Power Quality and Voltage Profile Analyses of High Penetration Grid-tied Photovoltaics: A Case Study

Arash Anzalchi, *Student Member, IEEE,* Aditya Sundararajan, *Student Member, IEEE,* Amir Moghadasi, *Member, IEEE,* and Arif Sarwat, *Senior Member, IEEE*

***Abstract*—Installed Photovoltaic (PV) capacity across the smart distribution grid has been on the rise in order to reduce greenhouse gas emissions. However, under high penetration of PV, there could be potential impacts on the operation and planning of distribution networks. In order to evaluate the impacts of grid-tied PV, a case study on power quality and voltage profile analyses is conducted using a 1.1 MW AC grid-tied PV power plant located at Florida International University. As part of the power quality analysis, study explores Total Harmonic Distortion (THD) and high power and high energy ramp rate analysis. Current THD is posed to trigger problems when generation is highly intermittent wherein Voltage THD does not have a tight relationship with power output. For voltage profile analysis, the case study considers peak and minimum daytime load scenarios under different levels of penetration, including the existing level, and appraises the plant's current and potential impacts in steady-state and time-series scenarios. The effect of using smart inverters with grid-support functions is also simulated. Results show that some major problems like voltage deviations and feeder losses can be expected at 60% PV penetration in minimum daytime load. The number of switching operations for voltage regulators also increase when smart inverters operate at Volt/VAr control mode. Results of the case study are discussed to highlight the significance of these issues in high penetration scenarios.**

***Index Terms*—Smart distribution grid, High penetration PV, Overvoltage, Power Quality, Total Harmonic Distortion (THD)**

I. Introduction

TRADITIONAL power plants are designed with centrally controlled power plants that have a large inertial response [1]. Renewable energy, however, is independently controlled and intermittent in nature. Hence, adapting the smart grid to include renewable generation sources, improving its energy delivery and efficiency, enhancing and maintaining its power reliability and quality, and ensure power availability with self-healing principles have emerged as the important cornerstones for the future smart grid renewable integration studies. It is common knowledge that synchronous generators are capable of riding through system disturbances in order to maintain the grid voltage and frequency at desired levels.

However, renewable energy, especially solar Photovoltaic (PV) and wind, is now a key contributor to our society's dynamic energy needs, but their integration into the power grid poses significant technical challenges [2]. As the penetration levels of PV increases, especially into the distribution grid network, its intermittency causes power quality and voltage fluctuation issues, among others [3]. The impact of PV integration into the smart grid at a particular feeder decreases with the increase in its distance from the distribution substation from which the feeder originates. Some critical power quality concerns are: 1) Voltage, frequency and power fluctuations at the point of interconnection caused by the intermittencies in PV generation that is, in-turn, dependent on local weather conditions [4]; and 2) Harmonics introduced by power electronic devices utilized in renewable energy generation under high penetration levels [5]. Additionally, voltage fluctuations could be observed in the form of: 1) Overvoltage scenarios where the maximum feeder voltage exceeds the threshold stipulated by grid codes and standards such as IEEE 1547 [6] and UL 1741; and 2) Significant voltage deviations observed which surpass the recommended limits of 3% at the primary and 5% at the secondary [7]. These changes cause the voltage regulators to undergo switching operations, which could be further aggravated when the plant's smart inverters operate in control modes such as Volt/VAr instead of unity power factor [8]. More frequently changing operations reduces the life of regulators, and makes them less efficient in the longer run. A summary of high penetration PV impacts on distribution grid is provided in Section II.

In order to understand and signify the impacts of PV penetration on the smart grid at a distribution grid level, a case study is proposed in this paper. To this effect, the paper explores two classes of analyses: power quality and voltage profiling. Remainder of the paper is organized as follows. Section II briefly summarizes the impacts of high-penetration PV scenarios on the distribution smart grid, highlighting impacts, reasons for those impacts, associated problems, and proposed mitigation solutions. Section III introduces the case study and its scope by describing the considered grid-tied PV power plant. Section IV provides the results gathered from real PV power plant data and the simulation studies, then discusses the observations inferred from them. The Section conducts both power quality as well as voltage profile analyses, each with multiple use-cases delineated correspondingly. Section V provides a brief conclusion summarizing the study and documents future work.

II. Impacts of PV

As briefly mentioned in Section I, there are multiple consequences that arise out of large-scale integration of PV into the distribution level smart grid. These impacts can be grouped as Voltage, Power Quality , Power Flow, Protection, and Active Device impacts. Voltage impacts can be further considered as High Voltage Impacts (HVIs) due to low load conditions but high PV generation, or Low Voltage Impacts (LVIs) due to peak load scenarios. While HVIs reduce the lifespan of electrical equipment and trip PV inverters off-line, LVIs trigger malfunctioning of appliances. To address HVIs, PV inverters could be operated at a lagging power factor in order to absorb reactive power, or the switch capacitor bank controls could be modified. Additionally, fixed Capacitor Banks (CB) could be removed or converted to switched capacitors. To mitigate LVIs, inverters must inject reactive power by operating at a leading power factor. Control settings of capacitors, Load Tap Changers (LTCs), and Voltage Regulators (VR) could be modified, besides installing additional voltage regulation equipment.

Power quality issues due to variations in PV output, cause fluctuations in customer service voltage. To curb power quality-related issues, the utility should review the phase balance of the circuitry, since a well balanced phase circuit offers better relief typically. Increased switching operations of LTCs, CBs, and VRs due to intermittencies in PV generation reduces their active lives, prompting frequent repairs and replacements. Changing setpoint voltage, bandwidth, and/or time delays for LTCs and VRs; and changing the control mode and time delays for capacitor banks are some mitigation strategies proposed in literature.

