CSI RD&D (Solicitation 4) Task 4 Subtask 4.1 Draft Final Report

# Distribution Feeder Hotspots

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# Abstract

In this report capacity limits for 14 representative San Diego Gas and Electric (SDG&E) distribution feeders are related to increasing distributed solar power systems. Our objective is to quantify feeder hotspots resulting from high photovoltaic (PV) penetration levels, characterized by (1) over- and under- voltage conditions, (2) power flows that exceeds the thermal rating of the electrical conductor, or (3) voltage variations above a threshold. Further, load tap changer and capacitor operations arising from solar power variability are quantified. Power flow simulations are performed over 3 months at 30-second time steps in OpenDSS for PV penetration levels up to 300%. The power flow simulations include PV generation profiles for each distributed PV system along each feeder that were generated from sky images. The results of the case study highlighted that significant increases in PV penetration levels across all of the 14 feeders are feasible, with hotspots identified at PV penetration levels that exceed or equal 100%. Further, the increase in PV penetration level that could be accommodated by each feeder (without costly upgrades to the distribution grid) depends on the feeder topology including conductor size, the rated PV power output of each unit, and location of the distributed PV systems along the respective feeder.

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# 1. *Introduction*

Distribution planners conduct power flow analysis to identify future network capacity limits for the distribution grid so that they may plan to remediate potential constraints before they occur. Network capacity limits typically include thermal rating limits of current carrying conductors, and over- and under voltages exceeding ±5% of the nominal voltage. Further, voltage variations creating perceptible flicker, significant increases in load tap changer operations, and the reach of protection devices to identify and isolate faults can also be considered when assessing network capacity limits.

Increasing existing capacity limits can lead to substantial network investment for a utility. For example, the need to re-conductor overhead lines to remediate future thermal capacity limits is often not only expensive in terms of the capital cost of equipment, but can also be costly in terms of the design, construction and associated labor costs. Moreover, a considerable lead time for the project may be required so that the thermal limit is not reached before the completion of the project is possible.

Consequently, identifying future capacity limits in the distribution grid can be helpful in terms of understanding the cost and time for remediation. In the context of analyzing capacity limits related to increasing solar power systems, future hotspots are mapped as a function of distributed PV penetration with the aid of power flow analysis tools. A hotspot is defined as (a) over- and under- voltages exceeding ±5% of a nominal 12 kV or (b) conductors exceeding a current carrying capacity. High PV penetration impacts are further quantified through load tap changer and capacitor operations and voltage variability at distribution load centers.

# 2. *Distribution Feeders*

## 2.1. Feeder Selection

San Diego Gas and Electric (SDG&E) provided the University of California (UC) San Diego with 15 distribution feeder models suitable for power flow applications. The models included the electrical connectivity of conductors, capacitors, voltage regulators, generators and load buses. Further, SDG&E provided UC San Diego a conductor database that described the positive sequence impedance of each conductor within the distribution feeder models.

Each of the 15 SDG&E feeders serviced load (primarily residential and commercial) in the vicinity of the locations illustrated in Figure 1. The 15 distribution feeders provided to UC San Diego were carefully selected by SDG&E for the purpose of identifying distribution hotspots requiring network augmentations due to growth of variable solar photovoltaic (PV) generation.

UCSD conducted power flow simulations for 14 of the 15 representative SDG&E feeders to quantify voltage variability, over- and under-voltage conditions, and load tap changer operations that resulted from increasing solar PV penetration. [1]

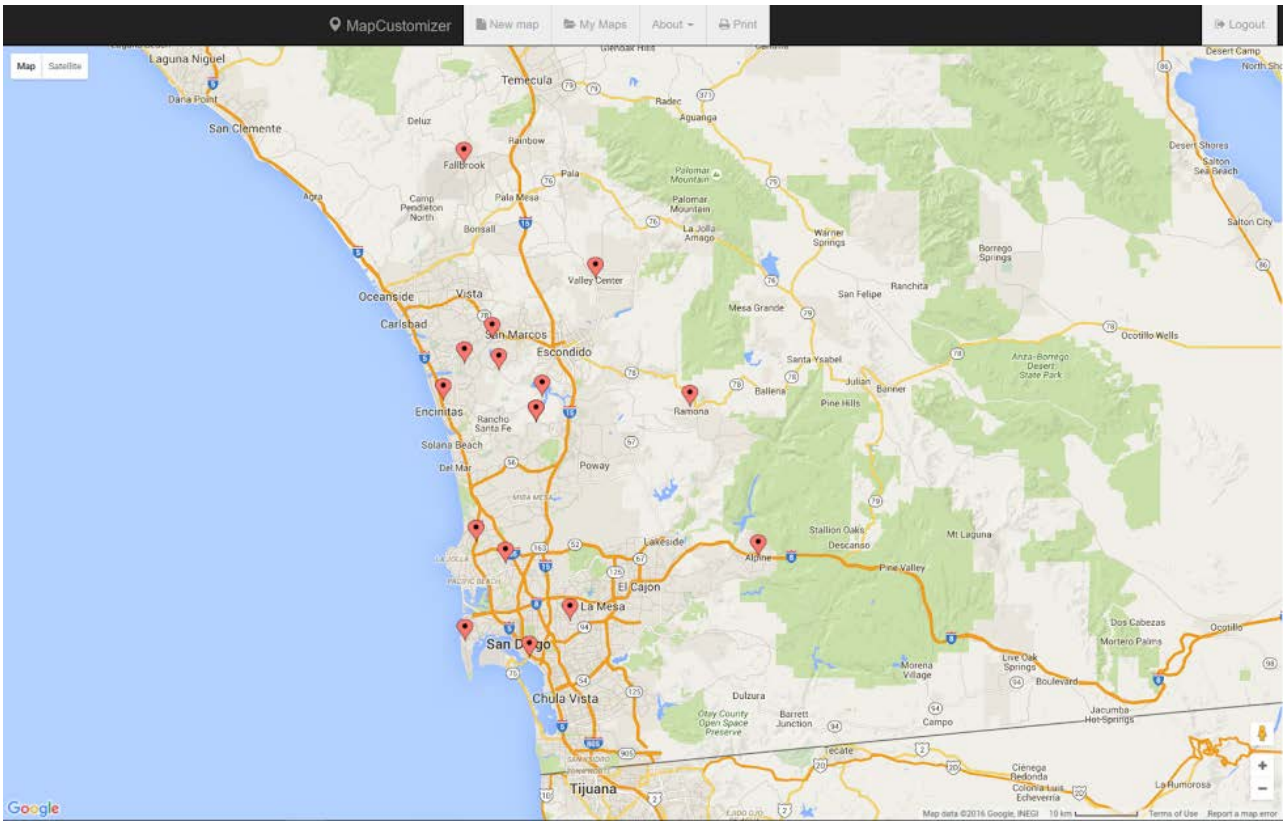


**Figure 1: Approximate locations of SDG&E Distribution Feeders[2]**

## 2.2. Model Validation

SDG&E provided simulated load flow results to UCSD for each of the distribution feeders to assist in the model validation. These load flow results were compared to those obtained in OpenDSS to highlight any potential model inaccuracies arising from importing the electrical models into OpenDSS. Any OpenDSS model inaccuracies identified were corrected before further analysis was conducted.

In the model validation, voltages at each node along a distribution feeder obtained from the OpenDSS simulations were compared against the voltages supplied by the utility. Voltages discrepancies of >0.01pu were investigated first. In some cases loads in the OpenDSS model were connected to the incorrect node. For example, some loads were connected to the

[1] Feeder 15 was found to be unsuitable for further analysis during the model validation process. Specifically there were concerns about the convergence of the power flow simulations that manifested in unreasonably large voltage swings at very high penetration, which also brought the results at lower penetration levels into question.

