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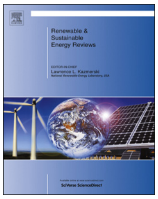

Local steady-state and quasi steady-state impact studies of high photovoltaic generation penetration in power distribution circuits

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ABSTRACT

Both steady-state and quasi steady-state impact studies in high Photovoltaic (PV) penetration distribution circuits are presented. The steady-state analysis evaluates impacts on the distribution circuit by comparing conditions before and after extreme changes in PV generation at three extreme circuit conditions, maximum load, maximum PV generation, and when the difference between the PV generation and the circuit load is a maximum. The quasi steady-state study consists of a series of steady-state impact studies performed at evenly spaced time points for evaluating the spectrum of impacts between the extreme impacts. Results addressing the impacts of cloud cover and various power factor control strategies are presented. PV penetration levels are limited and depend upon PV generation control strategies. The steady state and quasi steady-state impact studies provide information that is helpful in evaluating the effect of PV generation on distribution circuits, including circuit problems that result from the PV generation.

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1. Introduction

Photovoltaic (PV) generation is one of the most rapidly growing renewable energy sources, and is regarded as an appealing alternative to conventional power generated from fossil fuel [1]. This is leading to significant levels of distributed PV generation being installed on distribution circuits. Although PV generation brings many advantages, circuit problems are created due to the intermittency of the PV generation, and overcoming these problems is a key challenge to achieving high PV penetration. Without addressing these technical issues properly, PV generation can be limited from injecting more active power into a distribution network [2,3].

It is necessary for utilities to understand the impacts of PV generation on distribution circuits and operations. An impact study is intended to quantify the extent of the issues, discover any problems, and investigate alternative solutions. Researchers and systems operators will need to evaluate the impact of PV generation on system operation characteristics, such as voltage profile, power losses, stability, and reliability [4–6].

An impact study can be divided into two categories; system wide and local [7]. A system wide study addresses growth impacts of new technologies on the circuit, including Plug-in Hybrid or Electric Vehicles, Distributed Energy Resource (DER) generation, and energy storage systems. This study deals with the uncertainties and effects of new technology, including location, size, and operating characteristics [8,9].

On the other hand, local impact studies address expected impacts of new technologies on a distribution circuit as it exists today. The native loading and PV generation data are available along with the location and characteristics of the PV generation. A local impact study is presented in this article.

The potential impact of PV generation on power systems has been discussed in many articles. An extensive literature search is conducted to address potential problems associated with high penetration levels of PV generation in [10,11]. Furthermore, the impact of increased penetration of PV generation in the transmission system is studied for both steady and transient stability. The analysis with and without the existence of the PV generation is studied and compared to identify improvements or adverse effects of PV generation on the system [12].

The effects of the integration of distributed PV generation into distribution systems are examined in [13–20]. It is becoming apparent that local voltage issues are likely to precede protection, load, fault, harmonic, and stability issues as penetration increases. In addition, reverse power flow can negatively affect protection coordination and operation of voltage control and regulation equipment. Furthermore, PV generation introduces changes in the circuit loss and also imbalances of voltages and power flows. Barriers to the successful integration of DER generations into microgrids, including power quality, protection, and stability, are addressed in [21–23].

In this article both local steady-state and quasi steady-state PV impact studies are presented. The steady-state impact study investigates impacts at extreme circuit conditions and the quasi steady-state represents a series of steady-state studies over a set of time varying values. Thus, the quasi steady-state study evaluates a spectrum of impacts. In addition, PV generation power factor control for mitigating voltage variation problems is investigated.

This article is organized as follows. In Section 2 the most common expected impacts of PV on the distribution circuit are discussed. Section 3 presents simulation strategies addressing the impacts discussed in Section 2. In Section 4 the results obtained from existing circuits with individual customers modeled are presented. Finally, findings of the study are summarized in Section 5.

2. PV impact study

Some of the impacts from high PV penetration which should be considered in steady-state and quasi steady-state PV impact studies are discussed in this section.

2.1. Steady-state PV impact study

A steady-state PV impact study seeks to discover the worst case, or extreme impacts, on the distribution circuit. Circuit conditions that are considered include maximum loading, maximum PV generation, and maximum difference between PV generation and circuit load. The objective is to analyze extreme impacts by comparing circuit conditions before and after a change in PV generation. In these studies the effects of control actions are very important. Solar generation transients can be so rapid that traditional utility control devices cannot act sufficiently fast to correct circuit problems caused by the rapidly varying generation.

2.1.1. Customer voltage variation

Among the various technical challenges under high PV penetration, voltage variations caused by the intermittency of the PV generation are among the foremost concerns. The need to limit voltage variations resulting from rapidly varying PV generation can limit the amount of PV generation in the distribution circuit. The typical allowed variation in voltage is $\pm 5\%$ from a nominal voltage, but other concerns, such as causing excessive control motion of utility equipment, may place tighter restrictions on the allowable voltage variation [24].

It is important to maintain the voltage within allowable ranges at all components in the circuit. Many distribution circuits are radial and the voltage is controlled by automated devices (voltage regulators, switched capacitor banks, load tap changing transformers). Solar generation can vary rapidly up and down as clouds pass over, creating many voltage transients at the automated control devices. If typical utility control equipment attempts to control all of the rapid variations in voltage, the equipment will require much more maintenance and have a shorter life span. However, typical utility control equipment is not fast enough to control the initial voltage variations due to PV generation transients.

2.1.2. *Reverse power flow*

High PV penetration can lead to reverse power flow conditions in distribution circuits which were originally designed for unidirectional power flow from the substation to the loads. Bidirectional power flow can be detrimental to the performance of some devices, including protective devices and automated control devices. Reverse power flow conditions can cause malfunctions in protection coordination and the operation of voltage regulation equipment.

2.1.3. *Phase unbalance of power flow and customer voltage*

Supplying unbalanced phase power flows and voltages results in degraded performance of three-phase motors and other three-phase utilization devices. If the unbalance is significant, the motors and devices may overheat or become inoperative. It is common to maintain the voltage unbalance within 2% [13]. In this article the IEEE definition of voltage unbalance, also known as the phase voltage unbalance rate (PVUR), is used [25]:

$$PVUR = \frac{\text{Maximum deviation from average phase voltage}}{\text{Average phase voltage}} \tag{1}$$

Similarly, the phase power flow unbalance rate (PFUR) is calculated as:

$$PFUR = \frac{\text{Maximum deviation from average phase real flow}}{\text{Average phase real flow}} \tag{2}$$

2.2. *Quasi steady-state PV impact study*

The steady-state PV impact study evaluates impacts on the circuit at extreme circuit conditions, but does not show the spectrum of impacts between the extremes. The quasi steady-state PV impact study represents a series of studies run over a set of time varying values with some sample rate (i.e. one second, one minute, one hour). In this article the quasi steady-state PV impact studies use one hour measurements for evaluating the following concerns.

2.2.1. *Customer voltage variation*

The quasi steady-state study captures the effects of customer voltage variations within a given time frame. Information provided by the study includes how often overvoltage or undervoltage occurs, and how voltages fluctuate throughout the day.

2.2.2. *Circuit loss*

PV generation can have significant impacts on circuit loss. PV generation affects both real and reactive circuit losses. The quasi steady-state study provides information on both real and reactive circuit losses over the time varying generation. Optimal control of PV generation is required to minimize the circuit loss.

2.2.3. *Automated device steps*

Voltage rise and variations caused by the intermittency of PV generation can lead to frequent utility control device step changes. These frequent step changes can shorten the expected life of the devices and increase maintenance costs. The quasi steady-state study counts the number of times control devices move over the time varying generation. Optimal control of PV generation should consider controlling PV generation so that the control motion of utility control devices is minimized.

3. Simulation cases

The variation in PV generation is due to changes in the cloud cover, which is the main reason for rapid solar generation changes. The power factor that the PV generation operates at has significant effects on the circuit response, and determining the optimal power factor can minimize the detrimental circuit effects.