PV inverters are nonlinear loads and contribute to the harmonic distortion in the network. Different studies document their impacts on the harmonic distortion in the grid. The bottomline concern of these studies is that additional injection of harmonic currents by PV inverters increases voltage distortion in the network. Currently, while synchronous generators produce electric power, nonlinear loads remain the cause for voltage distortions. Under high penetration scenarios, however, the following changes come into effect: 1) Harmonic emission of PV inverters that currently act as current sources of distortion; and 2) Equivalent impedance of inverters behave as mainly capacitive elements in contrast with directly-coupled inductive electrical machines. While the earlier models of PV inverters had current Total Harmonic Distortions (THDs) between 10% and 20%, the standards stipulate the Total Demand Distortion (TDD) of all distributed generators to 5%. A harmonic distortion of 5% or less is specified by the recent models of PV inverters under nominal operating conditions, which is relatively low for loads in today's network.

Reverse power flow is caused due to light load and high PV generation, creating problems for the protection systems and voltage regulators, effectively lowering the system reliability. Using bidirectional protection, adding additional regulations and/or making modifications to the regulator control are some approaches available in literature to address this concern. When high levels of PV penetration is realized under the same transformer, it causes overloading and malfunctioning of critical devices, to mitigate which, distribution transformers are proposed to be replaced with those that can bear the entire PV output. Increase in the fault current levels can lead to system protection-related impacts. Desensitizing substation relays, surpassing interruption rating, fault sensing, asynchronous reclosing, and transient overvoltage are some problems that become pronounced under such conditions. Installing current-limiting devices, revising relay settings, reducing delay trip time for PV tripping, modifying inverter protection, and installing lightning arrestors are some mitigatory strategies proposed in literature. The case study emphasizes its focus on two of these wide range of impacts, namely the voltage and power quality impacts. Before discussing the results, it is important to provide context and scope for the case study by describing and highlighting the features of the PV power plant considered, included in the following Section.

III. PV Plant Description and Case Study Scope

In order to analyze the voltage profile and power quality due to grid-tied PV, a comprehensive study was conducted on a $1.10MW$ AC PV power plant, shown in Fig. 1 (a), tied to a distribution feeder network in Miami, Florida. Three types of solar panels are installed in this PV power plant: Jinko Solar, CSUN, and Canadian Solar. Fig. 1 represents the Point of Common Coupling (PCC), where the PV system is connected to the distribution feeder.

Although the substation services eight feeders, this paper deals with the impact of the plant on the feeder 808064 alone. The plant comprises: a) $4,460$ PV modules of three different types, each with rated power around $315W$; b) 46 SUNNY TRIPOWER 24000TL-US smart string inverters, each of $24kW$ size, and related combiner boxes shown in Fig. 1 (d); c) a local weather station that records irradiance and both ambient as well as module temperature; d) one SMA cluster controller for monitoring the string inverters in real-time; e) an Elkor production meter to record the plant's net energy production (Fig. 1 (a)); f) Panel boxes for testing and disconnection, which have different breakers for each inverter module along that column; g) a SCADA controller at the plant-level that interacts with the cluster controller; h) Revolution®Wireless Power Quality Recorder connected to the lower side of transformer at PCC and collects power quality data with a resolution of 1 minute from the plant including current and voltage THDs (Fig. 1 (e)); i) AC disconnect box connected to the AC output of the inverter and has necessary protection devices like switch and fuse (Fig. 1 (f)) ; and j) A Data Acquisition System (DAS) that measures the multivariate time-series data from inverters, meter and weather station and securely stores values in a cloud server (Fig. 1 (g)). The plant is currently at a 15% penetration into the grid, with a peak generation of $1MW$ on a clear, bright and sunny day and a peak circuit demand of $6.7MW$ on the feeder under study.

The PV plant has been operational from July 19, 2016, and has since generated a cumulative energy of more than $1GWh$. A time-series profile of the plant's generation from August 1, 2016 to May 31, 2017 is shown in Fig. 2, from which a seasonal pattern can be estimated. Immediately after its commissioning, the plant experienced device failure issues due to which the data obtained was not of good quality (that is, it lacked consistency and accuracy). Hence, the initial few days of operation, from July 19 through 31, 2016, were removed from this analysis. It can be observed that the plant experiences a higher generation between the months of April and September, while it showcases a lower production profile during the winter months between November and January.

