Impacts and Interactions of Voltage Regulators on Distribution Networks with High PV Penetration

Ali Hariri, M. Omar Faruque, Ruturaj Soman, Rick Meeker
Department of Electrical and Computer Engineering and the Center for Advanced Power Systems
Florida State University
2000 Levy Avenue, Tallahassee, FL., USA
ahh13@my.fsu.edu, faruque@caps.fsu.edu, soman@caps.fsu.edu, meeker@caps.fsu.edu

***Abstract*—This paper discusses the impacts and interactions of voltage regulation devices on systems with high PV penetration under different solar conditions and voltage control algorithms. The study is done using a tool that was developed under a Department of Energy (DOE) funded project, Sunshine State Grid Initiative (SUNGRIN). The tool is composed of Matlab scripts and functions that use a Component Object Model (COM) interface to communicate with the Open Distribution System Simulator (OpenDSS) developed by EPRI. The tool is applied in this paper to analyze and study the dynamic interaction between voltage regulation devices in a distribution network, and the impacts that photovoltaic (PV) systems have on the operation of these devices in the network. A real feeder from a Florida-based utility has been used to perform this study with different incident solar radiation (insolation) scenarios. Case studies show the difference in the activity of the voltage regulating devices with the variation of PV power injection to the grid. The case studies also investigate the impacts of allowing PV systems to participate in voltage regulation using different algorithms.**

***Index Terms*—Distribution systems, Dynamic simulation, High PV penetration, Matlab, OpenDSS, Qusi-static simulation, Solar energy, Voltage regulation.**

I. Introduction

The traditional power network was designed to accommodate unidirectional power flow from central generation to transmission lines that will deliver power to distribution feeders to distribute it to the loads [1]. With the introduction of distributed generation (DG) this traditional design is forced to accommodate new concepts and challenges. The existing distribution system components (such as regulators, protection devices and other switch gears) were not designed to accommodate bidirectional flow of power [1]. Therefore, the increase in the level of PV penetration in distribution systems is accompanied with a lot of concerns regarding the potential impacts that the PV will induce in the network [2].

These potential impacts are affected by various parameters such as the location of the PV in the system, the stiffness of the system, the voltage regulation equipment present in the feeder, the size of the PV plant etc. Moreover, the variability of solar irradiance, and the predictability of the operation of PV plants under different system conditions and the dispatchability of the PV plant also affect the severity of these impacts. One of the obvious impacts noticed in different networks, especially radial feeders, as the PV penetration increases is the impact on the feeder voltage levels [3].

The integration of PV in the grid has a great lifting effect on node voltages. The impact on voltage varies depending on the interconnection point of the PV. As the PV interconnection point gets closer to the end node of the feeder it causes greater influence on the line voltage distribution [3]. Depending on the capacity and the interconnection point of the PV and the characteristics of the system, the line voltage distribution will vary and may quite frequently rise above the standard limits such as those in ANSI C84.1 and IEEE 1547 [4]. Moreover, the variability in the generation of the PV may cause some voltage disturbances. The voltage fluctuations due to the fast changes in the weather conditions may have detrimental effects on the voltage regulation equipment present on the feeder, such as On Load Tap Changing (OLTC) transformers, Switched Capacitor Banks (SCB), and Step Voltage Regulators (SVR). Premature wear and tear could happen due to increased number of operation of these devices.

In this paper, a Quasi-Static Time Series (QSTS) simulation is performed using a tool developed at the Center of Advanced Powe Systems (CAPS). The tool has various functional capabilities, however, this paper focuses on utilizing this tool to investigate the impacts that PV systems might impose on existing voltage regulation devices. This issue is influenced by many variables that need to be considered such as system topology, location of PV, type of voltage regulators, implemented voltage regulation algorithms, etc. The PV is suspected to affect the number of operations of SCB and OLTC regulators which is reflected as additional costs that include tear and wear of regulator switches, increased maintenance costs, and failure of customer and utility equipments due to fast voltage transients in some cases.

