacity PV systems able to control reactive power absorption or generation can be connected to power grids, this study assumes that (1) PV systems with their total capacities of 2 MVA and 4 MVA are

installed on feeder J1 and (2) either Volt/Var control is available or not.



(a) Maximum feeder voltages



(b) Minimum feeder voltages

Figure 7. Maximum and minimum feeder voltages for total PV generation output with their capacity of 2 MVA in 15-minute intervals during a week.

Figure 8 plots maximum line-to-neutral feeder voltages according to total PV generation output in 15-minute intervals during the week when Volt/Var control is either available or not. In Figure 8 (a), since PV systems inject only active power at unity power factor, maximum feeder voltages show an increasing pattern as PV generation increases, particularly ten points exceed the limit of 1.05 PU. However, in Figure 8 (b), PV systems inject or absorb reactive power so that they can maintain terminal voltages within a specified range, typically within 0.95 to 1.05 PU of rated voltage. Figure 9 shows the daily line-to-neutral voltage profile of bus “B61252.CUST1.C.3,” one of the buses on feeder J1, in 15-minute intervals on June 21, 2012. The black solid line shows voltages of the case without PV systems, which is referred to as “No PV”; the blue dashed line shows voltages of the case with PV systems without the capability of Volt/Var control, referred to as “PV without V/V”; and the red dash-dotted line shows voltages of the case with PV systems with the capability of Volt/Var control, referred to as “PV with V/V.” PV systems without the capability of Volt/Var control (the blue dashed line) increase the voltage much more than the other cases, even exceeding 1.05 PU around noon. However,

PV systems with the capability of Volt/Var control (the red dash-dotted line) mitigate the overvoltage by absorbing reactive power. Since a PV system can inject or absorb its full reactive power according to the P-Q performance curve of an inverter (the curve of which is defined by a circle with \pm maximum Q at $P=0$), at night, voltages in the case of Volt/Var control (the red dash-dotted line) are lower than those of the case without the capability of Volt/Var control (the blue dashed line).

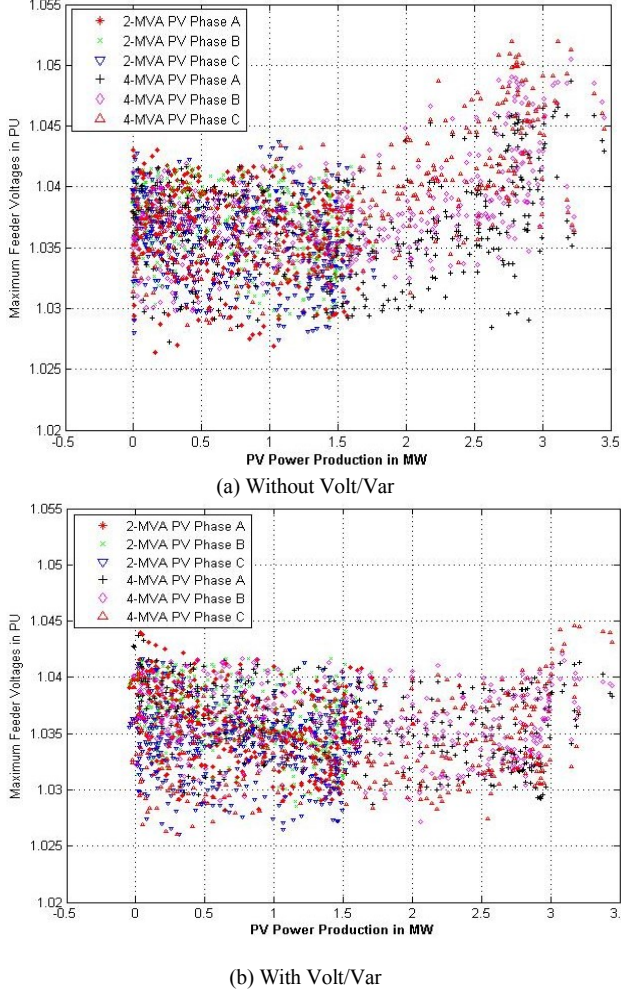


Figure 8. Volt/Var control of PV systems with total capacities of 2 and 4 MVA.

C. Techniques for Mitigating Overvoltage Issues

To mitigate the increase in overvoltage along a feeder (caused by active and reactive power injected by grid-connected DG systems), one can select among various strategies:

- 1) *Adding or reprogramming voltage-controlled capacitor banks, load tap change transformers, and voltage regulators.* Although overvoltage stemming from grid-connected DG systems may increase the operation of voltage-controlled capacitor banks, load tap changer transformers, and voltage regulators, and their frequent

operations reduce their life cycles and increase maintenance cycles, their well-coordinated interaction with DG systems may mitigate an increase in overvoltage.

- 2) *Allowing reactive power control.* Present regulations require that DG systems, including PV systems, wind farms, microturbines, plug-in electric vehicles, and distribution energy storage systems, operate at or near the unity power factor [13]. However, since advanced reactive power control techniques such as Volt/Var control (or Volt/Var optimization), Volt/Watt control, and dynamic Var control, and conservation voltage reduction methods have been developing for better voltage regulation, they may mitigate increases in voltage.
- 3) *Reducing or limiting DG system capacity.* Since the increases in voltage can be significant when high-capacity PV systems are installed on lightly loaded feeders, which are common in rural areas, reducing or limiting PV system capacity may mitigate overvoltage.
- 4) *Upgrading existing systems.* Although it is not economical, replacing transformers at the service entrance, upgrading primary and secondary conductors, or adding energy storage can be a mitigation technique.