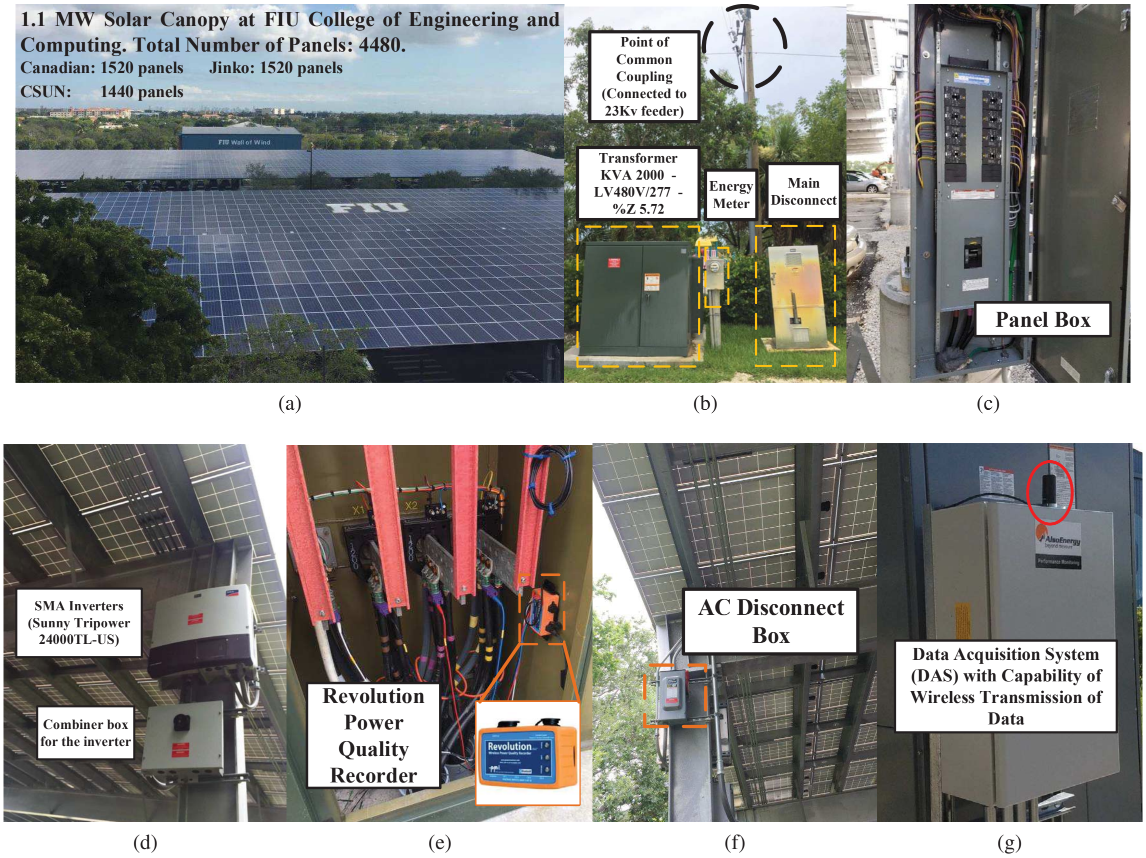


Fig. 1. PV Plant Components: a) 4460 PV modules of three different types but each with rated power around 315W, b) Transformer, Energy meter, and Main dosconnect at the Point of Common Coupling(PCC), c) Panel Boxes for testing and disconnection, d) Smart field SUNNY TRIPOWER 24000TL-US inverters, e) Revolution R Wireless Power Quality Recorder connected at the low side of transformer, f) AC disconnect box which is connected to the AC output of the inverter, g) DAS that measures the multivariate time-series data from inverters, meter and weather station and securely stores in a cloud server.

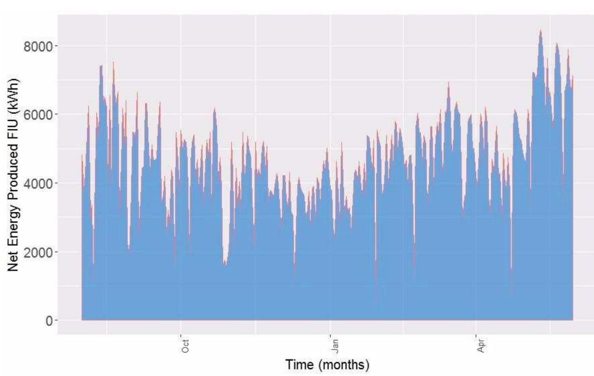


Fig. 2. Aggregated plant energy generation (kWh) of the PV plant since its commissioning

The plant is located at a distance of 1.7 miles from the feeder's substation, as represented in Fig. 3. At the substation, there is a $138kV/23kV$ step-down transformer and circuit breakers tapping into different feeders for distribution of power. At the plant, a $480V/277V$, 2000 KVA oil-cooled step-down transformer is present, as shown in Fig. 1 (b).

Prior to analysis, the real-time data recorded from the plant was subjected to an organized sequence of data pre-processing stages that involved reformatting, structuring, detecting and filtering missing data, and identifying and removing outliers. Exploratory visualization techniques were also employed to determine the nature, behavior and structure of the individual datasets. These steps were useful in determining not only the fitness of the data for further analysis, but also in understanding how the various datasets (such as weather and net production, for instance) are inherently dependent on one another. Further discussion of data cleansing and preprocessing steps is beyond the scope of this paper. However, once cleansed, the data is considered ready to be used for the power quality study and voltage profile analysis discussed in this paper.

Effective voltage profile analysis and power quality study are multi-step approaches which require developing the system model and reviewing the feeder monitoring criteria recommended by grid code requirements set by IEEE standard 1547. In order to develop the system model, Synergi, a modeling software with license, is used. Synergi is capable of advanced modeling applications where the feeder and substation model snapshots are loaded as Microsoft Access Database files into it and corresponding Single Line Diagrams (SLDs) are generated. Real-time solar irradiance data is acquired from the site's DAS and averaged to hourly values prior to importing into Synergi.