3.1. *Test circuit*

The distribution circuit to be analyzed is shown in Fig. 1. The circuit model is derived from actual data. It is a 13.2 kV, Y-connected circuit with 2751 residential customer and 111 industrial customers. Circuit lengths are 3.66 miles, 2.20 miles, 0.41 miles, and 3.22 miles from the substation to the left end, the right end, the top end, and the bottom end, respectively, as illustrated in Fig. 1. Due to the heavy residential load the circuit peaks later in the day, with the annual peak occurring during the summer. The time varying customer loads are estimated from averaged hourly SCADA measurements, hourly customer kWh load data, and monthly kWh load data processed by load research statistics to create hourly loading estimates for each customer [26,27].

The circuit contains two voltage regulators, two switched shunt capacitors, four protective devices, and numerous sectionalizing devices, with four sectionalizing devices illustrated in Fig. 1.

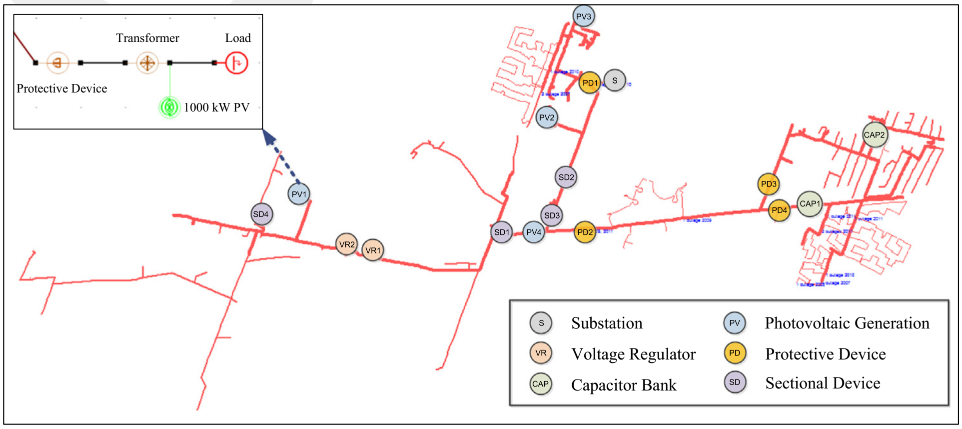

Fig. 1. Distribution circuit to be analyzed.

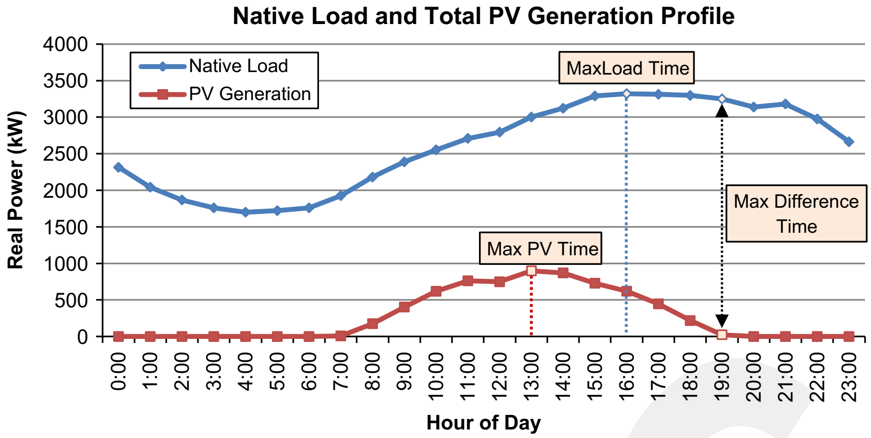

Fig. 2. Native load and total generation profile.

The voltage regulators operate based on voltage control using a 124 V base, +/−1.0 V bandwidth, and +/−16 steps. The switched shunt capacitors operate based on voltage control with specified turn on and turn off voltage setpoints.

In the simulation 1000 kW PV generators are considered. Time-varying PV generation data are imported through the Internet using the In My Backyard (IMBY) application from the National Renewable Energy Lab (NREL) [28]. For a given geographical location and size, the NREL interface provides hourly PV generation data for an entire year.

Four PVs, each with a 1000 kW rating, are randomly placed in the circuit. The PV penetration percentage is calculated based on the following equation:

$$\text{PV penetration } (\%) = \frac{\text{Max PV generation}}{\text{Native load at max PV generation time}} \tag{3}$$

The definition of PV penetration used in this article varies based on the selected time duration. The time varying PV generation and load for a day, July 15, is selected for analysis in this article and is shown in Fig. 2. Due to heavy residential loading the circuit peaks late in the day, with the annual peak load occurring during the summer. The annual PV generation peak also occurs during the summer. Using Eq. (3), the PV penetration for the selected day for analysis is approximately 30%.

3.2. *Time point selection*

For the steady-state impact study, time points are determined for evaluating the worst impacts on the circuit. The maximum PV generation time point is selected to show the extreme effects on the circuit due to the largest amount of PV generation. The maximum load time point is selected to evaluate effects at the extreme loading condition. The minimum load time is not selected here because this load occurs at night when PV generation does not impact the circuit operation. The time at which the maximum difference exists between the circuit load and the PV generation is selected when the PV generation is greater than zero. The three time points selected for the steady-state PV impact study are illustrated in Fig. 2 and are:

- Maximum PV generation: 01:00 PM
- Maximum circuit load: 04:00 PM
- Maximum difference between PV generation and circuit load: 07:00 PM

3.3. *Cloud cover simulation*

Changing cloud cover is the main reason for solar ramping producing rapid fluctuations in PV generation. Changing cloud cover has to be considered in dynamic PV impact studies. However, the cloud cover simulation is also used in the steady-state impact study. In the simulations here, four cloud cover cases are considered as:

- Study with 25% cloud cover resulting in 25% loss of PV generation.
- Study with 50% cloud cover resulting in 50% loss of PV generation.
- Study with 75% cloud cover resulting in 75% loss of PV generation.
- Study with 100% cloud cover resulting in 100% loss of PV generation.

3.4. *Automated device control simulation*

Automated control devices act to regulate the voltage in the distribution circuit. The purpose of the steady-state impact study is to find the extreme impacts of PV generation. The automated utility control devices considered here have a slow response relative to the possible rates of change of solar generation. That is, large changes in solar generation can occur before the utility control devices can react. Therefore, the impact of PV generation changes is investigated in the following two ways:

- Study with automated control devices operating.
- Study without automated control devices operating.

3.5. *Control of PV generation simulation*

Voltage control capability of PV generation is studied in [29]. PV generation can use both active and reactive power injection for control. It is useful for utilities to provide the impacts of PV generation when they are controlled. There are many research efforts to develop optimal control strategies for PV generation [30–39]. It is out of scope to test these advanced control algorithms here. In this article, fixed power factor control is considered and used to provide insights into the effect of the power factor control, where the power factors considered in the simulations are given by:

- 0.8 leading power factor PV control.
- 0.9 leading power factor PV control.
- 1.0 power factor PV control.
- 0.9 lagging power factor PV control.
- 0.8 lagging power factor PV control.

3.6. Simulation cases

The steady-state PV impact studies for evaluating customer voltage variations performs power flow analysis runs associated with the loss and restoration of PV generation as given by the following, where the notation Vi, i = 1, 2, 3, 4, 5, indicates voltage values for the stated condition:

- V1: the voltage for the base condition (current status).
- V2: the voltage following loss of generation due to cloud cover prior to automated device operation.
- V3: the voltage following loss of generation due to cloud cover after automated device operation.
- V4: the voltage following the return of generation to the original status (i.e., V1) without automated device operation.