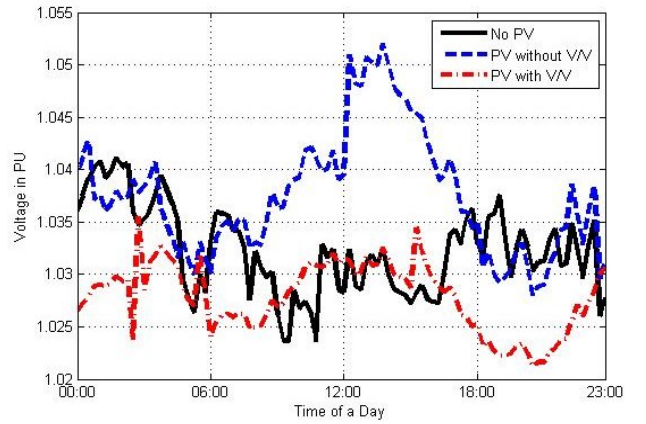


Figure 9. Daily voltage profile at bus "B61252.CUST1.C.3" on June 21, 2014.

VI. CONCLUSION

The main objective of this study has been to analyze the time-series steady-state behavior of a distribution network when low- and high-capacity renewable PV (photovoltaic) systems generate or absorb reactive power (which means Volt/Var control). For this purpose, this study (1) has modeled feeder J1 (which is located in the northeastern United States and enhanced by thirteen PV systems) as an example of a distribution network; (2) examined the time-series steady-state behavior of the feeder when PV systems generate or absorb reactive power; and (3) addressed the overvoltage issues caused from the deployment of grid-connected PV systems.

The results from the time-series steady-state analysis of feeder J1 show that grid-connected PV systems can effectively reduce peak load. However, high-capacity PV systems (e.g., 30.6 percent of a total peak generation of 11.86 MW) without the capability of Volt/Var control may cause an increase in overvoltage along the feeder, even exceeding a voltage of 1.05

PU. In contrast, PV systems with the capability of Volt/Var control could also mitigate voltage rise (caused from grid-connected PV systems), in other words, not exceeding the limit of 1.05 PU. However, this study has not analyzed the long-term, typically annual, behavior of a distribution network when DG systems such as PV systems, wind farms, and microturbines systems are operating. In addition, it has not analyzed the other reactive power control methods such as Volt/Watt control and dynamic Var control, which can be also used to mitigate the overvoltage issues, but the proposed case study could be extended for such cases by modeling advanced reactive power control and then performing time-series steady-state analysis.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the National Science Foundation under Grant #1232070, which was used for part of the work presented herein. The authors also would like to thank (1) Frank Lambert at the National Electric Energy Testing Research and Applications Center for his input to discussions pertaining to not only the time-series steady-state power flow of distribution networks but also Volt/Var control and (2) EPRI for their publication of feeders J1, K1, and M1 on their public domain for research studies.

REFERENCES

- [1] *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems - Amendment 1*, IEEE Std 1547a-2014, 2014.
- [2] R. C. Dugan and T. E. McDermott, "Distributed Generation," *IEEE Industry Applications Magazine*, vol. 8, pp. 19-25, 2002.
- [3] J. Driesen and R. Belmans, "Distributed Generation: Challenges and Possible Solutions," *IEEE Power Engineering Society General Meeting*, Montreal, Canada, 18-22 June, 2006.
- [4] H. M. Ayres, W. Freitas, M. C. de Almeida, and L. C. P. da Silva, "Method for determining the maximum allowable penetration level of distributed generation without steady-state voltage violations," *IET Generation, Transmission and Distribution*, vol. 4, pp. 495-508, 2010.
- [5] J. Smith, B. Seal, W. Sunderman, and R. Dugan, "Simulation of Solar Generation with Advanced Volt-Var Control," *21st International Conference on Electricity Distribution*, Frankfurt, Germany, 6-9 June, 2011.
- [6] J. Smith, "Stochastic Analysis to Determine Feeder Hosting Capacity for Distributed Solar PV," Electric Power Research Institute, Tech. Rep., 2012.
- [7] F. Katiraei and J. R. Agüero, "Solar PV Integration Challenges," *IEEE Power and Energy Magazine*, vol. 9, pp. 62-71, 2011.
- [8] S. K. Solanki, V. Ramachandran, and J. Solanki, "Steady state analysis of high penetration PV on utility distribution feeder," *IEEE PES Transmission and Distribution Conference and Exposition*, Orlando, FL, USA, 7-10 May, 2012.
- [9] J. Smith, "Modeling High-Penetration PV for Distribution Interconnection Studies," Electric Power Research Institute, Tech. Rep., 2013.
- [10] A. Hoke, R. Butler, J. Hambrick, and B. Kroposki, "Steady-State Analysis of Maximum Photovoltaic Penetration Levels on Typical Distribution Feeders," *IEEE Transactions on Sustainable Energy*, vol. 4, pp. 350-357, 2013.
- [11] Electric Power Research Institute, *Distributed PV Monitoring and Feeder Analysis*. Available from: <http://dpv.epri.com/>
- [12] Electric Power Research Institute, *Smart Grid Resource Center*. Available from: <http://www.smartgrid.epri.com/SimulationTool.aspx>
- [13] *IEEE Application Guide for IEEE Std 1547(TM), IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*, IEEE Standard 1547.2-2008.
- [14] I. Kim, R. G. Harley, and R. Regassa, "Distribution Networks at Peak Load and the Analysis of the Impact of Volt/Var Control on the Improvement of the Voltage Profile," *North American Power Symposium*, Pullman, Washington, USA, 7-9 September, 2014.
- [15] Electric Power Research Institute, *OpenDSS PVSystem Element Model*, Tech. Rep., 2011.
- [16] Electric Power Research Institute, *Feeder J1*, Tech. Rep., 2014.