[2] https://www.mapcustomizer.com/

downstream node of a conductor rather than an upstream node (or vice versa), which resulted in higher (or lower) conductor losses and a discrepancy with the reported voltages. Accordingly, some loads were moved to the closest upstream or downstream node. The process of investigating large voltage disparities was repeated until the voltage error in the OpenDSS results was less than 0.005 Vpu, where possible.

An example of the model validation results for Feeder 1 is presented in Figure 2. The team compared in (Figure 2-left) voltages at each node along the distribution feeder obtained from the OpenDSS simulations, against the voltages supplied by the utility. The team observed (Figure 2 -right) the voltage error at each node arising from the OpenDSS simulation is very small and less than 0.005 Vpu. In summary, 13 of the 14 feeders had a voltage error less than 0.005 Vpu, with the exception of feeder 4 that had an error of less than 0.01 Vpu.

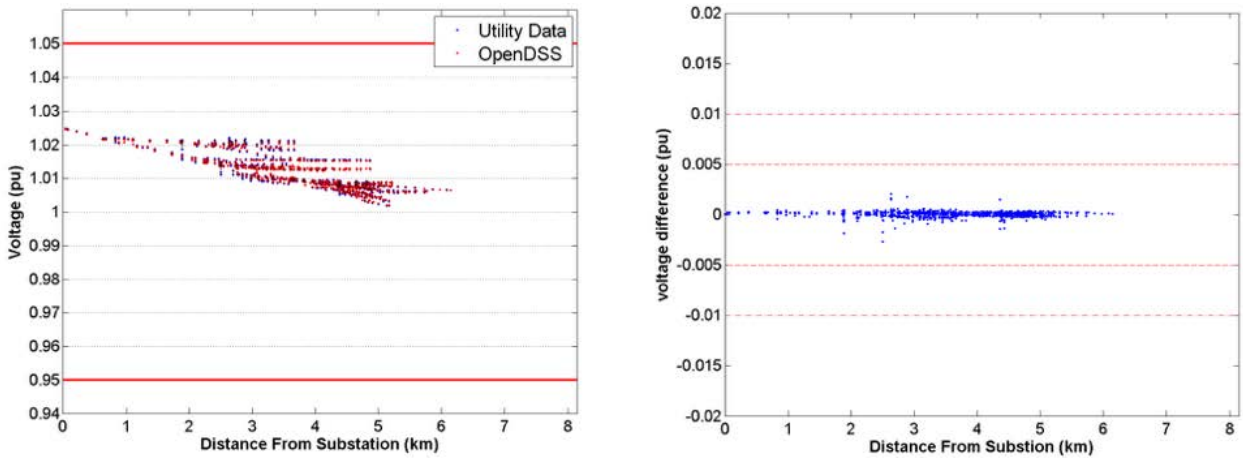


**Figure 2: (left) A comparison on the voltage profile along Feeder 1, where blue markers denote the utility results and red markers denote the OpenDSS results after the feeder validation. Figure 2 (right) presents the respective voltage error along Feeder 1.**

## 2.3. Feeder Topology Overview

Table 1 presents an overview of the circuit topology of the 14 distribution feeders. Feeders 12, 13, and 14 were classified as rural, and the remaining feeders as urban. It was assumed that all capacitors have 20 steps, with step size determined from the rated reactive power. It was also assumed all distribution transformers have 32 tap positions, where the tap position selected either lowers or raises the voltage at the distribution substation to maintain the substation set-point voltage within $\pm 0.833\%$.

**Table 1: Distribution feeder properties. The maximum number for each category / row is in bold.**

| Circuit ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Feeder Type | urban | urban | urban | urban | urban | urban | urban | urban | urban | urban | urban | rural | rural | rural |
| Total Feeder length (km) | 53 | 58 | 41 | 45 | 52 | 55 | 49 | 56 | 45 | 51 | 40 | 35 | 52 | 115 |
| # Supply Transformers | 298 | 312 | 285 | 243 | 416 | 324 | 212 | 139 | 260 | 376 | 322 | 281 | 276 | 649 |
| Peak Load (MVA) | 8.0 | 9.7 | 9.5 | 5.9 | 10.8 | 13.2 | 9.8 | 8.8 | 8.0 | 13.6 | 8.4 | 4.9 | 3.9 | 6.3 |
| # Capacitors / Rated Reactive Power (MVAr) | 1/ 1.2 | 1/ 1.2 | 3/ 1.2, 0.8, 1.2 | 1/ 1.2 | 1/ 1.2 | 1/ 1.2 | (3)*/ 1.2, 1.2, 1.2 | 2/ 1.2, 1.2 | 1/ 1.2 | 4/ 1.2, 1.2, 1.2, 1.2 | (2)*/ 1.2, 1.2 | (2)*/ 1.2, 1.2 | (1)*/ 1.2 | (1)*/ 1.2 |
| # Substation Transformers and Voltage Regulators | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 |
| # PV systems | 180 | 105 | 106 | 83 | 95 | 62 | 69 | 147 | 66 | 71 | 340 | 364 | 104 | 387 |
| Peak PV output ($MW_{AC}$) | 1.9 | 1.1 | 0.7 | 0.8 | 0.9 | 0.8 | 0.8 | 1.9 | 1.1 | 1.3 | 5.1 | 1.3 | 2.7 | 2.4 |
| 2015 PV Penetration Level[3] (%) | 24 | 12 | 7 | 13 | 8 | 6 | 8 | 22 | 14 | 9 | 60 | 51 | 71 | 38 |
| Capacity (MW) of large PV systems (>0.5 MW) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.14, & 0.86 | 0 |
| Substation set-point voltage (pu) | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.01 | 0.98 | 0.99 | 1.01 |

* In the simulations that follow these capacitors are taken out of service to accommodate increasing levels of PV penetration.

[3] The PV penetration level is defined in Section 2: Feeder Hotspots.

# 3. *Feeder Hotspot Methodology*

## 3.1. Hotspot Criteria

Sections of each distribution feeder that are most affected by high PV penetration are identified. A feeder hotspot along a distribution feeder is defined by:

(1) An over- or under-voltage at a node that exceeds ±5% of a nominal 12 kV,

(2) A steady-state power flow that exceeds the thermal rating of the conductor, or

(3) Voltage fluctuations measured at 30-second time steps along a distribution feeder that exceed 2%, a threshold that may prompt an investigation into the customer impacts (e.g., perceptibility of flicker, (Woyte, Thong, Belmans, & Nijs, 2006)). [4]

For a specified PV penetration level, we define the maximum voltage variability for each node $n$ along the feeder by,

$$V^* = \max_{k \in \{1,2,\ldots,K-1)} |V(n,k+1) - V(n,k)|,$$

where $V(n,k)$ is the voltage at node $n$ corresponding to time index $k$, and $K$ denotes the number of time indices. Time index $k$ increments by 30-seconds, and $K$ represents a time window of 3 months.

We map the maximum voltage variability for each node $n$, for the lowest PV penetration level corresponding to a hotspot defined by criteria (1) and/or (2) above. The map of maximum voltage variability assists in the identification of hotspots arising from criteria (3) above.

PV impacts on load tap changer and capacitor operations were also quantified.

## 3.2. Hosting Capacity

Hosting capacity is defined by the maximum amount of PV generation that a feeder can accommodate before feeder hotspots along the feeder occur (Rylander, Smith, Lewis, & Steffel, 2013).