IV. Results and Analysis

Based on the review of grid code requirements documented by standards IEEE 1547 and UL 1741, different feeder moni-

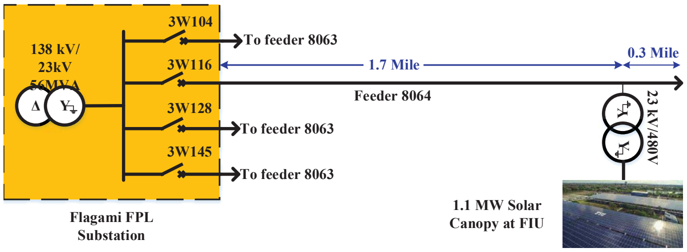


Fig. 3. Single Line Diagram of concerned system

TABLE I
FEEDER MONITORING CRITERIA

Category	Criteria	Basis	Flag
Voltage	Overvoltage	Feeder voltage	$> 1.05Vpu$
	Voltage deviation	Deviation from no PV to full PV	3% primary, 5% secondary
Power Quality	Individual harmonics	Harmonic magnitude	$> 3\%$
	Voltage THD	Total harmonic	$> 5\%$
Legacy Devices	LTC, Regulator	Increased Duty	$> basecase + 1$
	Capacitor	Increased Duty	$> basecase + 1$

toring criteria were elicited, summarized in Table I. It clearly shows the criteria, basis and threshold values for both the power quality study as well as voltage profile analysis. It is noteworthy that the concerned feeder, which serves 700 residential and 200 commercial customers, has three capacitor banks, one voltage regulator, and two transformers. Following subsections look at power quality and voltage profile analysis.

A. Power Quality Study

The power quality study under grid-integrated PV scenarios is examined in this section under two analyses: a) Power Ramp Rate study, and b) Harmonic Distortion study. While the power ramp rate study includes the analysis of high power density and high energy density ramp rates, the harmonic distortion study looks at both current as well as voltage THDs.

1) Power Ramp Rate Study: Ramp rates in power can be caused due to multiple reasons, of which cloud-induced power intermittencies are considered as a major characteristic. Single-sided power ramp rates, either ramp-up or ramp-down, at the point of interconnection (also called Point of Common Coupling or PCC), are represented in Fig. 4, which shows that majority of the power ramps are under $50kW/min$, and almost 20% of them exceed the 12% limit (corresponding to $140kW/min$). Thus, it is clear that ramp rates will pose serious threat as penetration levels increase. However, power ramps of this order can be easily mitigated and smoothed by integrating them with hybrid energy storage systems.

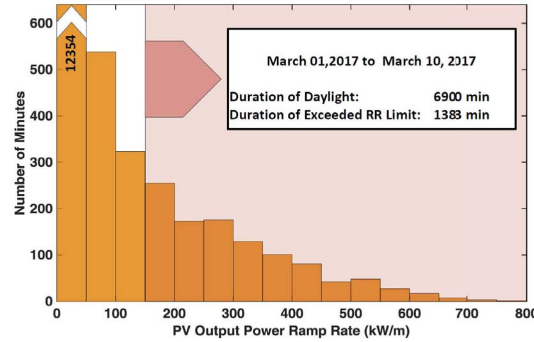
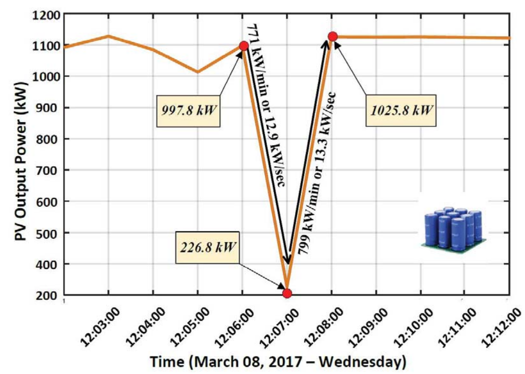
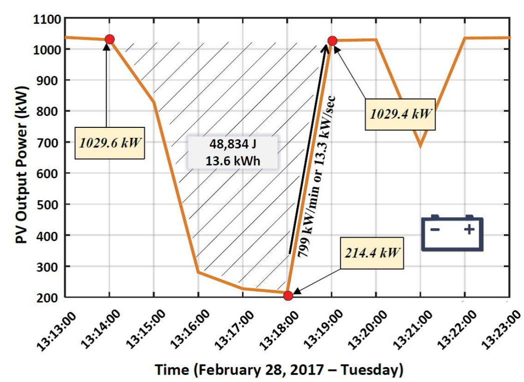


Fig. 4. Histogram of real power ramp rates for Mar 1-10, 2017



(a)

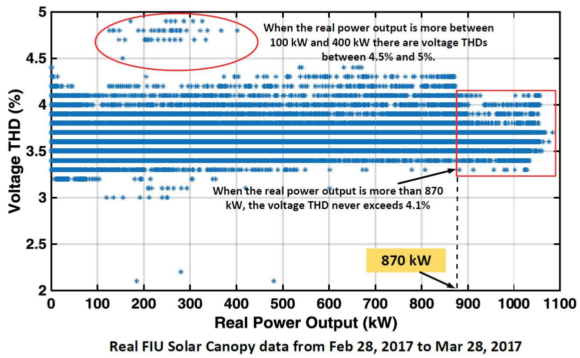


(b)

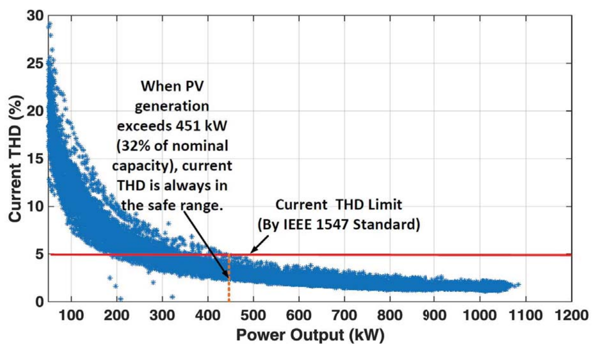
Fig. 5. Power ramping scenarios for the PV power plant. a)High power density ramp rate profile, b) High energy density ramp rate profile.