The paper will present the modeling of a real Florida-based distribution feeder that has been reduced and validated using proper model reduction techniques [5]. Moreover, synthetic solar data were produced and validated in order to perform different types of studies for different irradiance conditions with high resolution (1 minute) insolation data. The tool will be used in this paper to study the interaction between voltage regulation devices when PV is allowed to regulate the voltage,

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using different regulation algorithms, through the inverter. The study also considers the "No PV regulation" case so that the impact of PV penetration on voltage regulators can be well demonstrated.

II. Potential Impacts and Interactions of Voltage Regulators

The study of voltage variations imposed by PV in the system due to the variability of the PV output has been a discussion topic since the 1980's where the impacts of moving clouds on systems with PV generation has been studied in [6]. This study concluded that the variation in PV output due to moving clouds is a slow process and showed that the severity of the impacts is heavily correlated with the system conditions, such as system loading, and that the effects were greater at the substation level. One of the first efforts to investigate the impacts of PV systems on voltage regulation is found in [7]. Moreover, some experimental work from the field was presented in [8] that suggested that the variability in PV generation is insufficient to cause flicker issues and that voltage regulation in case of penetration levels below 15% will not be an issue. However, the paper suggests that a potential increase in the number of transformer tap changing operations may be observed. The issue of flicker due to variability in PV generation for higher penetration levels was concluded to be insufficient in [2].

Since the PV integration levels were still relatively low in distribution networks, the voltage regulation impacts and interactions were considered insignificant until recent years when the PV penetration levels started to increase and showed noticeable impacts. Recent studies suggested that the high penetration of PV will increase the number of operation of OLTCs and that this could be mitigated by allowing the PV inverter to regulate the voltage [9]. Another study, [4], shows that there is a difference in the impacts of large PV plants versus smaller distributed plants and that the impacts and interaction with voltage regulation devices vary in both cases which concludes that coordinated voltage control is required to minimize the operation of voltage regulators while maintaining appropriate voltage levels.

Voltage fluctuations is one of the major power quality concerns that DG impose on the system [2]. Fig. 1 shows a voltage profile at the PV bus using a highly variable solar insolation period that demonstrates the impacts on voltage levels. These fluctuations shown in Fig. 1 are due to severe variability in PV generation and might cause the voltage to go above or below the standard limits. In such cases the voltage regulation devices will have to operate in such a way to bring the voltage back to acceptable levels.

III. Overview of the Used Tool

The tool consists of a set of Matlab functions and scripts that interface with OpenDSS, where the feeder is modeled, and are used to set up the interface between Matlab and OpenDSS, run the time series simulation, extract the output data from OpenDSS and perform the post processing of data.

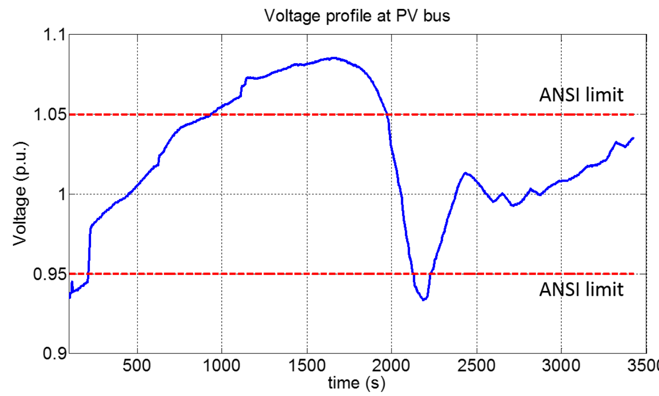

Fig. 1. Voltage profile at the PV bus for a highly variable solar data

A. QSTS Simulation for PV Impact Study

A QSTS simulation is a set of consecutive power flow solutions where the initial conditions for one solution are the results of the previous one. QSTS is adequate for studying some PV impacts due to the variable generation of PVs since QSTS captures slow variations. Thus if the system dynamic changes are slow relative to the time interval separating two consecutive snapshot solutions the slow frequency variations are accurately reproduced by a QSTS. QSTS simulation is accurate enough for studying the impacts of PV on voltage regulation devices since the operation of voltage regulation devices is a relatively slow mechanical operation.