## 3.3. PV Penetration

PV penetration is defined by $\frac{P_{pv_peak}}{P_{load_peak}} \times 100\ \%$, where $P_{pv_peak}$ is the cumulative rated AC power of all PV systems. $P_{load_peak}$ is the non-coincident feeder load (ignoring feeder losses), and was calculated by summing the per-node load data provided by SDG&E along each respective feeder. The special case where the PV penetration level is 0% is equivalent to taking all PV units out of service.

[4] In the IEEE standard (IEEE Power & Energy Society , 2009) $P_{ST}$ is a measure of the magnitude and frequency of voltage fluctuations over a range of short-term timescales. Typical permissible magnitudes for voltage fluctuations in a distribution grid range from 0.2-2 $P_{ST}$, where $P_{ST}$=1 is most commonly used for medium voltage planning purposes (IEEE Power Engineering Society, 2005).

### 3.4. Solar Input Data

PV locations for the distribution feeders with feeder ID's 1-10 is consistent with that provided by SDG&E. The PV locations for the remaining 4 distribution feeders with ID's 11-14 are as described in (Nguyen, et al., 2016), and is a combination of existing PV sites and additional randomly chosen virtual PV sites. To consider the impact of high PV penetration levels on each of the feeders, the rated PV output for each existing and virtual (only for feeders 11-14) PV system was scaled.

Note that all PV units and loads located on the secondary side of the supply transformers were moved to the primary side in the models provided by SDG&E. This approach greatly simplifies the complexity of the models under consideration, however, it does affect the results presented. By not modeling the secondary side impedances and associated supply transformers some losses are ignored, which will impact the simulated power flows along the feeder. Consequently, a reported PV penetration associated with a feeder hotspot might change by a small amount. Further studies to quantify the impact of not modeling the secondary side systems are possible, however, approaches will require customer specific data (e.g., the actual location and size of existing PV units and peak load data). This customer specific data is not publically available due to privacy reasons, and therefore obtaining this data may not be feasible.

To realistically consider the impact of PV generation variability arising from moving cloud cover, PV generation profiles were simulated using sky images. More specifically, sky images taken every 30 seconds were used to produce unique generation profiles at each of the PV sites on each distribution feeder. Since sky imagers were not installed at each feeder, data from nearby sky imagers was utilized. The sky image data used for feeders 1, 3, 4, 5, 6, 7, 8, 9, 13 and 14 came from camera USI 1.2 at UC San Diego, for feeders 2 and 10 USI 1.8 at Fallbrook was used, for feeder 11 USI 1.9 at Point Loma was used, and USI 1.14 at Alpine was used for feeder 12. The algorithm used to produce PV generation profiles along each distribution feeder is described in more detail in (Murray, et al., 2015).

### 3.5. Load Input Data

For four feeders, the 15 min resolution load demand timeseries was available from SDG&E (Nguyen, et al., 2016). For the remaining feeders, data from one of these four feeders was used, but rescaled using the maximum power consumed by all loads along a given feeder $P_{load_peak}$ as provided in the simulation results from SDG&E. The total load was distributed to each supply transformer according to its maximum power consumed. Therefore, the supply transformers along a given feeder had the same load profile, yet the peak load magnitude for each supply transformer was unique.

## 4. *Feeder Hotspot Results*

PV generation and load profiles along each distribution feeders over a 3.5 month period spanning the winter of 2014 (December 6$^{th}$) to spring 2015 (March 20$^{th}$) are simulated. Three-phase unbalanced quasi-static time series power flow analysis is conducted at 30 sec intervals over this 3.5 month period in OpenDSS to assess impacts of high PV penetration levels. Results are reported by feeder followed by a summary table and discussion at the end.

### 4.1. Feeder 1

Feeder 1, operated at a nominal 12kV, is characterized as urban with a length of 53.3 km, carries a peak load of 8.037 MVA, and connects 298 supply transformers that step the voltage down to a lower voltage from which residential and commercial loads are supplied. Further, 180 PV units are connected to the secondary side of the respective supply transformers, the majority of which are located on residential rooftops. Approximately 7 larger likely commercial PV units are connected to the secondary side of the supply transformer. Recall, in the models that follow all secondary side loads and PV units are located on the primary side of the respective supply transformers. In Figure 3 the location and size of PV units included in the model of the 12 kV feeder are depicted by circles.

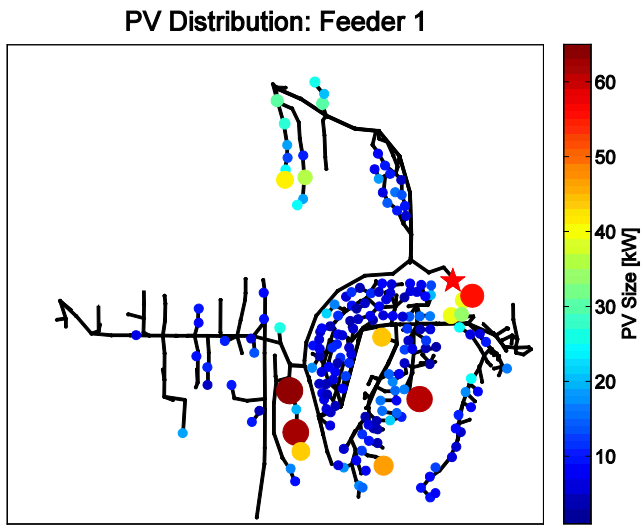


**Figure 3: PV distribution map for feeder 1, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located.**

Feeder 1 includes a single three-phase 1.2 MVAr capacitor with assumed 60 kVAr steps located 2.78 km from the distribution substation that is controlled with the purpose of improving voltages along the 12kV feeder. Further, feeder 1 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.02 Vpu that is also operated with the purpose of improving voltages along the 12kV feeder. Unless otherwise mentioned, these voltage regulation devices were included in the simulations.

In Figure 4 geo-schematic single line diagrams of feeder 1 are presented. Figure 4 (left) presents feeder hotspots[5] corresponding to various PV penetration levels, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding ±5% of the nominal 12 kV. Figure 4 (right) presents the

[5] In the Appendix the hotspots arising from thermal limits of electrical conductors are presented separately from hotspots corresponding to voltages exceeding ±5% of the nominal 12 kV.

maximum voltage variability observed along each node of the feeder for a 280% PV penetration level.

The feeder can accommodate PV penetration below 280% without the need for network augmentation to mitigate thermal limits of the conductors and/or voltage violations exceeding ±5% of the nominal 12 kV. The majority of the feeder can accommodate PV penetration up to or possibly above 300% and feeder hotspots solely resulted from voltage violations. That is, all conductors were sufficiently rated for PV penetration up to 300%. Since PV penetration of more than 300% were not examined, hotspots at 300% could tolerate even higher penetration levels.

From Figure 4 (right) maximum voltage variations along the feeder ranged from 0.6% to 2% for a 280% PV penetration level. Further, the voltage variations presented in Figure 4 (right) are below the 2% threshold for the majority of the feeder. The customer impact of voltage variations below the 2% threshold might be investigated by a utility on a case-by-case basis with an instrument based on IEC 61000-4-15 (IEEE Power Engineering Society, 2005).