The power ramp rates have been categorized in this case study as high power and high energy density ramp rates, each of which are shown in Figs. 5 (a) and 5 (b), respectively. A high power density ramp rate with a $771kW/min$ of ramp down and a $799kW/min$ ramp up was observed. Using supercapacitors minimizes impacts of these ramps. The high energy density ramp exhibits an energy deviation of $13.6kWh$ in less than 5 minutes, effectively mitigated by battery banks.

2) Harmonic Distortion Study: THD is not the best measure of PV-induced harmonics, since the fundamental current is reduced by PV generation, making harmonics larger by comparison and consequently increasing THD values. The effect of low solar irradiation level on injected current emissions is



(a)



(b)

Fig. 6. THDs monitored over 1 month for the case study. a) Voltage THD for the PV power plant, b)Current THD for the PV power plant.

accounted for in the case study. Monitored for a period of one month, the voltage and current THDs recorded for the power plant are plotted against the real power output in Figs. 6 (a) and 6 (b). It can be seen that the total current THD is highly sensitive to changes in irradiance but the total voltage THD does not maintain such a strong relation with the same. As the real power output crosses $870kW$, the voltage THD does not exceed 4.1%, with its values ranging between 4.5 and 5% when the power output is between 100 and $400kW$.

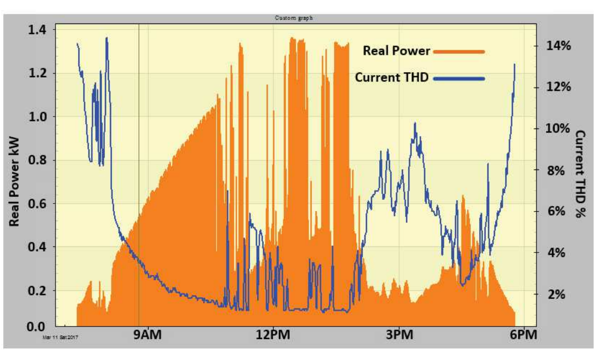


Fig. 7. Current THD with respect to real power and time

The power output and current THD for March 11, 2017, when a lot of fluctuations in irradiance was observed, is depicted by Fig. 7. This goes on to validate the relation between power and current THD more precisely. It can be further noted that the shape of current THD curve is nearly inverted to that of the output real power.

B. Voltage Profile Analysis

Analyzing real time voltage data from January 2017 to July 28 2017, does not show any voltage violation above 5%, except for days May 17 to May 24, 2017 and June 21 to July 16, 2017. Real RMS voltage of the lower side of transformer, real PV power output data from Provision PQ meter is illustrated in Fig. 8. Since most of voltages out of limit were happened during this period, these days were selected. As it can be seen from the right side of Fig. 8, these violations happened mostly at night time, when there is no PV output. Moreover, the overall voltage rises throughout the day as the load decreases (during late night). Therefore, these voltage violations are not due to PV penetration to the feeder. The voltage profile analysis under grid-integrated PV scenarios is examined in this section as two analyses: a) Steady-state, and b) Time-series. While the steady-state analysis determines the worst-case feeder response that would occur when the PV generation changes drastically from zero to maximum, time-series analysis is conducted for the load or PV time-of-day coincidental scenarios.

1) Steady-State Scenario Study: Considering steady-state scenario is static in nature, the load flow analysis for the system is conducted for different use-cases. Each use-case has two scenarios that define it: the dynamic load profile scenario, and the different levels of PV penetration scenario. Although the existing level of penetration is 15%, this study considers futuristic scenarios where the penetration could go as high as 140% of the peak load. The load scenarios, on the other hand, could be the Peak Daytime Load (PDL) day, or the Minimum Daytime Load (MDL) day. Accordingly, the mapping between these two classes of scenarios as shown in Fig. 9 would create multiple use-cases for which the results are shown. For each use-case, all steady-state technical criteria tabulated in Table I are verified.

Voltage Deviation Study: In order to conduct this study, the two load scenarios were each mapped to two different penetration levels (existing and 60%), to generate four use-cases. It is to be noted that for this setup, the voltage deviation in accordance with the recommendations from Table I should not exceed 0.3V. Fig. 10 (a) shows the voltage deviation for the PDL scenario under existing penetration level with respect to the distance from the substation. It is a general trend that the deviations subside as the distance increases. Moreover, it is seen that the values are well below the recommended one shown in Table I. However, at 60% penetration, shown in Fig. 10 (b), although the deviations are still below the threshold, they are dangerously close to exceeding it, especially at distances closer to the substation. Much similarly, Fig. 11 shows the deviation in voltage for the MDL scenario again for existing and 60% penetration levels with respect to distance from the substation. While the deviations are below the stipulated threshold for existing penetration level, they exceed the same under levels of 60% penetration significantly by $0.15V$, at a distance closest to the substation. Considering PV is located at the end of the feeder, no significant impacts were observed.