The used tool performs a QSTS simulation using OpenDSS to run the consecutive power flow solutions. The user can define the DSS file of the feeder model and the file containing the load and insolation profiles then the tool is responsible for setting up the interface with OpenDSS and running the simulation using the loaded data. The tool is designed to support different types of feeders, PV data, load data, etc. Some of the functions of the used tool include:

1) Execution of a simulation with an OpenDSS model and retrieval of results.
2) Computation and visualization of metrics describing system behavior based on time-domain results (number of voltage regulation device operation, reactive power contribution by the capacitor banks and substation, load impact indices which are modified reliability indices based on SAIDI and SAIFI).
3) Implementation of reactive power controls for inverters and control of capacitor banks.
4) Performing parametric study using a PV sweeping approach to study the correlations and interactions between variety of system variables for determining optimum limits, rating and locations of the PV plants.
5) Setting/Getting information to/from OpenDSS models

B. Solar Data Synthesis for Impact Studies

A major requirement for any QSTS-base impact study is an accurate solar data. Even though real solar data is available and could be gathered from utilities and solar farms, the measured solar data might not have the required resolution for QSTS simulation, or it may not contain the variability required for performing impact studies that consider different cases for solar output. For this reason, it is important to have a synthetic solar data that can accurately represent real data and that can be produced by the user to get different types of data under various weather conditions.

Synthetic data was produced, and will be made publicly available on a web portal that could be accessed through CAPS website to perform impact analysis and parametric studies. The data considers different types of days (clear, foggy, cloudy, rainy, thunderstorm, etc.) and seasons with the ability of having combinations of different conditions in the same day. The synthesized data is based on a yearly set of real measured data that has been used as a base to synthesize different sets of daily profiles. The procedure used to synthesize the PV profiles is outlined below:

1) Segregation: partitioning of available data per day into respective types depending on weather conditions.
2) Quadrants: dividing daily data into 4 quadrants of 6 hours each for better examination of the profiles.
3) Moving Root Mean Square (RMS): to generate the base signal (low frequency component of the profile).
4) Wavelet noise calculation: adding a realistic noise to the base signal calculated using [10]. The noise added differs depending on the type of day and season.
5) Signal synthesis: adding the RMS low frequency signal to the wavelet noise.

The produced data were all one minute interval data with high accuracy. The synthesized data were compared with the real data for validation using statistical t-test and f-test and comparing cumulative distribution functions (CDF) of ramp rates for both profiles. Detailed results, comparison and validation are presented in [12].

IV. Modeling of The Test Feeder in OpenDSS

OpenDSS is an open-source distribution system simulator developed by EPRI [11]. It is a script-based phasor simulation software that is capable of running power flow and QSTS simulations for performing different types of studies and analysis that range from the basic snapshot solution to a very basic generator dynamics analysis and harmonic analysis.

The developed feeder model is a reduced model of an actual Florida-based feeder that has been reduced from the full size model provided by the utility. The feeder model is built using OpenDSS under the SUNGRIN project effort and is released for open-use. It has 4 MW large PV plant installed at the end of the feeder 4.5 miles away from the substation in the real feeder. The feeder is a basic 12.47 KV distribution feeder. The voltage regulation devices installed in the network are:

1) Three 600 Kvar capacitor banks, one of them is non-switched capacitor bank and the other two are SCBs that are controlled based on an algorithm that monitors the power factor at the feeder head, they operate sequentially in such a way to maintain a 0.99 power factor (leading or lagging)
2) Three single phase OLTC transformers installed at the substation with a $\pm 10\%$ regulation limit with 32 steps and 125.6V regulator voltage with a 2V bandwidth. They operate on a single phase basis based on the voltage at the feeder head.

Fig. 2 shows the topology of the feeder.