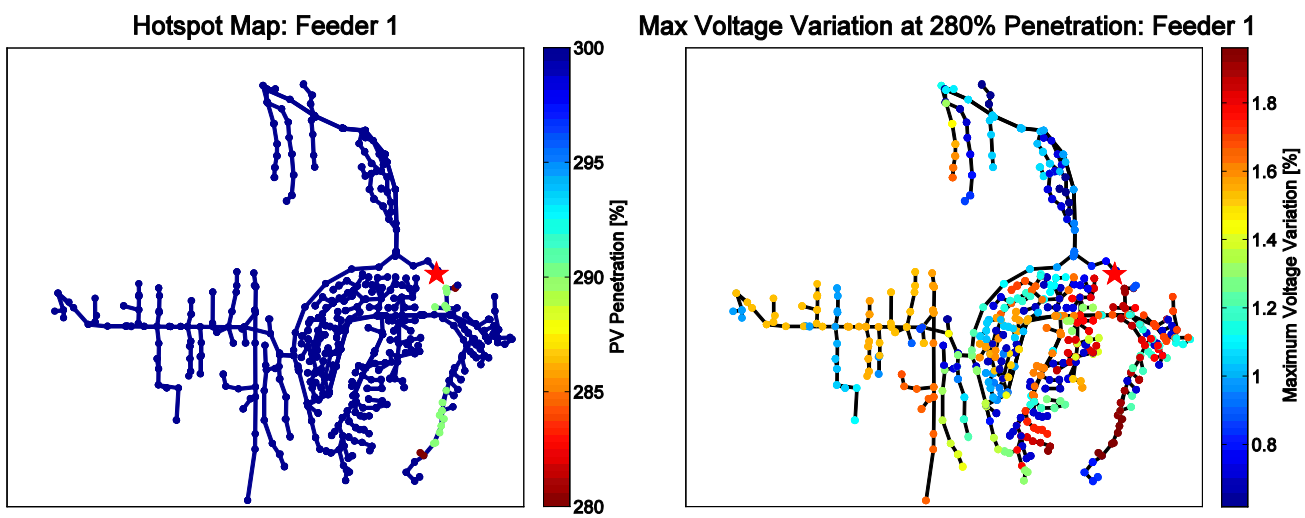


**Figure 4: Hotspot map for feeder 1. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 280%.**

In Figure 5 (left) the average number of daily tap operations for the on-load tap changing transformers at the distribution substation is presented with PV penetration levels from 0% to 300% (where 0% is the case where all PV units have been taken out of service). From Figure 5 (left) the number of daily tap operations does not change as the PV penetration level increases.

In Figure 5 (right) the average of the daily capacitor switching events is presented for increasing PV penetration. Figure 5 (right) shows a very small number of switching events for all PV penetration levels. That is, on most days the capacitor switched state remained unchanged, and the capacitor was typically supplying 1.2 MVAr.

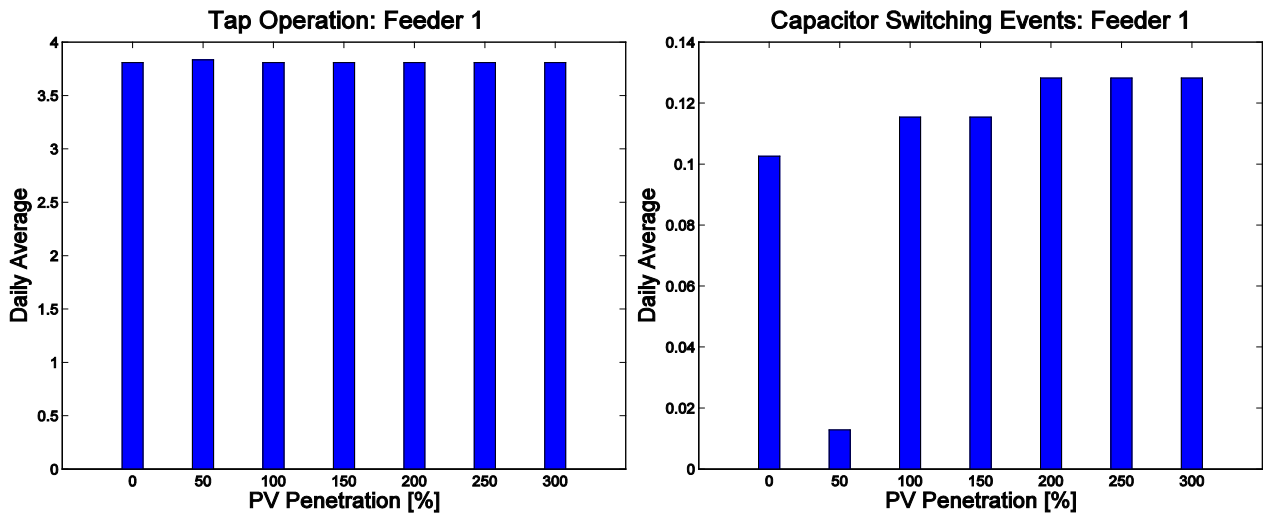


**Figure 5: Left, the average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Right, the daily average switching events for the capacitor located on feeder 1.**

In summary, the PV hosting capacity of feeder 1 can be raised considerably from 23.5%. Further investigation into the impact of voltage variability for some customers is recommended for PV penetration close to or above 280%.

### 4.2. Feeder 2

Feeder 2, operated at a nominal 12 kV, is characterized as urban with a length of 58.2 km, carries a peak load of 9.74 MVA, and connects 312 supply transformers. Further, 105 PV units are connected to the secondary side of the supply transformers, the majority of which are located on residential rooftops. Approximately three larger likely commercial PV units are connected to the secondary side of the supply transformer (Figure 6).

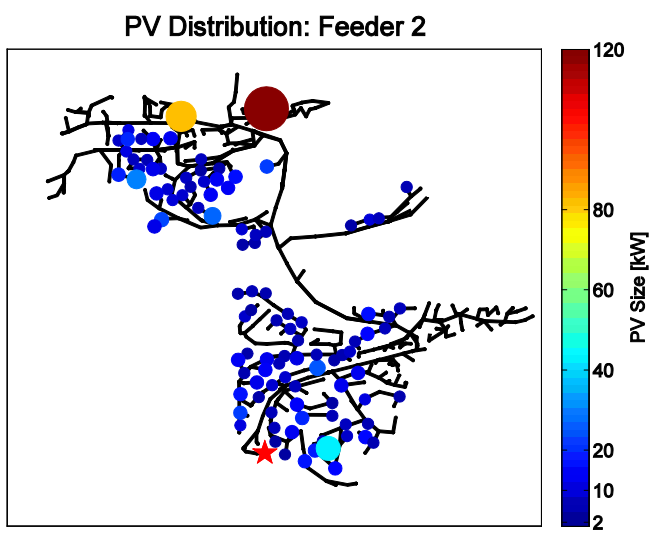


**Figure 6 PV distribution map for feeder 2, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located.**

Feeder 2 includes a single three-phase 1.2 MVAr capacitor with assumed 60 kVAr steps located 5.6 km from the distribution substation that is controlled with the purpose of improving voltages along the 12 kV feeder. Further, feeder 2 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.02 Vpu that is also operated to improve voltages along the 12 kV feeder.