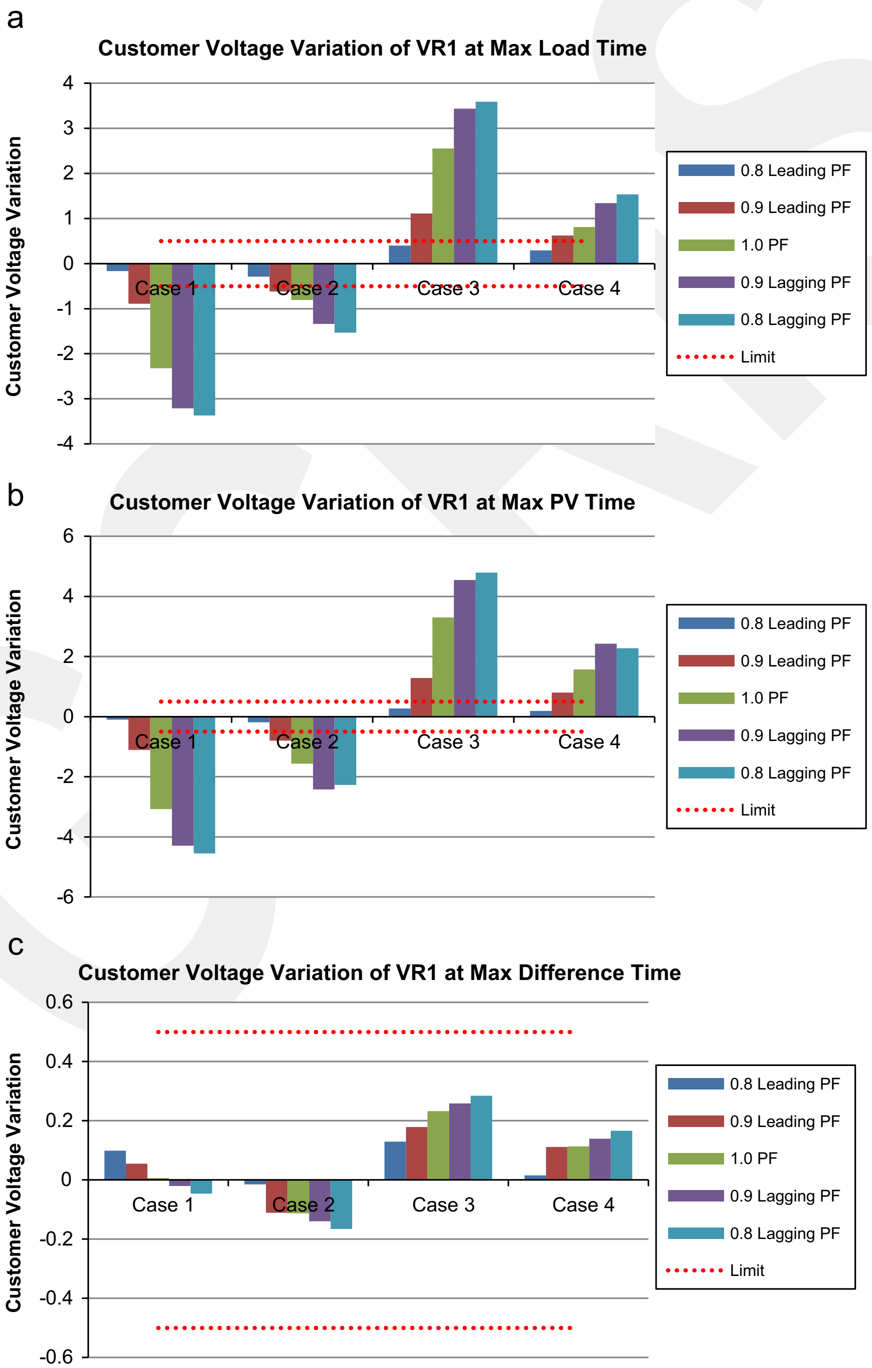

Fig. 3. Customer voltage variation with 50% cloud cover.

- V5: the voltage following the return of generation to the original status with automated device operation.

After obtaining the voltages from the above power flow analysis runs, the variations in steady state voltage are calculated as:

- Case 1: the voltage difference between V2 and V1 (V2–V1).
- Case 2: the voltage difference between V3 and V1 (V3–V1).
- Case 3: the voltage difference between V4 and V3 (V4–V3).
- Case 4: the voltage difference between V5 and V3 (V5–V3).

The above cases are run for the selected extreme circuit condition time points and for the different specified PV generation power factor control values.

The steady-state PV impact study for evaluating reverse power flows, power flow phase unbalance, and customer voltage phase unbalance determines the time at which the maximum voltage variations occur with changing PV generation and PV generation power factor control.

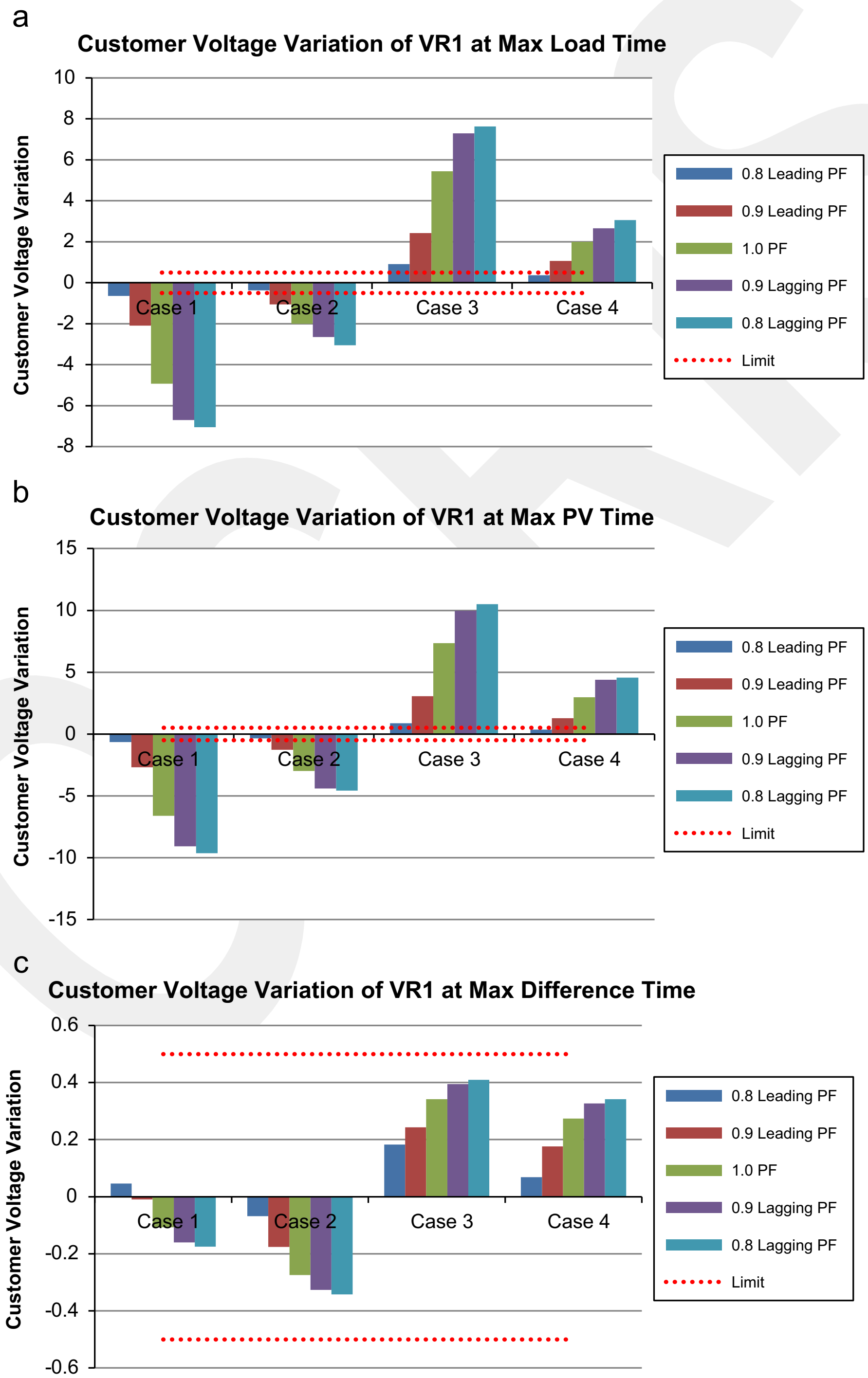

Fig. 4. Customer voltage variation with 100% cloud cover.