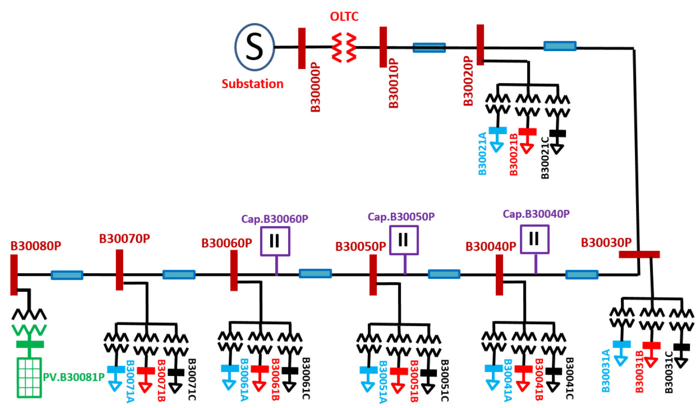

Fig. 2. Feeder topology

V. Impacts and Interaction Analysis: Case Studies

Several case studies were implemented using two load profiles, shown in Fig. 3 and Fig. 4, representing a typical weekend profile (low load) and a typical weekday profile (high load). The studies are conducted using two PV profiles representing two different weather conditions. In each case the simulation is run with and without allowing the PV inverter to assist in voltage regulation.

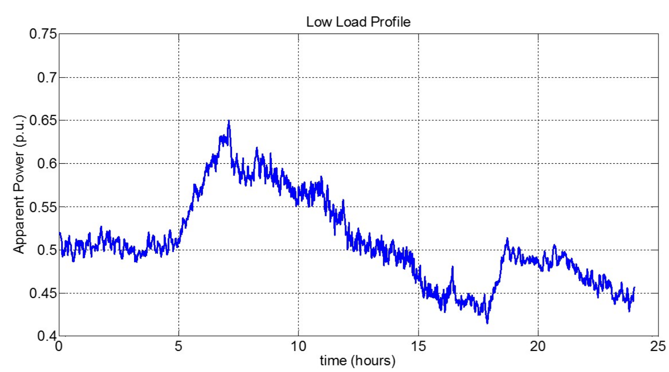

Fig. 3. Typical weekend low load profile

A. *Case I: Clear sunny summer day profile*

In this case, the solar profile used is a synthesized profile for a typical clear sunny day in the summer in Florida. Fig. 5 shows the per-unit real power output profile of the PV plant.

1) *Low load profile*

The low load profile shown in Fig. 3 is used to perform a study where at first the PV system is not contributing to