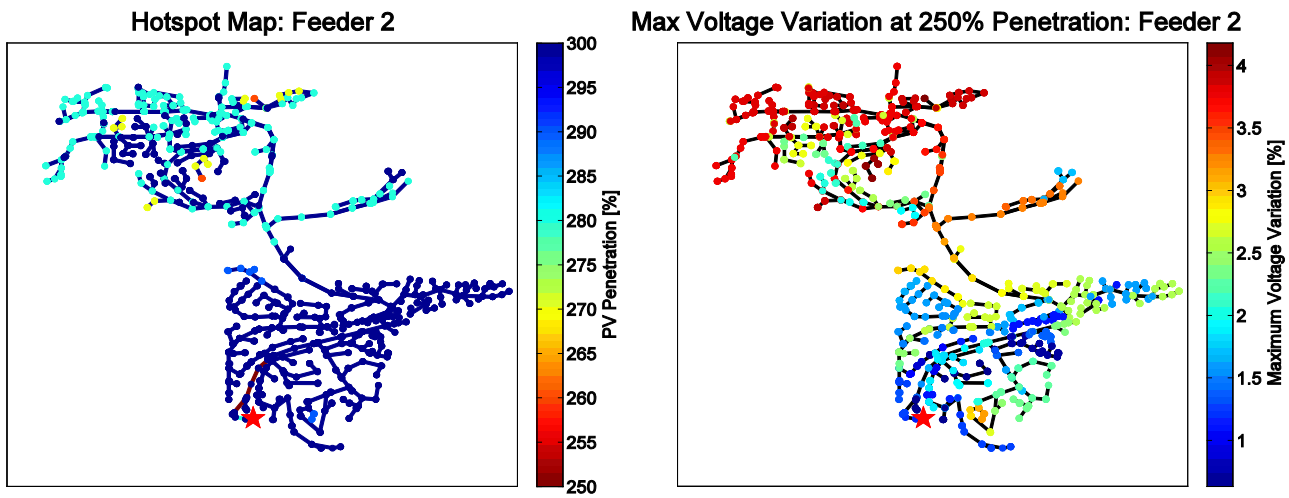


**Figure 7: Hotspot map for feeder 2. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 250%.**

The feeder can accommodate PV penetration below 250% without the need for network augmentation to mitigate thermal limits of the conductors and/or voltage violations exceeding ±5% of the nominal 12kV. The majority of the feeder can accommodate PV penetration up to or possibly above 300%, and voltage violations were responsible for the majority of observed feeder hotspots. That is, only a small section of conductor was insufficiently rated for PV penetration up to 250%. The hotspots associated with a PV penetration level of 250% were located towards the end of the distribution feeder.

From Figure 7 (right) maximum voltage variations were observed along the feeder ranging from 0.6% to 4.2% for 250% PV penetration. A significant proportion of voltage variations are above the 2% threshold. Accordingly, for PV penetration of 250% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 4% is recommended.

No changes in the number of daily tap operations were observed as the PV penetration increases (Figure 8 left). An increase in the number of switching events were observed as PV penetration increases (Figure 8 (left) because the capacitor reduces reactive power output as PV generation increases, and increase reactive power output as PV generation decreases and the load increases in the evening.

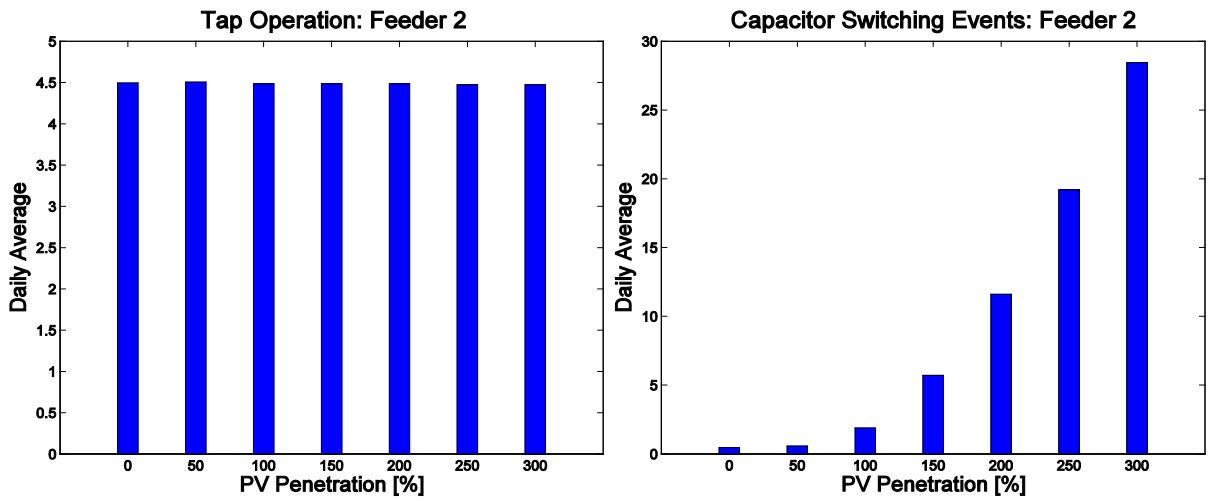


**Figure 8: Left, the average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Right, the daily average switching events for the capacitor located on feeder 2.**

### 4.3. Feeder 3

Feeder 3, operated at a nominal 12 kV, is characterized as urban with a length of 41 km, carries a peak load of 9.51 MVA, and connects 285 supply transformers. Further, 106 PV units are connected to the secondary side of the supply transformers, the majority of which are located on residential rooftops (Figure 9).

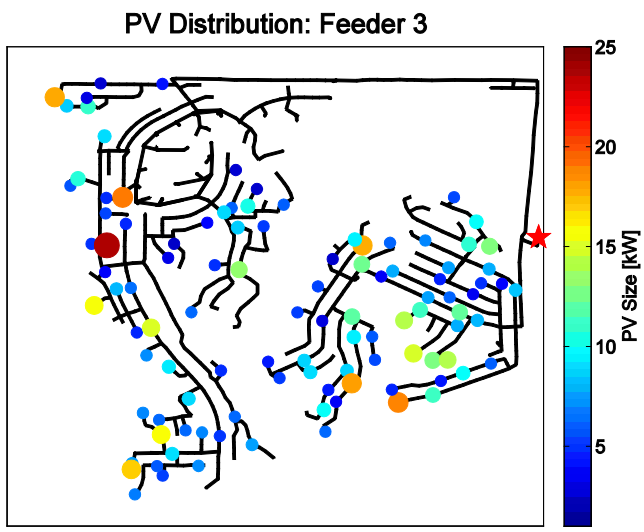


**Figure 9: PV distribution map for feeder 3, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located..**

Feeder 3 includes two 1.2 MVAr capacitors with assumed 60 kVAr steps and a single 0.789 MVAr capacitor with assumed 39.45 kVAr steps located 2.82 km, 4.53 km, and 3.4 km, respectively, from the distribution substation. Each capacitor is controlled for the purpose

of improving voltages along the 12kV feeder. Further, feeder 3 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.02Vpu that is also operated with the purpose of improving voltages along the 12kV feeder.

In Figure 10 geo-schematic single line diagrams of feeder 3 are presented. Figure 10 (left) presents feeder hotspots corresponding to various PV penetration levels, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding ±5% of the nominal 12 kV. Figure 10 (right) presents the maximum voltage variability observed along each node of the feeder for 125% PV penetration.