The quasi steady-state PV impact study for customer voltage variations, circuit losses, and automated device steps performs a series of power flow analysis runs associated PV generation status on and off with PV generation power factor control.

4. Simulation results

In this section, the simulation results of steady-state and quasi steady-state PV impact study cases are presented using the circuit and selected time periods discussed in the Section 3.

4.1. Steady-state simulation results

4.1.1. Customer voltage variation

Figs. 3 and 4 show the customer voltage variation at VR1 as a function of varying the power factor of the PV generation for 50% and 100% cloud cover. Each figure contains the results for the three different extreme circuit condition time points - maximum load, maximum PV generation, and the time at which the difference between the load and the PV generation is the greatest. The greatest voltage variation is observed at the time of maximum PV generation and the next at the time of the maximum load.

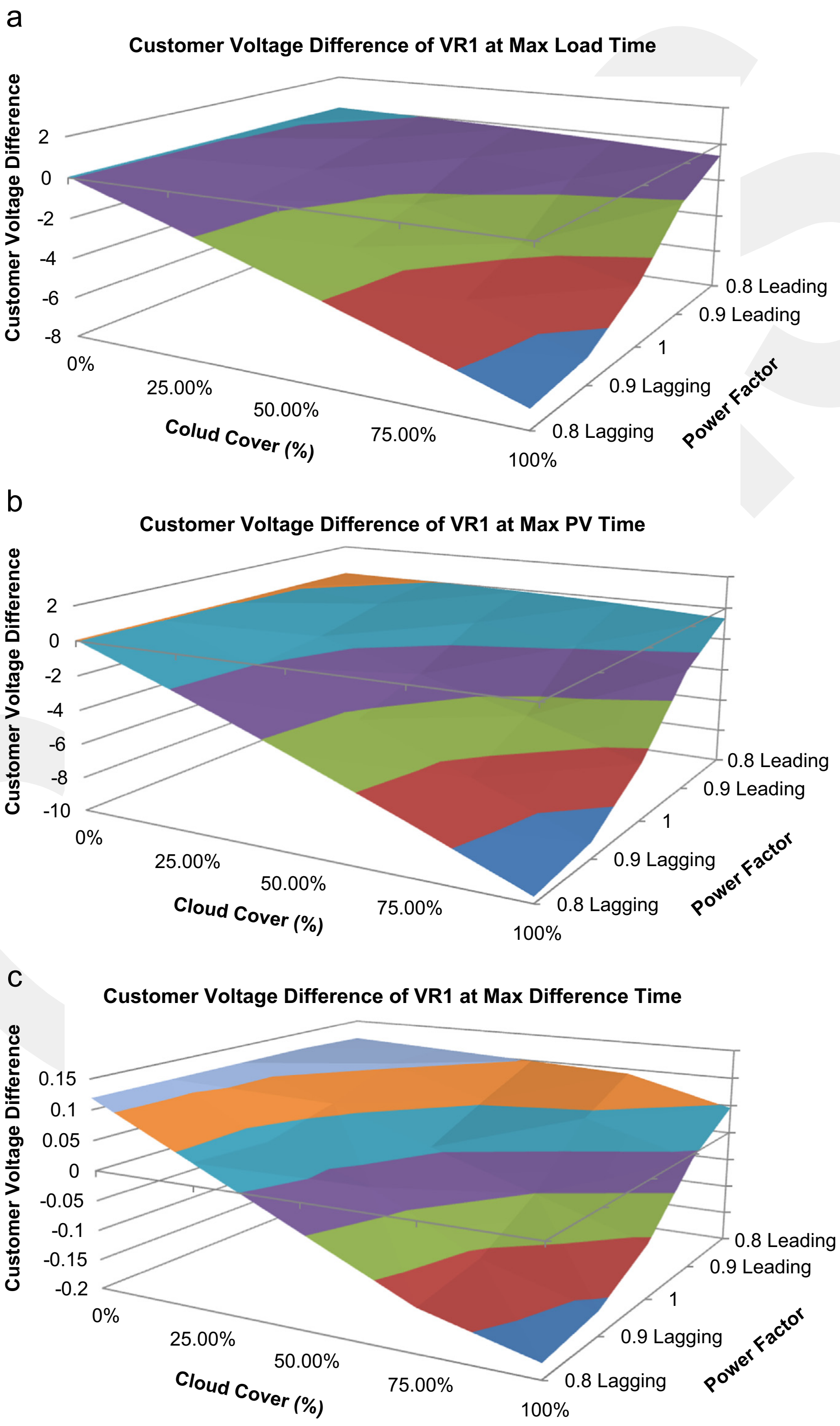

Fig. 5. 3-D Customer voltage variation for Case 1. (a) 3-D Customer voltage variation at VR1 at max load time. (b) 3-D Customer voltage variation at VR1 at max PV time. (c) 3-D Customer voltage variation at VR1 at max difference time.

Cases 1 and 2 show a negative voltage variation, whereas cases 3 and 4 show a positive voltage variation at the VR1 location. It is also observed, as expected, that the voltage variation is less following the operation of the automated control devices.

These figures also include the limits of the voltage variation. ANSI C84.1 provides a guideline for voltage variations from 114 V to 126, V where the desired voltage is 120 V [40]. In the work here a much smaller voltage variation (+/−0.5 V) is used for the voltage change limit. This limit is imposed so that the voltage regulator will not try to chase changes in the solar generation. The voltage variation at the maximum difference time is within the range for all cases because of the small amount of PV generation. A greater variation in voltage is observed for lagging power factor control of the PV generation than for leading power factor control. Therefore, in this case it is necessary to absorb reactive power to help mitigate the voltage variation caused by the rapidly varying PV generation. Most of the voltage variations at the 0.8 leading power factor control are within the 0.5 voltage change limit evaluated here.