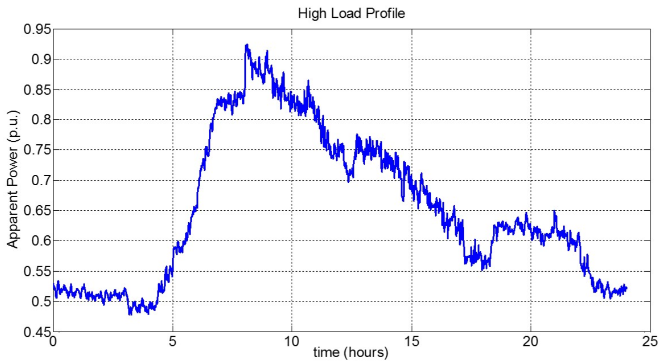

Fig. 4. Typical weekday high load profile

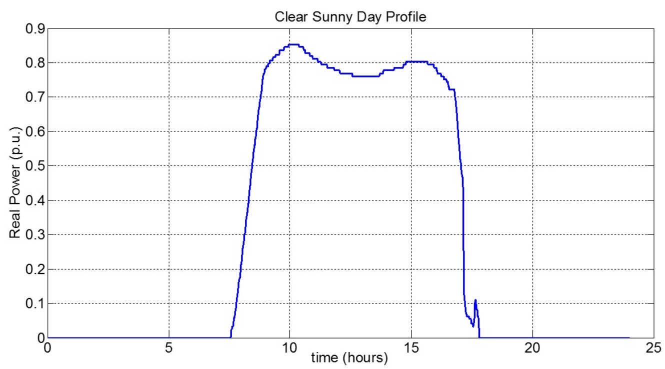

Fig. 5. Synthesized Profile for a clear sunny summer day

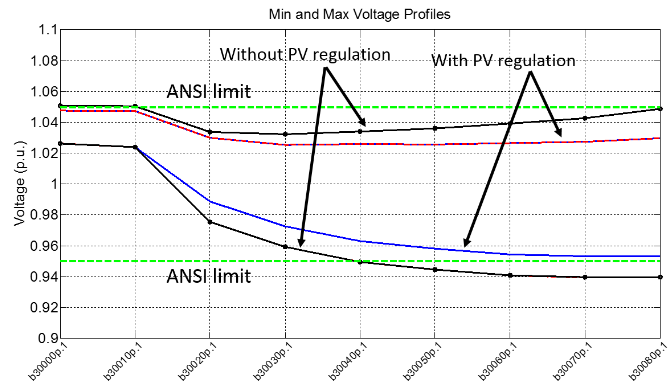

Fig. 6. Minimum and maximum voltage levels at each bus - case I.1

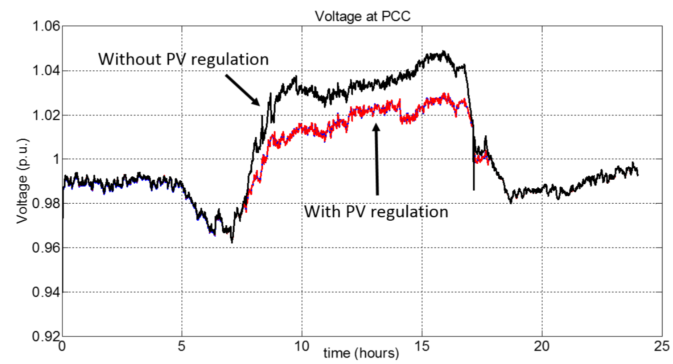

Fig. 7. Voltage profile at the PCC - case I.1

voltage regulation and then two algorithms, constant VAR injection (mode 1) and Volta-Var curve (mode 2), were implemented to allow the PV inverter to regulate the voltage at the point of common coupling (PCC). Fig. 6 shows that when the PV system is regulating the voltage at the PCC the voltage profiles are in most cases within the ANSI limits. This is also reflected in Fig. 7 where the voltage at the PCC is reduced with PV regulation. Both figures show that both voltage regulation algorithms gave very close results in terms of voltage profiles. However, table. I shows that PV voltage regulation was at the cost of increased voltage regulator operations which contradicts with what was expected since there is no coordination among the voltage regulation devices and the voltage regulators on the system operate based on the power factor measured at the substation and not based on the voltage along the feeder and thus the regulators operated in a way to accommodate the change in substation power factor due to the injected/absorbed reactive power by the PV system.

TABLE I
NUMBER OF REGULATION DEVICE OPERATION - CASE I.1

	SCB 1	SCB 3	OLTC	**Total**
No PV Reg.	1	1	8	10
With PV Reg. mode 1	1	1	14	16
With PV Reg. mode 2	3	3	14	20

2) High load profile

The high load profile shown in Fig. 4 is used to perform the same simulation as in the low load case. Fig. 8 shows that the maximum voltage profile was affected more than the minimum voltage profile by the PV voltage regulation. The two regulation algorithms showed almost matching results in terms of voltage profiles as shown also in Fig. 9 that shows the voltage reduction at the PCC when the PV is regulating the voltage. However, as shown in table II the voltage regulators operations also increased for the same reason mentioned in the previous case.