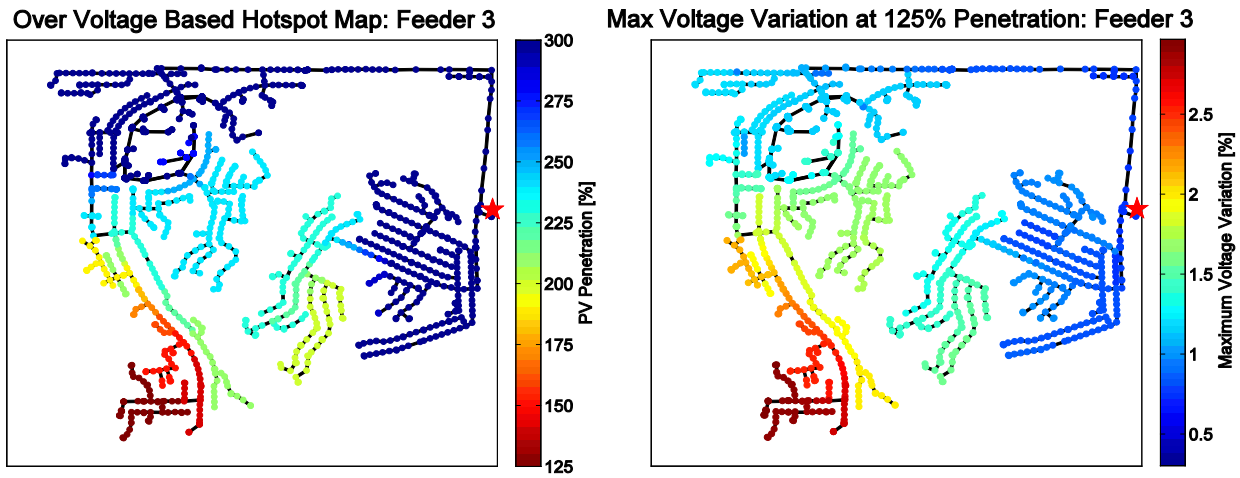


**Figure 10: Hotspot map for feeder 3. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 125%.**

The feeder can accommodate PV penetration below 125% without the need for network augmentation to mitigate thermal limits of the conductors and/or voltage violations exceeding ±5% of the nominal 12kV. A significant proportion of the feeder can accommodate PV penetration up to or possibly above 300%. Both voltage violations and thermal capacity constraints contributed to the observed feeder hotspots in Figure 10 (left). That is, in the simulation results a number of conductors were insufficiently rated for PV penetration up to 300%. The hotspots associated with a PV penetration level of 125% were located towards the end of the distribution feeder.

From Figure 10 (right) maximum voltage variations were observed along the feeder ranged from 0.4% to 3% for a 125% PV penetration level. A number of voltage variations presented in Figure 10 (right) are above the 2% threshold. Accordingly, for PV penetration of 125% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 3% is recommended.

Figure 11 (left) presents the average number of daily tap operations for the on-load tap changing transformers at the distribution substations for the 3 month period. Increases in the number of daily tap operations for PV penetration above 150% were observed.

Figure 11 (right) presents the daily average capacitor switching events for the 3 month period. The number of switching events increases as PV penetration increases because the capacitor reduces reactive power output as PV generation increases, and increases reactive power output as PV generation decreases and the load increases in the evening.

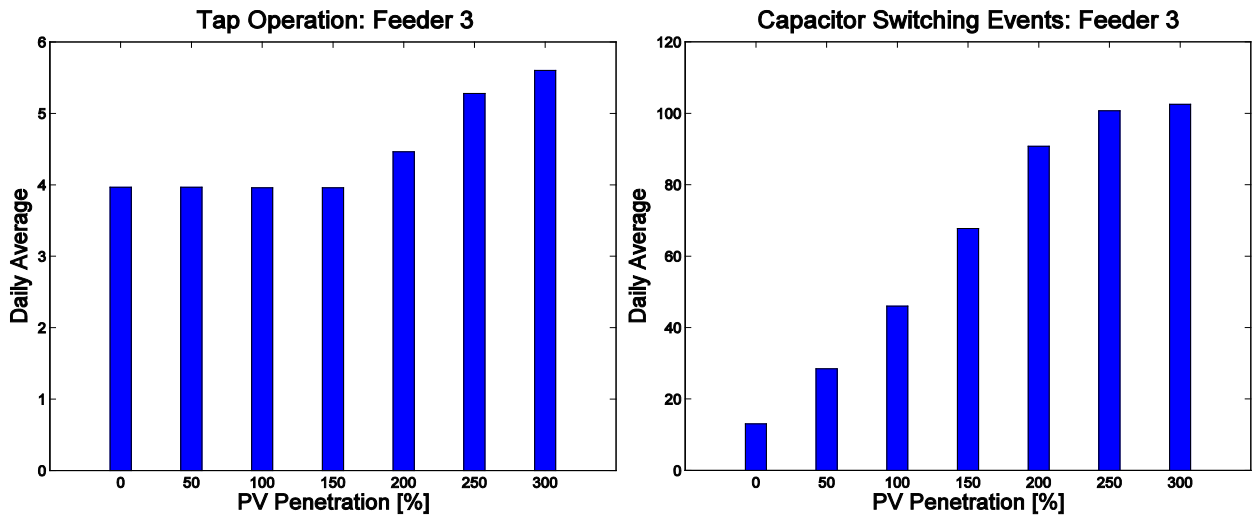


**Figure 11: Left, the average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Right, the daily average switching events for the capacitor located on feeder 3.**

## 4.4. Feeder 4

Feeder 4, operated at a nominal 12 kV, is characterized as urban with a length of 44.7 km, carries a peak load of 5.9 MVA, and connects 243 supply transformers. Further, 83 PV units are connected to the secondary side of the supply transformers, the majority of which are located on residential rooftops. Approximately 1 larger likely commercial PV unit is connected to the secondary side of the supply transformer (Figure 12).

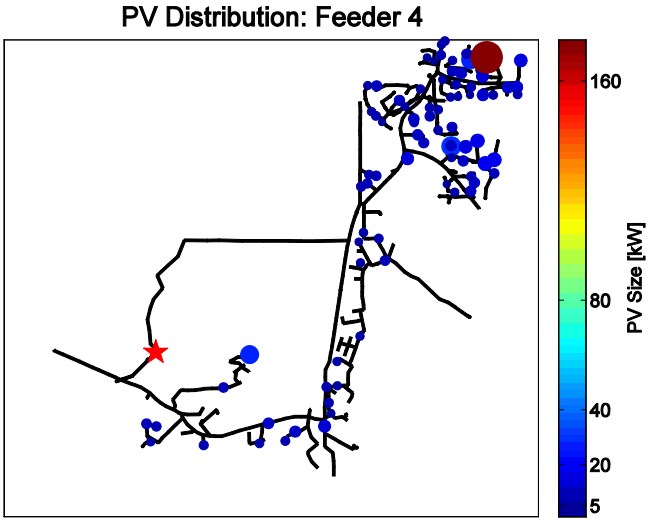


**Figure 12: PV distribution map for feeder 4, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located..**

Feeder 4 includes a single three-phase 1.2 MVAr capacitor with assumed 60 kVAr steps located 4.02 km from the distribution substation, which is controlled to improve voltages along the 12 kV feeder. Further, feeder 4 includes an on-load tap changing transformer at the distribution substation with a set-point of 1.02 Vpu that is also operated to improve voltages along the 12 kV feeder.

In Figure 13 geo-schematic single line diagrams of feeder 4 are presented. Figure 13 (left) presents feeder hotspots corresponding to various PV penetration level, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding $\pm 5\%$ of the nominal 12 kV. Figure 13 (right) presents the maximum voltage variability observed along each node of the feeder for 200% PV penetration.