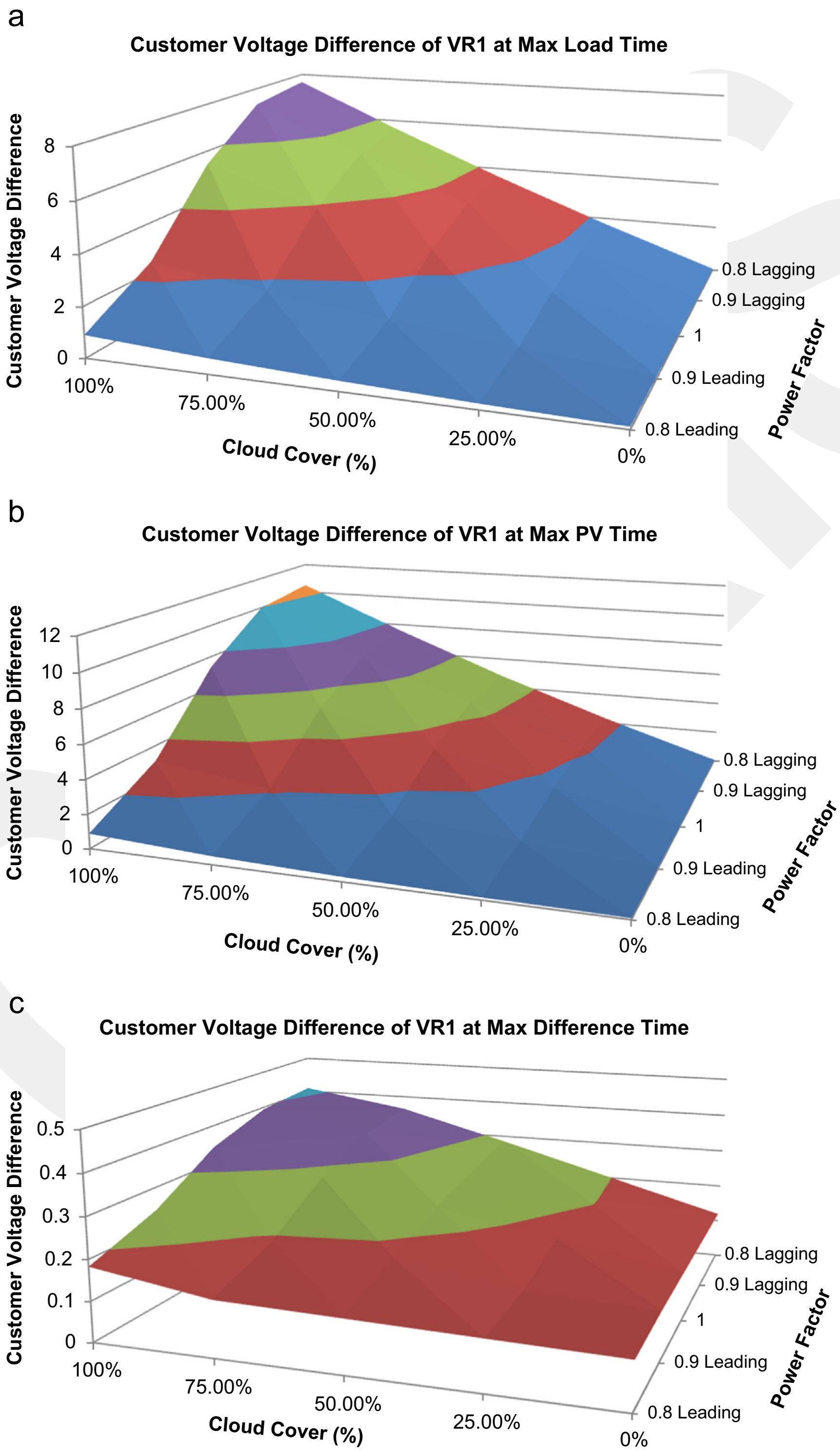

Fig. 6. 3-D Customer voltage variation for Case 3. (a) 3-D Customer voltage variation at VR1 at max load time. (b) 3-D Customer voltage variation at VR1 at max PV time. (c) 3-D Customer voltage variation at VR1 at max difference time.

Figs. 5 and 6 show 3-D graphs as a function of PV generation power factor and cloud cover at VR1 for cases 1 and 3, respectively. Each figure contains the results of the three extreme circuit condition time points. This 3-D graph can be used to estimate voltage variations when the PV generation operates with some cloud cover and fixed power factor control. In Fig. 5, voltage variation increases negatively for case 1 when cloud cover increases and the power factor varies from leading to lagging. On the other hand, voltage variation increases positively for case 3 when cloud cover increases, and the power factor varies from leading to lagging as shown in Fig. 6. Hence, for optimal response the power factor control needs to change as a function of the generation.

4.1.2. *Customer voltage variation by coloring the circuit*

Fig. 7 shows customer voltage variations by circuit color. This figure includes the results of phase A voltage difference when PV generation is on and off. The voltage difference below 0.25 V, between 0.25 V and 0.50 V, between 0.50 V and 0.75 V, between 0.75 V and 1.0 V, and over 1.0 V are colored by blue, green, yellow,

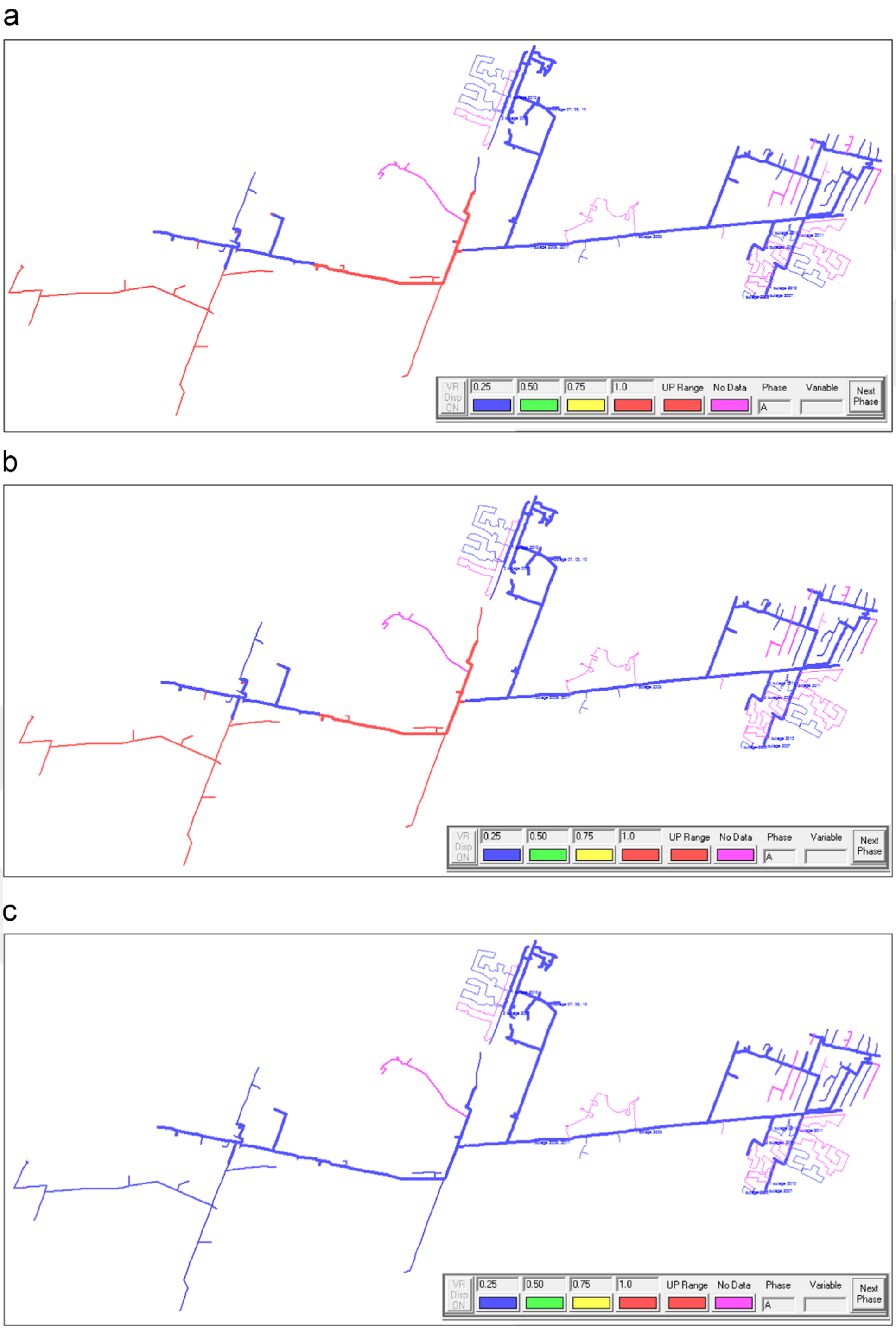

Fig. 7. Customer voltage variation by coloring the circuit for Case 2 with 100% cloud cover. (a) Customer voltage variation by coloring the circuit at maximum circuit load time. (b) Customer voltage variation by coloring the circuit at maximum PV generation time. (c) Customer voltage variation by coloring the circuit at maximum difference between circuit load and PV generation.