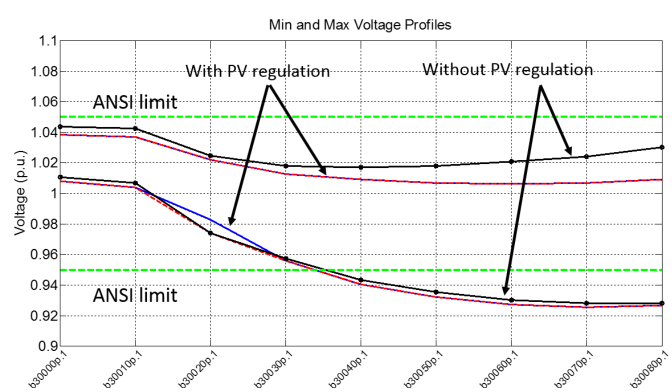

Fig. 8. Minimum and maximum voltage levels at each bus - case I.2

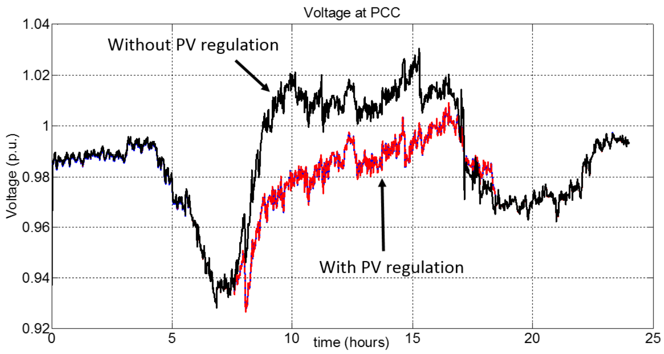

Fig. 9. Voltage profile at the PCC - case I.2

TABLE II
NUMBER OF REGULATION DEVICE OPERATION - CASE I.2

	SCB 1	SCB 3	OLTC	**Total**
No PV Reg.	1	1	14	16
With PV Reg. mode 1	1	1	20	22
With PV Reg. mode 2	3	3	26	32

B. Case II: Summer day with fast changes in irradiation with thunderstorm profile

This case uses the profile of a day in the summer during a thunderstorm. The profile is shown in Fig. 10 which depicts more severe fluctuations than the clear day with lower average output power.

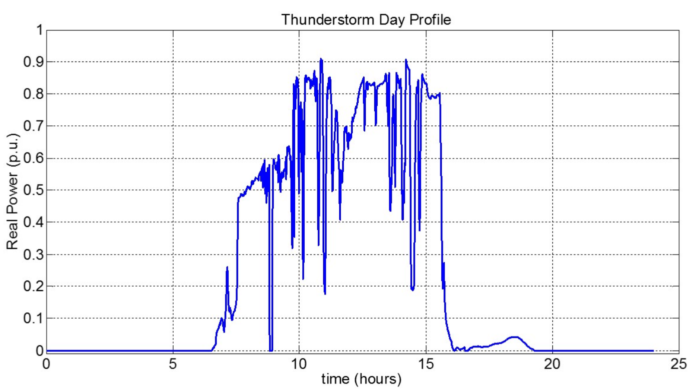

Fig. 10. Synthesized profile for a summer day with recorded thunderstorm

1) Low load profile

The low load profile is used and the same study as in the previous section is repeated. Fig. 11 shows that the voltage profile was enhanced when the PV was contributing to voltage regulation and the voltage at the PCC was reduced as shown in Fig. 12 which also shows much more fluctuations in voltage due to the severe fluctuations in the PV output. Both voltage regulation techniques showed similar voltage profiles, however table III showed that Volt-Var curve (mode 2) algorithm had a worse impact on voltage regulator number of operations and both algorithms caused an increase in voltage regulator operation number.