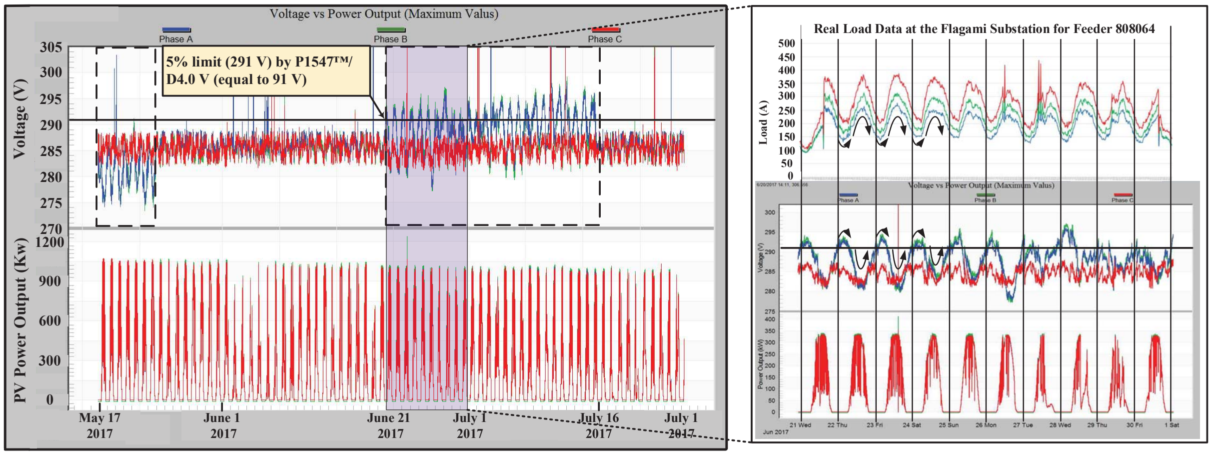


Fig. 8. Maximum RMS values for voltage, Power output, and Load (May 17 - Jul 27, 2017.

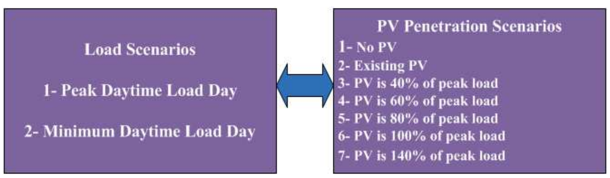
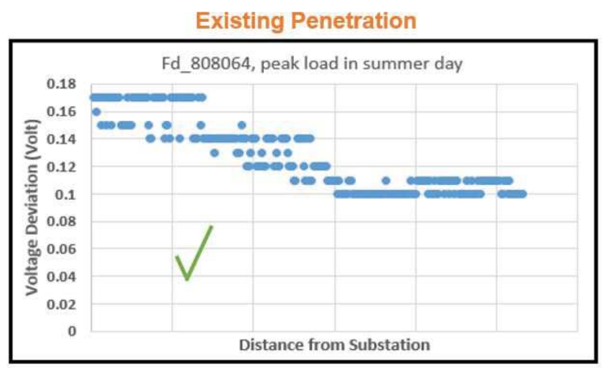


Fig. 9. Mapping scenario classes for use-case generation



(a)

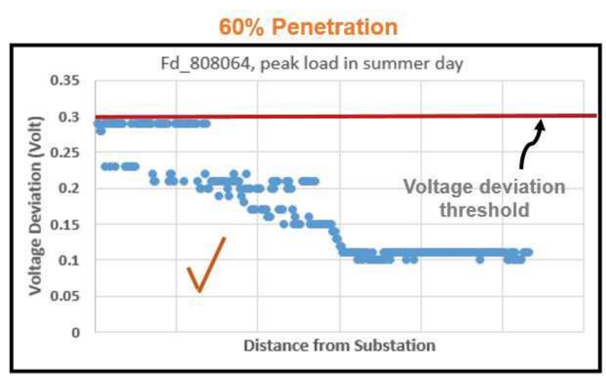
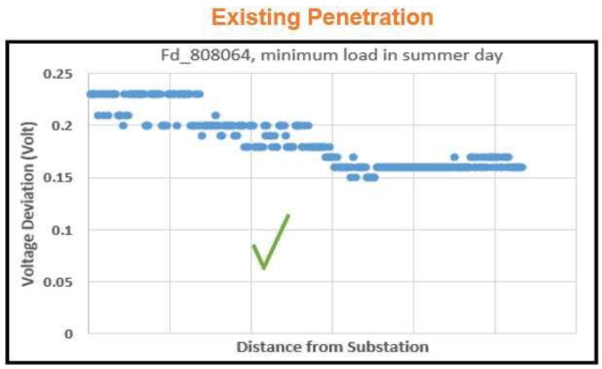


Fig. 10. Voltage deviation study for PDL scenario. a)Existing Penetration, b) 60% Penetration

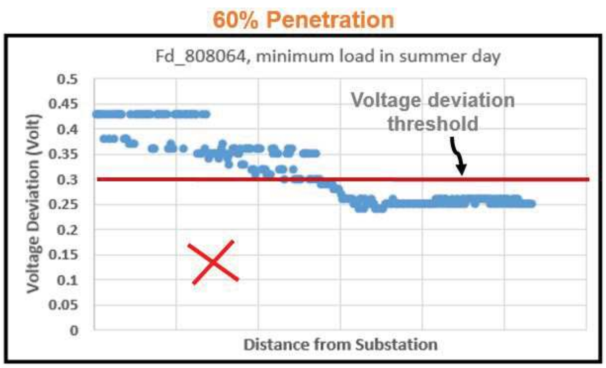
Feeder Loss Study: The feeder losses (kW) for the PDL and MDL scenarios under different penetration levels is illustrated graphically in Fig. 12. It can be observed that the losses show a gradually declining trend for the PDL scenario where the losses drop by a factor of 66% from 0 to 140% penetration, but the same cannot be said for the MDL scenario, where the losses initially seem to decline, with the lowest losses observed for $60-80\%$ penetration, but steadily climb up again as the penetration hikes to 140%. It is incidentally seen the losses are more or less the same for both extremities of the penetration level in this load scenario.