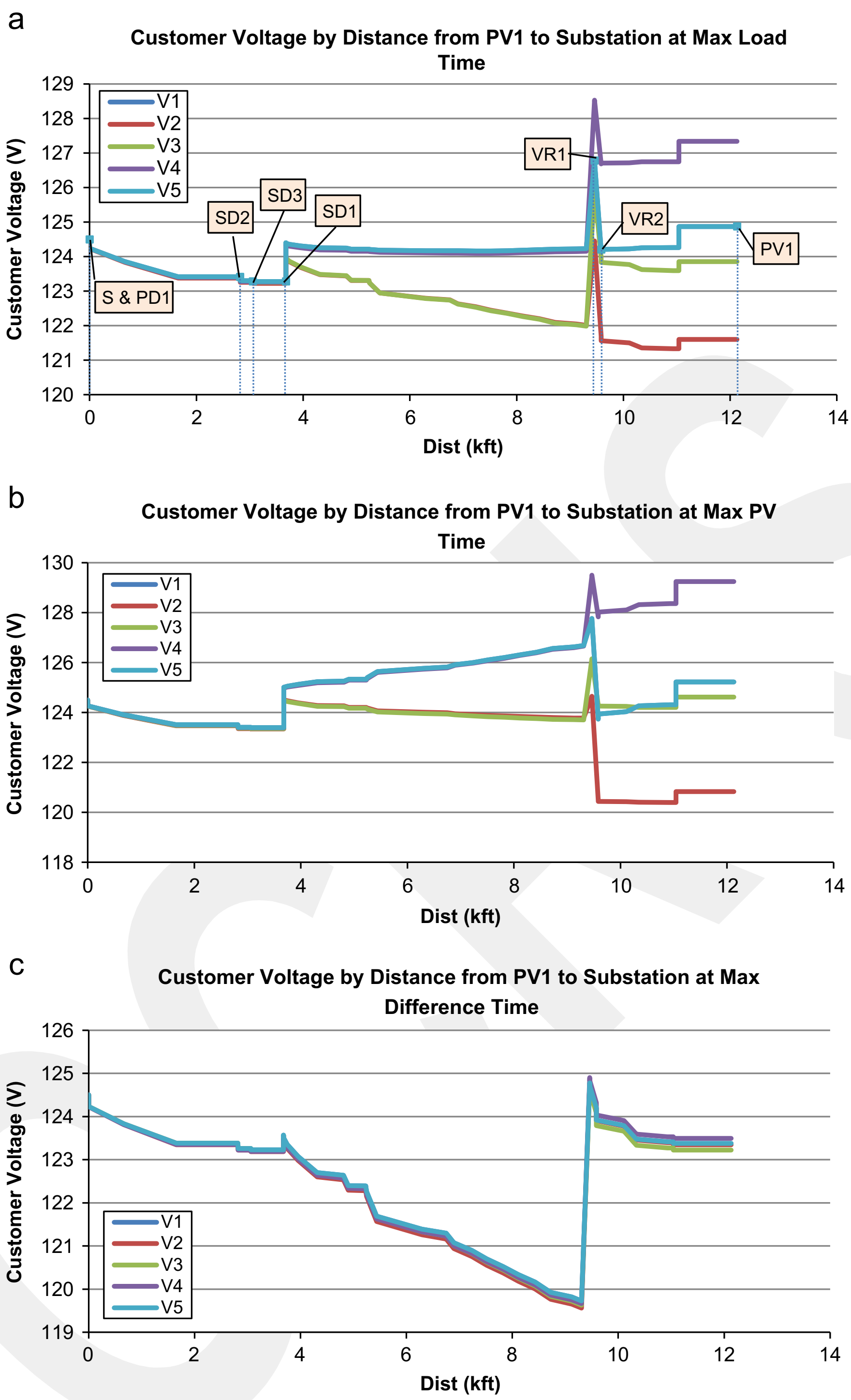

Fig. 8. Customer voltage by distance with 50% cloud cover. (a) Customer voltage by distance at maximum circuit load time. (b) Customer voltage by distance at maximum PV generation time. (c) Customer voltage by distance at maximum difference between circuit load and PV generation time.

red, and red respectively. If the results (phase A) are not available, it is colored by pink. The figure contains the results of the three different extreme circuit condition time points. The greater voltage variations are observed from PV4 to VR1 and downstream of SD4 at maximum circuit load and maximum PV generation times. The display of the results in this form shows the circuit locations that require some form of mitigation of the voltage problems created by the PV generation.

4.1.3. *Customer voltage variation by distance*

Figs. 8 and 9 show customer voltage variation as a function of distance from PV1 to the substation for both 50% and 100% cloud cover. In these figures V1 and V5 have the same values. Similar voltage variations are observed from the substation to SD1, but the voltage starts to vary after SD1 because of the loss of PV4 which is close to SD1. After VR1, distinct voltage variations are observed for the different cases. There is a greater variation from VR1 to PV1 in

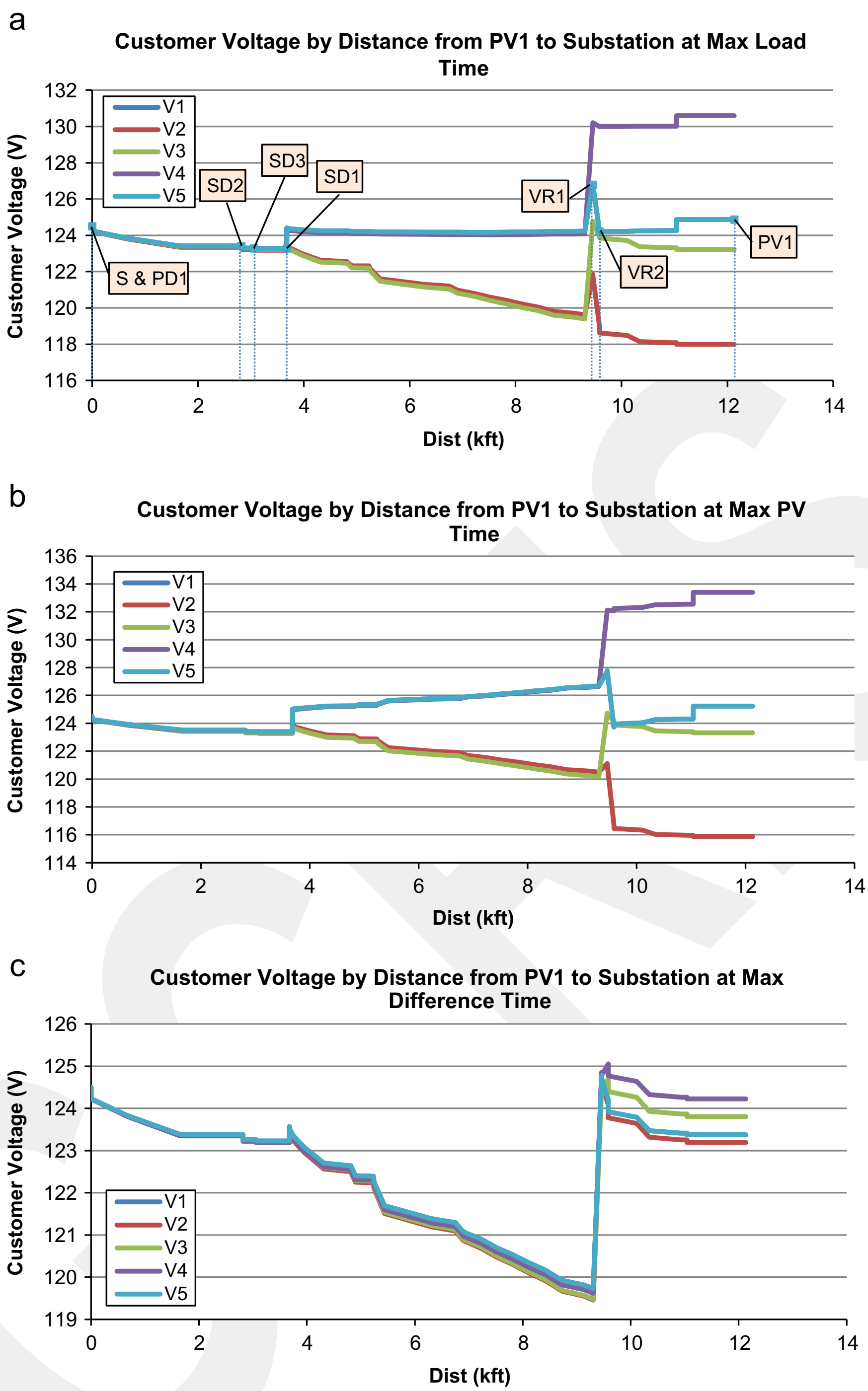

Fig. 9. Customer voltage by distance when 100% cloud covers. (a) Customer voltage by distance at maximum circuit load time. (b) Customer voltage by distance at maximum PV generation time. (c) Customer voltage by distance at maximum difference between circuit load and PV generation time.