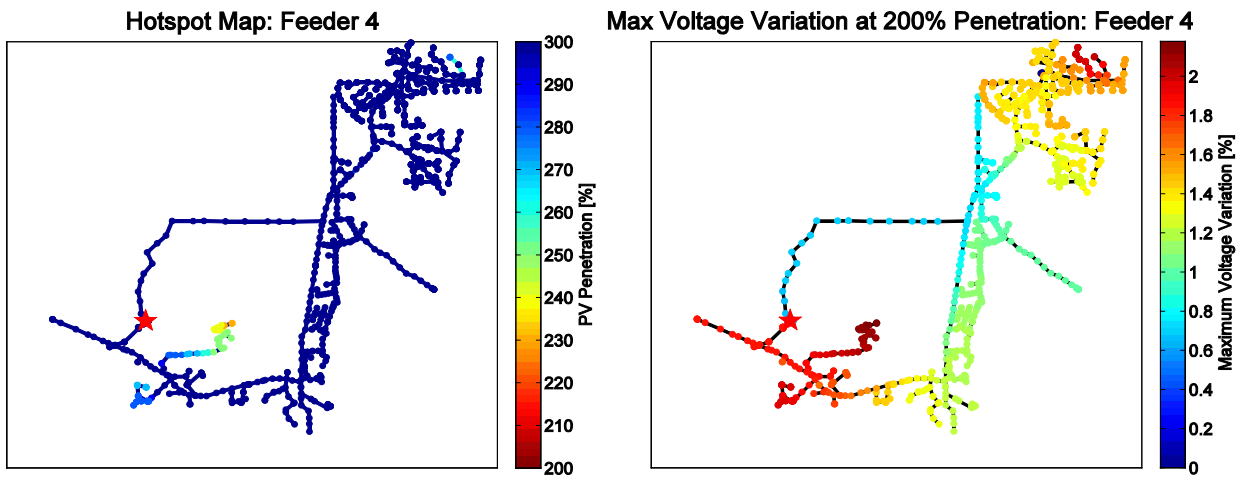


**Figure 13: Hotspot map for feeder 4. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 200%.**

The feeder can accommodate PV penetration below 200% without the need for network augmentation to mitigate thermal limits of the conductors and/or voltage violations exceeding $\pm 5\%$ of the nominal 12kV. The majority of the feeder can accommodate PV penetration up to or possibly above 300%, and the majority of feeder hotspots are a result of over-voltages. That is, only a small number of conductors are insufficiently rated for PV penetration up to 300%. The hotspots associated with a PV penetration level of 200% were located on small branches of the distribution feeder that were rated for 180A, and there were 5 PVs located along these branches that produced up to 400 kW each.

From Figure 13 (right) maximum voltage variations were observed along the feeder ranged from 0.5% to 2.2% for a 200% PV penetration level. A small number of voltage variations presented in Figure 13 (right) are above the 2% threshold. Accordingly, for PV penetration of 200% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 2.2% is recommended.

In Figure 14 (left) the average number of daily tap operations for the on-load tap changing transformers at the distribution substations for the 3 month period is presented. Increases in the number of daily tap operations have been observed for PV penetration above 50%.

In Figure 14 (right) the average daily capacitor switching events are presented for the 3 month period when increasing PV penetration levels. The number of switching events increases as PV penetration increases because the capacitor reduces reactive power output as PV generation increases, and increases reactive power output as PV generation decreases and the load increases in the evening.

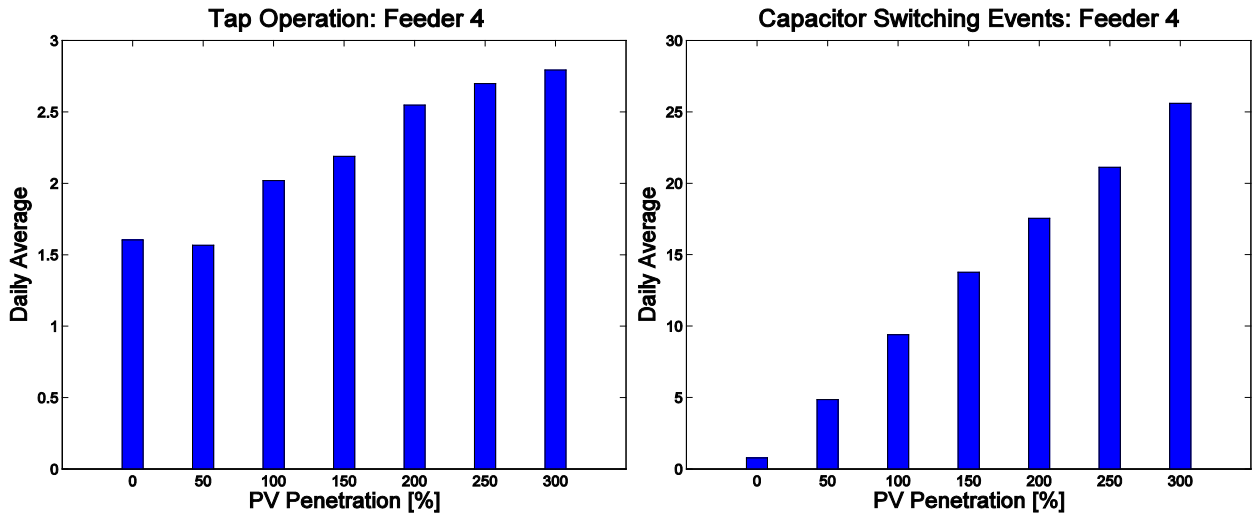


**Figure 14: Left, the average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Right, the daily average switching events for the capacitor located on feeder 4.**

## 4.5. Feeder 5

Feeder 5 is operated at a nominal 12 kV, is characterized as urban with a length of 52.2 km, carries a peak load of 10.82 MVA, and connects 416 supply transformers. Further, 95 single-phase PV units are connected to the secondary side of the supply transformers, the majority of which are located on residential rooftops. Approximately 4 larger likely commercial PV units are connected to the secondary side of the supply transformer (Figure 15).

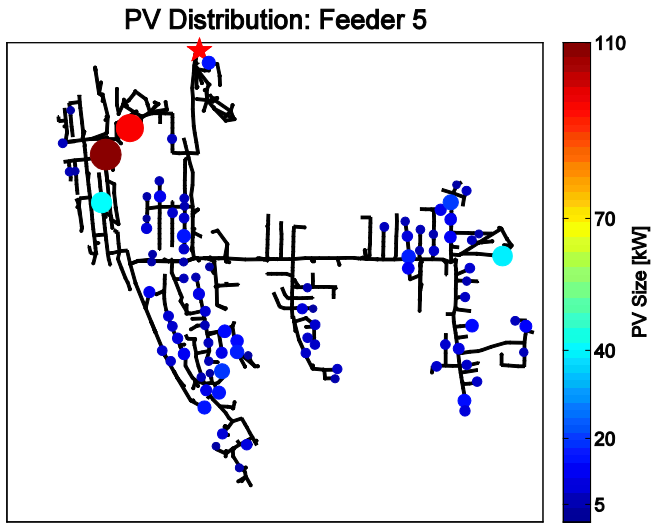


**Figure 15: PV distribution map for feeder 5, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located..**

Feeder 5 includes a single three-phase 1.2 MVAr capacitor with assumed 60 kVAr steps located 3.08 km from the distribution substation, which is controlled to improve voltages along the 12kV feeder. Further, Feeder 5 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.02 Vpu that is operated with the purpose of improving voltages along the 12 kV feeder.

In Figure 16 geo-schematic single line diagrams of feeder 5 are presented. Figure 16 (left) presents feeder hotspots corresponding to various PV penetrations, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding $\pm 5\%$ of the nominal 12 kV. Figure 16 (right) presents the maximum voltage variability observed along each node of the feeder for 150% PV penetration.