2) Time-Series Scenario Study: Unlike the steady-state scenario, the time-series study requires a different kind of system modeling, also conducted on Synergi. All distributed loads are assumed to be modeled as urban residential loads and all spot loads are modeled as urban commercial loads in order to construct the load model for the study, shown in Fig. 13. Further, two scenarios are considered here: a sunny day where the sky is clear and bright blue, and a cloudy day where the sky is overcast. The irradiance models for both these scenarios using 15-min irradiance interval data are shown in Fig. 13. However, in Synergi software, the one-hour resolution data is used by taking an average from 15-min resolution data. Further, three different PV inverter control modes are considered for this study, namely: Power Factor control, Volt/VAr control, and Volt/Watt control.

For PF control mode, PF=0.85 was considered. The voltage profile analysis was then conducted for a sunny day scenario, as depicted by Fig. 14, by varying PV penetration levels as: existing (sky blue), 40% (orange), 60% (grey), 80% (yellow), 100% (deep blue), 120% (green), and 140% (dark blue). As shown in Fig. 14 (a), the maximum voltage exceeds the threshold at 60% penetration and above for PF=0.85. Similarly, the threshold is exceeded at the same level of penetration even for Volt/VAr control mode, shown in Fig. 14 (b). This might prompt the inverters to be operated at PF=1 considering the limit is not violated. However, this contradicts the recommendations made by IEEE 1547 which requires inverters to operate in Volt/VAr control mode. Hence, appropriate mitigation strategies are required. It can be further



(a)



(b)

Fig. 11. Voltage deviation study for MDL scenario. a) Existing Penetration, b) 60% Penetration.

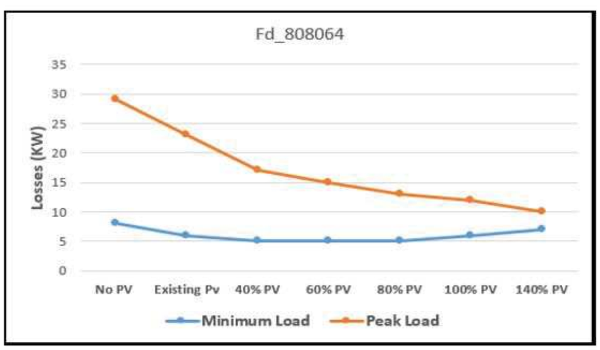


Fig. 12. Feeder Losses for MDL and PDL scenarios

noted that the number of switching operation is 6 for PF=0.85, and jumps to 36 for Volt/VAr mode

The above study was now repeated for a cloudy day scenario, and the number of switching operations was observed for PF=0.85, and Volt/VAr control modes. The maximum feeder voltage variations are shown in Fig. 15. At 60% penetration level and beyond, the maximum feeder voltage exceeds the threshold for both PF=0.85 and Volt/VAr modes, depicted respectively in Figs.15 (a) and 15 (b), with corresponding switching operations as 6 and 69. When compared with their operations on a sunny day, it can be observed that when PV inverters operate in Volt/VAr mode on a cloudy day, the voltage regulators undergo switching operations nearly twice more, which significantly reduces their performance and spells adverse effects on the grid.

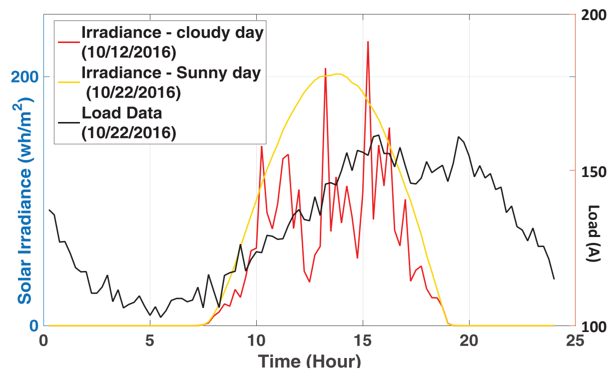
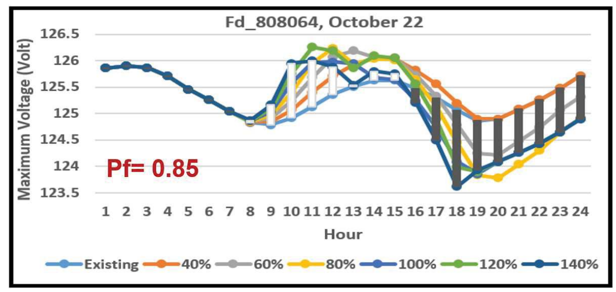
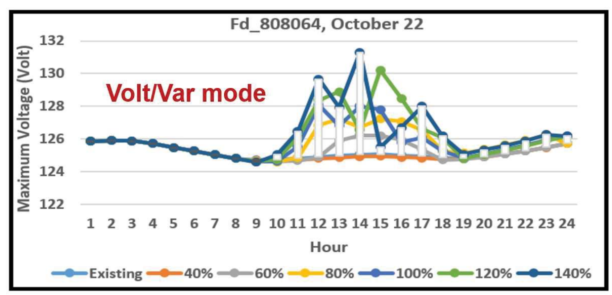


Fig. 13. Irradiance and Load models for System Modeling. Irradiance model for sunny day (10/22/2017), Irradiance model for cloudy day (10/12/2017), Load Model



(a)



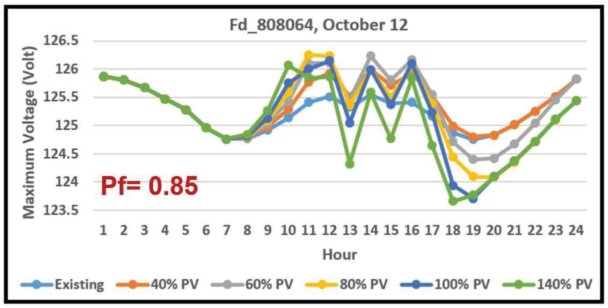
(b)