Figs. 8 and 9, but greater voltage variations are observed from SD1 to VR1 in Fig. 7 due to automated device operations. In Figs. 8 and 9 it may also be observed that when the automated devices operate, the greatest voltage variation is observed from SD1 to VR1 for case 2 (V3-V1). This figure provides further information concerning where remedial actions are needed to reduce the voltage impacts.

4.1.4. *Reverse power flow*

Table 1 shows reverse power flow results for Case 2 involving 100% cloud cover. Results are shown at voltage regulators, capacitor banks, protective devices, and sectionalizing devices shown in Fig. 1. Results are shown for the circuit with and without PV generation. The results show the maximum reverse flow and the time of occurrence of the maximum reverse flow. Reverse power flow occurs on phase A at VR1 and SD1 and on phase B at VR2 when PV generation is at its maximum (01:00 PM). Although reverse power flow does not occur, large power flow differences do occur at PD1, SD1, and SD3 due to the PV generation. These results provide information as to where utility control and protection equipment need to be bidirectional.

4.1.5. *Customer voltage phase unbalance*

Table 2 shows customer voltage phase unbalance for Case 2 with 100% cloud cover. Results are given for voltage regulators, capacitor banks, protective devices, and sectionalizing devices shown in Fig. 1.

Table 1
Reverse power flow results for Case 2 when 100% cloud covers.

No.	Component Name	Max Difference Time	Phase	Flow Before (kW)	Flow After (kW)	Flow Difference
1	VR1	13:00	Phase A	156.19	***−77.19***	***233.38***
			Phase C	225.59	17.46	***208.13***
2	VR2	13:00	Phase B	54.59	***−163.90***	***218.49***
			Phase C	225.33	17.40	***207.92***
3	CAP1	14:00	Phase A	1285.15	1287.10	−1.96
			Phase B	1425.20	1426.66	−1.47
			Phase C	1218.64	1218.98	−0.34
4	CAP2	14:00	Phase A	234.53	234.88	−0.35
			Phase B	123.96	124.04	−0.08
			Phase C	17.78	17.79	−0.02
5	PD1	13:00	Phase A	3001.82	2096.34	***905.48***
			Phase B	2510.72	1613.99	***896.73***
			Phase C	2812.96	1916.43	***896.53***
6	PD2	14:00	Phase A	1508.92	1511.21	−2.29
			Phase B	1735.67	1737.31	−1.64
			Phase C	1553.27	1553.81	−0.54
7	PD3	13:00	Phase A	156.32	156.56	−0.24
			Phase B	156.67	156.76	−0.09
			Phase C	160.00	160.13	−0.12
8	PD4	14:00	Phase A	1285.86	1287.82	−1.96
			Phase B	1432.30	1433.77	−1.47
			Phase C	1219.08	1219.41	−0.33
9	SD1	13:00	Phase A	213.29	***−16.01***	***229.30***
			Phase B	277.20	53.89	***223.32***
			Phase C	365.98	145.05	***220.93***
10	SD2	13:00	Phase A	1939.35	1487.22	***452.13***
			Phase B	2225.76	1779.59	***446.17***
			Phase C	2134.45	1689.30	***445.15***
11	SD3	13:00	Phase A	1657.57	1205.48	***452.08***
			Phase B	1943.63	1497.67	***445.95***
			Phase C	1852.80	1407.81	***445.00***
12	SD4	13:00	Phase A	0.74	0.74	0.01
			Phase B	0.75	0.76	−0.01
			Phase C	0.68	0.73	−0.05

Table 2
Voltage phase unbalance for Case 2 with 100% cloud cover.

No.	Component Name	Max Difference Time	Phase	PVUR Before	PVUR After	Unbalance Difference
1	VR1	13:00	Phase A	***0.0459***	0.0165	***0.0294***
2	VR2	14:00	Phase B	***0.0508***	0.0188	***0.0320***
3	CAP1	13:00	Phase A	0.0010	0.0005	0.0006
4	CAP2	16:00	Phase B	0.0071	0.0078	−0.0007
5	PD1	–	–	0.0000	0.0000	0.0000
6	PD2	11:00	Phase A	0.0008	0.0003	0.0005
7	PD3	13:00	Phase A	0.0009	0.0003	0.0006
8	PD4	13:00	Phase A	0.0009	0.0003	0.0006
9	SD1	13:00	Phase A	0.0006	0.0000	0.0006
10	SD2	13:00	Phase A	0.0005	0.0000	0.0005
11	SD3	14:00	Phase A	0.0005	0.0000	0.0005
12	SD4	13:00	Phase C	***0.0680***	***0.0203***	***0.0477***

Results are shown for the circuit with and without the PV generation. The results show the maximum unbalance and the time of occurrence of the maximum unbalance. Note that a positive unbalance difference shown in the last column of the table indicates an improvement in the unbalance. This circuit has some excessive voltage unbalances (more than 2%) at VR1, VR2, and SD4 without the PV generation. Note that the voltage unbalance improves after the integration of PV generation (smaller PVUR values). Overall the voltage unbalance is improved at all selected components except CAP2. This output provides information about where actions are needed to reduce voltage unbalance, especially if three-phase motor loads are present.

Table 3
Power flow phase unbalance for Case 2 with 100% cloud cover.

No.	Component Name	Max Difference Time	Phase	PFUR Before	PFUR After	Unbalance Difference
1	VR1	10:00	Phase A	0.1751	***7.1525***	***−6.9774***
2	VR2	16:00	Phase B	0.6169	***13.3801***	***−12.7633***
3	CAP1	07:00	Phase A	0.0164	0.0181	−0.0017
4	CAP2	16:00	Phase B	0.0228	0.0235	−0.0007
5	PD1	11:00	Phase B	0.1140	0.1641	−0.0501
6	PD2	07:00	Phase A	0.0292	0.0278	0.0014
7	PD3	13:00	Phase A	0.0085	0.0079	0.0006
8	PD4	07:00	Phase A	0.0148	0.0165	−0.0017
9	SD1	13:00	Phase A	0.2529	***1.2626***	***−1.0097***
10	SD2	13:00	Phase A	0.0764	0.0998	−0.0233
11	SD3	13:00	Phase A	0.0882	0.1203	−0.0320
12	SD4	13:00	Phase C	0.0680	0.0203	0.0477

4.1.6. Power flow phase unbalance

Table 3 shows the power flow phase unbalance for Case 2 with 100% cloud cover. Results are given for voltage regulators, capacitor banks, protective devices, and sectionalizing devices shown in Fig. 1. Results are shown for the circuit with and without PV generation. The results show the maximum unbalance and the time of occurrence of the maximum unbalance. Note that a positive power flow unbalance difference shown in the last column of the table indicates an improvement in the unbalance. Contrary to the voltage phase unbalance, the greater power flow unbalance is observed at VR1, VR2, and SD1 after integration of PV generation. Furthermore, the unbalance increases at most of the selected locations. The results here provide information about where actions need to be taken to help balance power flows.

4.2. Quasi steady-state simulation results

4.2.1. Customer voltage variation

Fig. 10 shows time-varying voltage at CAP1 as a function of the PV generation power factor. When the no PV generation case is compared to the case with PV generation, a voltage rise occurs at unity and lagging power factors. The analysis shows that leading power factor PV generation control mitigates the voltage rise. Note that 0.9 leading power factor control maintains the customer voltage level at CAP1 approximately at the value that existed before introducing the PV into the circuit. Furthermore, a 0.8 leading power factor control can reduce the voltage level below that which existed prior to the introduction of the PV generation. These results provide information on power factor control that can help mitigate voltage rise. Results for voltage regulator VR1 operation will be presented in automated device steps.