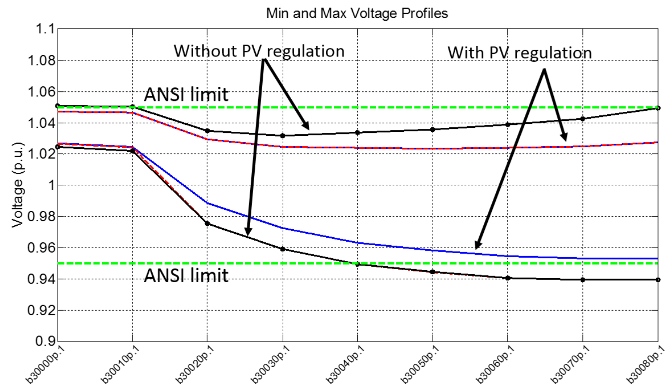

Fig. 11. Minimum and maximum voltage levels at each bus - case II.1

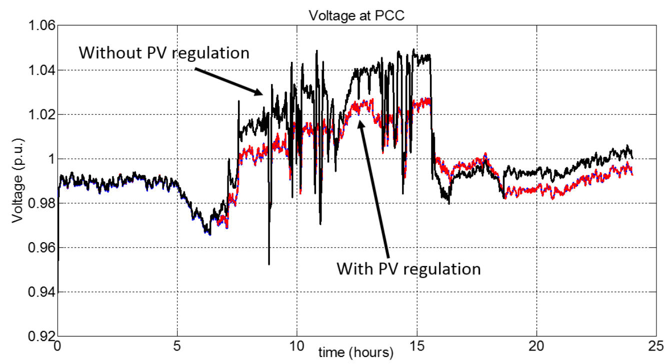

Fig. 12. Voltage profile at the PCC - case II.1

TABLE III
NUMBER OF REGULATION DEVICE OPERATION - CASE II.1

	SCB 1	SCB 3	OLTC	**Total**
No PV Reg.	1	1	8	10
With PV Reg. mode 1	1	1	12	14
With PV Reg. mode 2	5	13	33	51

2) High load profile

The high load profile shown in Fig. 4 is used. Fig. 13 shows that the high load profile has a great impact on lowering the voltage profile and allowing the PV to regulate the voltage had a positive impact in pulling the profiles closer to the ANSI limit. Fig. 14 shows the voltage at the PCC has less fluctuations when the PV is regulating the voltage. However, also in this case the number of voltage regulator operations increased when the PV is contributing to voltage regulation as shown in table IV where again mode 2 algorithm had a worse effect on voltage regulator operations.

TABLE IV
NUMBER OF REGULATION DEVICE OPERATION - CASE II.2

	SCB 1	SCB 3	OLTC	**Total**
No PV Reg.	1	1	20	22
With PV Reg. mode 1	1	1	26	28
With PV Reg. mode 2	13	5	52	70

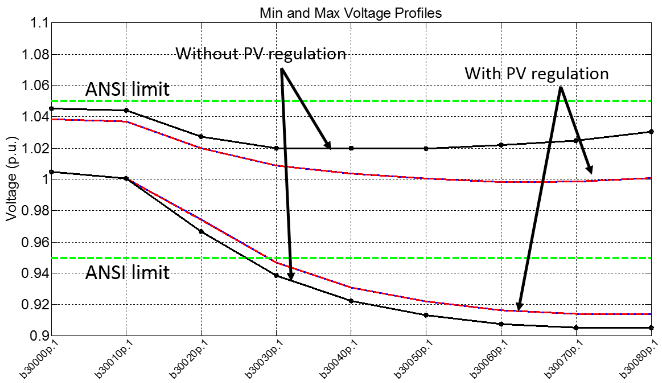

Fig. 13. Minimum and maximum voltage levels at each bus - case II.2

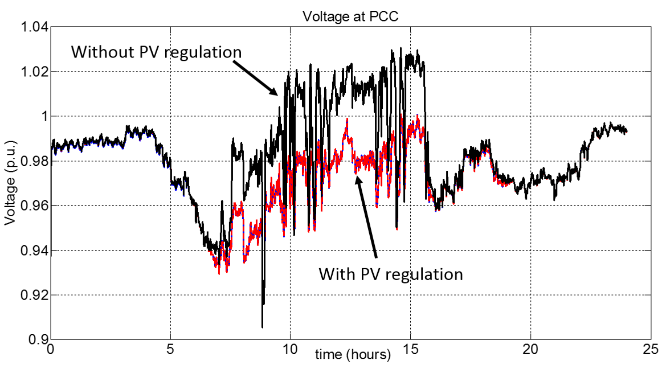

Fig. 14. Voltage profile at the PCC - case II.2

VI. Conclusions and Future Work

This paper uses a QSTS developed tool to study the impacts and interactions of voltage regulation devices in the presence of PV systems. The paper also discussed the synthesis approach of high accuracy solar profile for different weather conditions based on real data provided by utilities. Different case studies were performed and presented using different solar data and load data. The cases studied the effect of allowing a PV inverter to contribute to voltage regulation of the system and it's impact on the operation of voltage regulation devices.