Fig. 14. Maximum Feeder Voltage for different control modes on sunny day a)Power Factor = 0.85 b) Volt/VAr mode

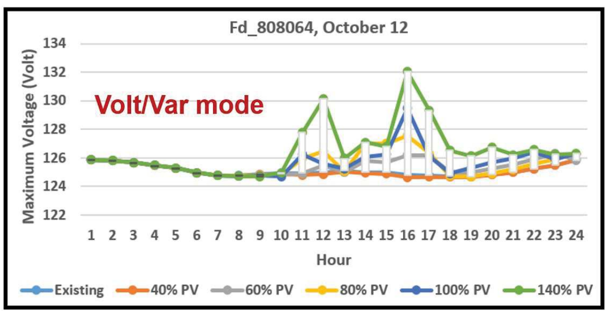
A consolidated representation of the number of switching operations for the 8 voltage regulators operating under various control modes in both sunny as well as cloudy days. As can be seen in Table II, the number of switching operations is relatively stable between 1 and 2 until 100%, with the number creeping to 3 on a cloudy day scenario. When PF=0.85, the number of operations show a steady rise with penetration levels, peaking at 11 and 15 operations for sunny and cloudy days, respectively at 140% penetration. Similarly, when operated under Volt/Watt mode, the operations peak at 16 and 19 for the same penetration level, represented in Table II. Finally, under Volt/VAR, maximum number of switching operations is observed, with 44 on sunny and 113 on cloudy day for maximum penetration scenario considered in this paper. This supports the hypothesis that number of operations increases with penetration levels, and that Volt/Watt and Volt/VAR modes are more dramatic than PF. This might

TABLE II
TOTAL NUMBER OF SWITCHING OPERATIONS.

	PF= 1		PF= 0.85		Volt/Watt		Volt/Watt	
	Sunny	Cloudy	Sunny	Cloudy	Sunny	Cloudy	Sunny	Cloudy
20% PV	1	2	1	2	1	2	1	2
40% PV	1	2	1	2	1	2	1	2
60% PV	1	2	2	3	2	3	5	16
80% PV	1	2	3	3	6	6	22	42
100% PV	2	2	6	6	8	11	36	69
140% PV	2	3	11	15	16	19	44	113



(a)



(b)

Fig. 15. Maximum Feeder Voltage for different control modes on cloudy day a) Power Factor = 0.85 b)Volt/VAr mode

prompt the inverters to be operated at PF considering the limit is not violated. However, it contradicts recommendations made by IEEE 1547 which require inverters to operate in Volt/VAr mode. Hence, mitigation strategies are required.

V. Conclusion and Future Work

A case study was presented in this paper for evaluating the impacts of high penetration PV on the distribution level of smart grid. Two crucial impacts were selected from literature, power quality and voltage impacts. A system model using Synergi and data from the plant's data acquisition unit and power quality recorder was constructed. Multiple use-cases and scenarios were delineated for the two studies. Power quality issues were studied using high resolution data for current and voltage THDs based on real measurements. It was concluded that no problematic issues persisted at the existing penetration level of 1.1 MW. Current THDs over 5% has been increased when the power output is less than 451 kW and it has a tight connection to the output power. Voltage profile analyses for steady-state and time-series scenarios revealed that at 60% penetration level, significant impacts due to voltage deviation and feeder losses could be observed. Further, the number of switching operations for voltage regulators increases dramatically when PV inverters operate in Volt/VAr control mode, followed by Volt/Watt, and finally Power Factor. Although unity power factor causes least number of operations, the grid codes require the use of Volt/VAr mode for inverter control. Hence, strategies to mitigate these impacts are required.

References

[1] A. Anzalchi, M. M. Pour, and A. Sarwat, "A combinatorial approach for addressing intermittency and providing inertial response in a grid-connected photovoltaic system," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, July 2016, pp. 1–5.

[2] A. Anzalchi and A. Sarwat, "Artificial neural network based duty cycle estimation for maximum power point tracking in photovoltaic systems," in *SoutheastCon 2015*, April 2015, pp. 1–5.

[3] R. Seguin, J. Woyak, D. Costyk, J. Hambrick, and B. Mather, *High-Penetration PV Integration Handbook for Distribution Engineers*, Jan 2016. [Online]. Available: http://www.osti.gov/scitech/servlets/purl/1235905

[4] X. Liang, "Emerging power quality challenges due to integration of renewable energy sources," *IEEE Transactions on Industry Applications*, vol. 53, no. 2, pp. 855–866, March 2017.

[5] A. Anzalchi, M. Moghaddami, A. Moghaddasi, A. I. Sarwat, and A. K. Rathore, "A new topology of higher order power filter for single-phase grid-tied voltage-source inverters," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 12, pp. 7511–7522, Dec 2016.

[6] "Ieee application guide for ieee std 1547(tm), ieee standard for interconnecting distributed resources with electric power systems," *IEEE Std 1547.2-2008*, pp. 1–217, April 2009.

[7] T. T. Ku, C. H. Lin, C. S. Chen, C. T. Hsu, W. L. Hsieh, and S. C. Hsieh, "Coordination of pv inverters to mitigate voltage violation for load transfer between distribution feeders with high penetration of pv installation," *IEEE Transactions on Industry Applications*, vol. 52, no. 2, pp. 1167–1174, March 2016.

[8] A. O'Connell and A. Keane, "Volt-var curves for photovoltaic inverters in distribution systems," *IET Generation, Transmission Distribution*, vol. 11, no. 3, pp. 730–739, 2017.