4.2.2. Circuit loss

Figs. 11 and 12 show time-varying real and reactive circuit losses, respectively, as a function of PV generation power factor. Both real and reactive circuit losses decrease after integration of PV generation operating with unity power factor. Lagging power factor control reduces the circuit loss further. A 0.9 leading power factor control has similar circuit losses as the no PV generation case, whereas a 0.8 leading power factor control increases the circuit loss. Therefore, PV generation leading power factor can help mitigate voltage rise problems, but such control causes the circuit losses to increase. Hence, a balance must be sought in the control of voltage and losses.

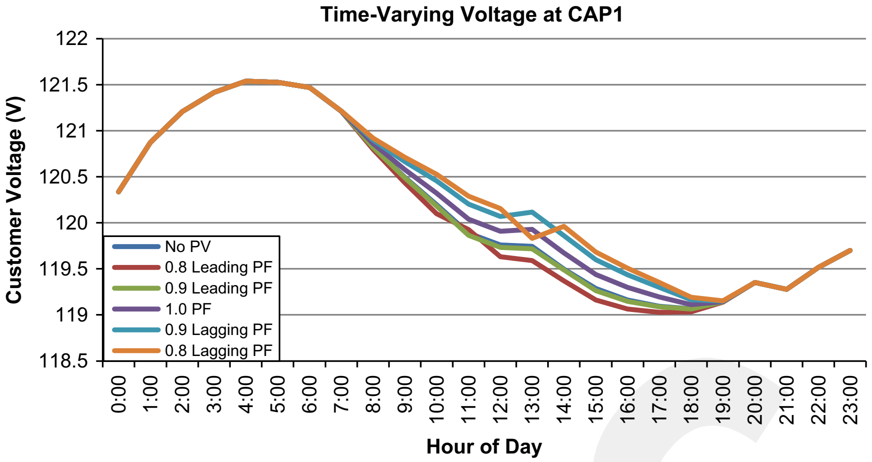

Fig. 10. Time-varying voltage at CAP1 for Case 2 with 100% cloud cover.

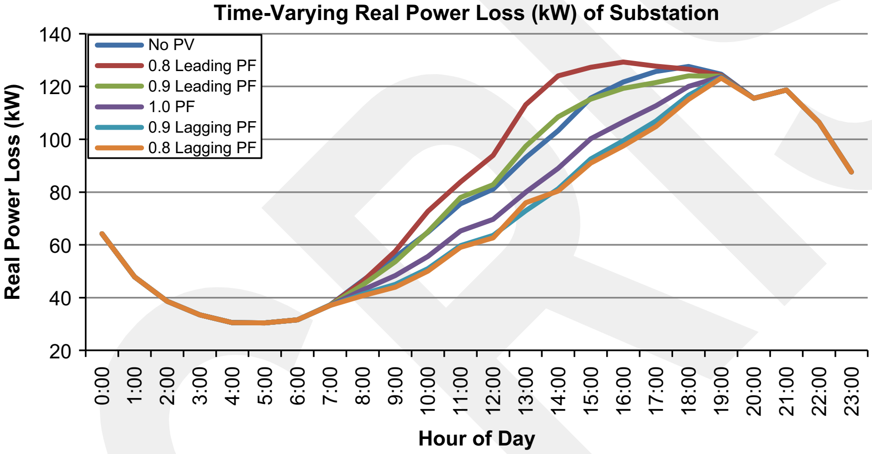

Fig. 11. Time-varying real power circuit loss for Case 2 with 100% cloud cover.

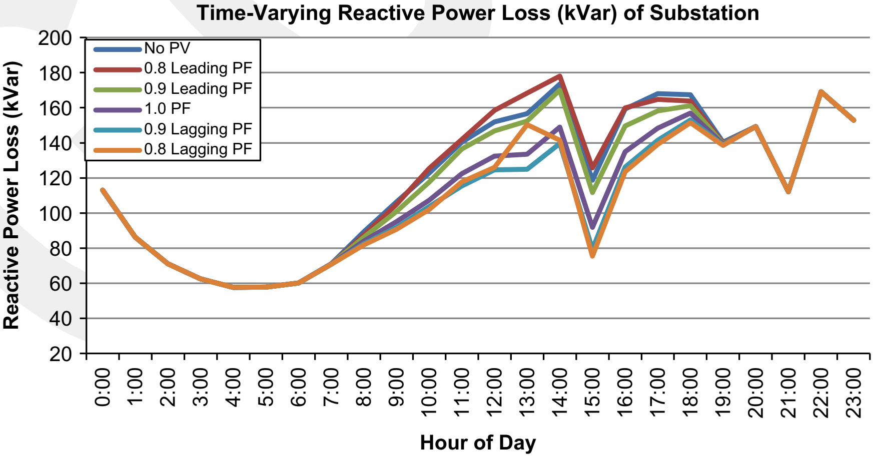

Fig. 12. Time-varying reactive power circuit loss for Case 2 with 100% cloud cover.

4.2.3. Automated device steps

Fig. 13 shows the step variations of VR1 across the day as a function of PV generation power factor. Total steps variations are 20, 18, 18, 24, 36, and 40 steps for no PV generation, 0.8 leading, 0.9 leading, 1.0, 0.9 lagging, and 0.8 lagging power factors, respectively. With the PV generation operating at unity power factor, the total steps across the day increases by 4 steps over the no PV generation case. As can be seen, leading power factor control reduces the total steps and the lagging power factor control increases the total steps significantly. The results here provide information that can be used to minimize maintenance activities and prolong life of utility control equipment.

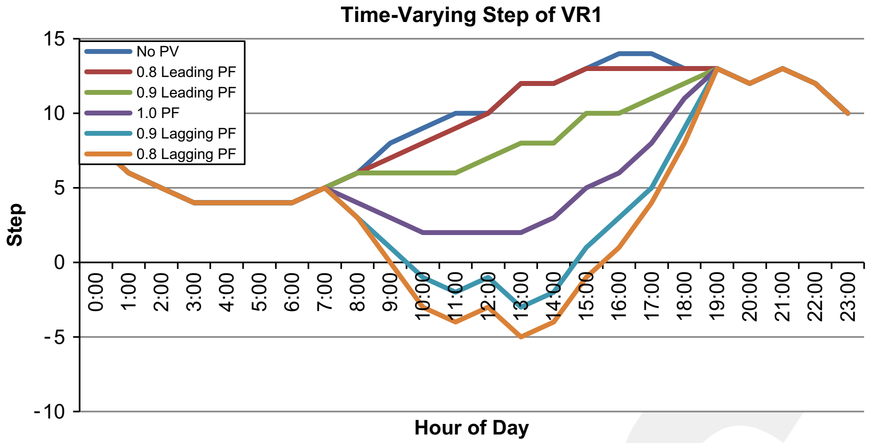

Fig. 13. Time-varying steps of VR1 for Case 2 with 100% cloud cover.

5. Conclusions

In this article the impacts of PV generation are investigated. Model data for a real distribution circuit is employed. Both steady-state and quasi steady-state impact studies are performed. In the studies changing cloud cover conditions and variations in PV generation power factor control are considered. Both improvements and adverse effects of PV generation on the circuit are discussed.

The steady-state impact studies consider voltage variations, reverse power flows, voltage phase unbalance, and power flow phase unbalance. In considering the voltage variations, several visualizations are provided, including 3-D voltage variation graphs, coloring the circuit model by voltage variations, and graphs of voltage variations versus distance. Each visualization provides information that is helpful in pursuing remedial actions needed to reduce voltage impacts. Reverse power flow, voltage phase unbalance, and power flow phase unbalance are also considered.

The quasi steady-state impact studies consider voltage variations, circuit losses, and automated device steps, across the time varying operation of the circuit. Voltage rise problems caused by the PV generation are observed in the simulation. In this particular simulation real and reactive losses are improved following the integration of PV generation. However, increases in automated control device steps are observed across the day. It is shown that PV generation power factor control can help to mitigate the impacts. However, there are tradeoffs between controlling voltage variations, circuit losses, and motion of automated utility control devices.

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