The results showed that the impacts of PV integration are influenced by a variety of variables other than the weather conditions and solar output. For instance, the system load conditions affect the interaction between voltage regulation devices. The control algorithms of current voltage regulation devices will govern the interaction with the PV systems, thus the addition of PV into the system might require updating the system controls. The studies showed that voltage regulator operations might increase when the PV inverters assist in voltage regulation contrary to the initial hypothesis which leads to the conclusion that each feeder is unique and requires separate studies and the voltage regulator operation has to be coordinated to accommodate the contribution of PV systems and operate at optimum most efficient conditions. In addition, different voltage regulation algorithms can yield different results based on the system conditions. Traditional voltage regulation devices were set to monitor the voltage at the substation which is the case in the real feeder used in this study. However, the introduction of the PV introduces voltage issues at buses close to the location of the PV. The introduction of PV systems thus requires interactive control that consider the new rising issues.

This work is the first step in a wider study that takes into consideration more variables such as the type of control algorithms used by the available regulators and by the PV inverter, the location of the PV, the system load, the PV distribution, etc. These results give an idea about the complexity of the issue under study and the variety of cases to be considered, nevertheless it can be concluded that allowing the PV to contribute to voltage regulation will have positive impacts on the system when properly integrated.

Acknowledgment

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References

[1] J. Bank, B. Mather, J. Keller and M. Coddington, High Penetration Photovoltaic Case Study Report, NREL, Tech. Rep. Jan, 2013.
[2] A. Hariri, M. O. Faruque, "Impacts of Distributed Generation on Power Quality," in *North American Power Symposium*, 2014.
[3] L. H. Yang, G. S. Yun and L. Hong, Analysis of the Effect of Distributed Generation on Power Grid, in *Power and Energy Engineering Conference*, 2012.
[4] H. Ravindra, M. O. Faruque, K. Schoder, M. Steurer, P. Mclaren and R. Meeker, Dynamic Interactions Between Distribution Network Voltage Regulators for Large and Distributed PV Plants, in *Transmission and Distribution Conference and Exposition*, 2012.
[5] H. Ravindra, M. O. Faruque, K. Schoder, R. Meeker, M. Steurer, and P. Mclaren, "Model Reduction and Validation of Distribution Networks for Studying the Impact of PV Integration," in *IEEE T&D conference and exposition*, Chicago, 2014.
[6] W. Jewell and R. Ramakumar, "The effects of moving clouds on electric utilities with dispersed photovoltaic generation," in *IEEE Trans. on Energy Conversion*, vol. EC-2, No. 4, Dec. 1987.
[7] D. L. Garrett and S. M. Jeter, "A photovoltaic voltage regulation impact investigation technique: part I - model development," in *IEEE Trans. on Energy Conversion*, vol. 4, No. 1, March 1989.
[8] E. C. Kern, E. M. Gulachenski and G. A. Kern, "Cloud efefcts on distributed photovoltaic generation: slow transients at the Gardner, Massachusetts photovoltaic experiment," in *IEEE Trans. on Energy Conversion*, vol. 4, No. 2, June 1989.
[9] G. K. Ari and Y.Baghzouz, "Impact of high PV penetration on voltage regulation in electric distribution systems," in *IEEE T&D conference and exposition*, 2012
[10] H. Moaveni, D. K. Click, R. H. Meeker, R. M. Reedy and A. Pappalardo, "Quantifying solar power variability for a large central PV plant and small distributed PV plant," in *Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th*, June 2013.
[11] R. C. Dugan, "Reference Guide: The Open Distribution System Simulator (OpenDSS)," EPRI, Tech. Rep. June, 2013.
[12] R. Meeker, M. Steurer, H. Li, O. Faruque, M. Bosworth, J. Langston, I. Leonard, H. Ravindra, K. Schoder, R. Soman, M. Sloderbeck, D. Soto, A. Hariri, T. Kayiranga, Y. Yang, D. Click, B. Reedy and H. Moaveni, "High Penetration Solar PV Deployment," the Center for Advanced Power Systems (CAPS), Tech. Rep., submitted to DOE office of Energy Efficiency and Renewable Energy, April 2015, to be published.