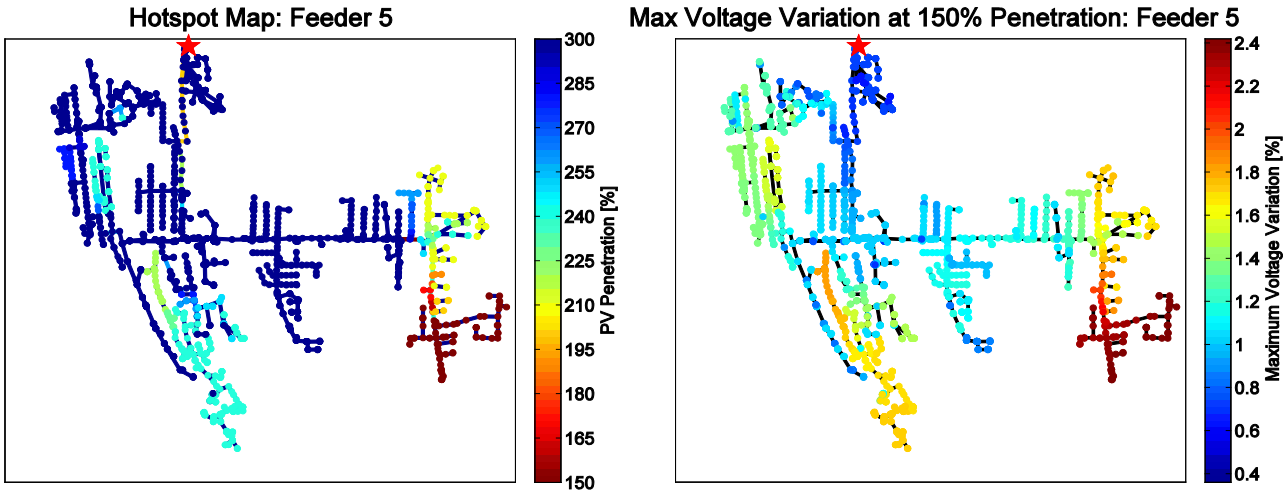


**Figure 16: Hotspot map for feeder 5. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 150%.**

The feeder can accommodate PV penetration below 150% without the need for network augmentation to mitigate thermal limits of the conductors and/or voltage violations exceeding ±5% of the nominal 12kV. A significant portion of the feeder can accommodate PV penetration up to or possibly above 300%. The observed feeder hotspots for feeder 5 were a result of both over-voltages and thermal rating limits of the existing conductors. The hotspots associated with a PV penetration level of 150% were located towards the end of the distribution feeder.

From Figure 16 (right) the observed maximum voltage variations along the feeder ranged from 0.4% to 2.4% for 150% PV penetration. Further, a number of load buses have voltage variations above the 2% threshold. Accordingly, for PV penetration of 150% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 2.4% is recommended.

Figure 17 (left) presents the average number of daily tap operations for the on-load tap changing transformers at the distribution substations for the 3 month period when increasing PV penetration levels. A very small change in the number of daily tap operations is observed for all PV penetration levels.

Figure 17 (right) presents the daily average capacitor switching events for the 3 month period when increasing PV penetration levels. In Figure 17 (right) an increase in the number of switching events is observed as PV penetration increases because the capacitor reduces reactive power output as PV generation increases, and increase reactive power output as PV generation decreases and the load increases in the evening.

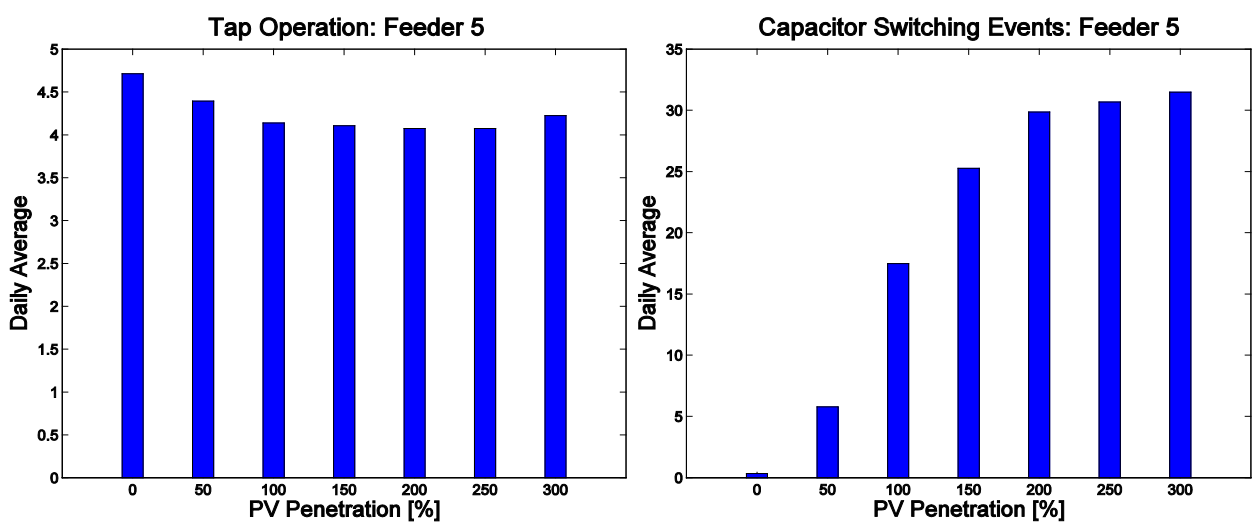


**Figure 17: Left, the average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Right, the daily average switching events for the capacitor located on feeder 5.**

## 4.6. Feeder 6

Feeder 6 is operated at a nominal 12 kV, is characterized as urban with a length of 55.4 km, carries a peak load of 13.15 MVA, and connects 324 supply transformers. Further, 62 single-phase PV units are connected to the secondary side of the supply transformers, the

majority of which are located on residential rooftops. Approximately 7 larger likely commercial PV units are connected to the secondary side of the supply transformer (Figure 18).

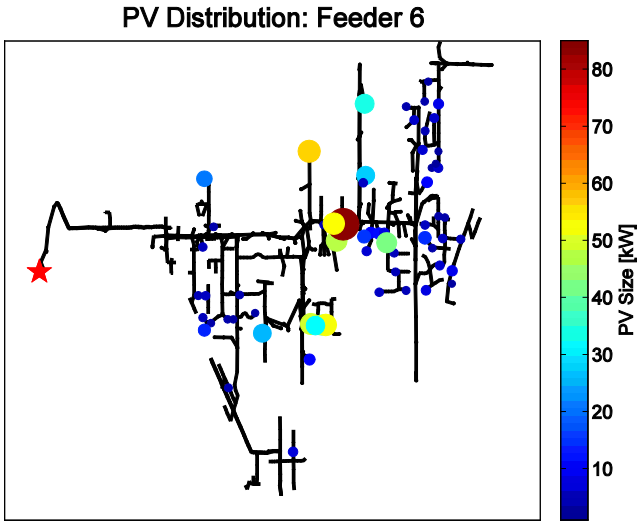


**Figure 18: PV distribution map for feeder 6, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located..**

Feeder 6 includes a single three-phase 1.2 MVAr capacitor with assumed 60 kVAr steps located 6.18 km from the distribution substation, which is controlled to improve voltages along the 12kV feeder. Further, feeder 6 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.02Vpu that is also operated to improve voltages along the 12kV feeder.

In Figure 19 geo-schematic single line diagrams of feeder 6 are presented. Figure 19 (left) presents feeder hotspots corresponding to various PV penetration levels, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding $\pm 5\%$ of the nominal 12kV. Figure 19 (right) presents the maximum voltage variability observed along each node of the feeder for a 125% PV penetration level.

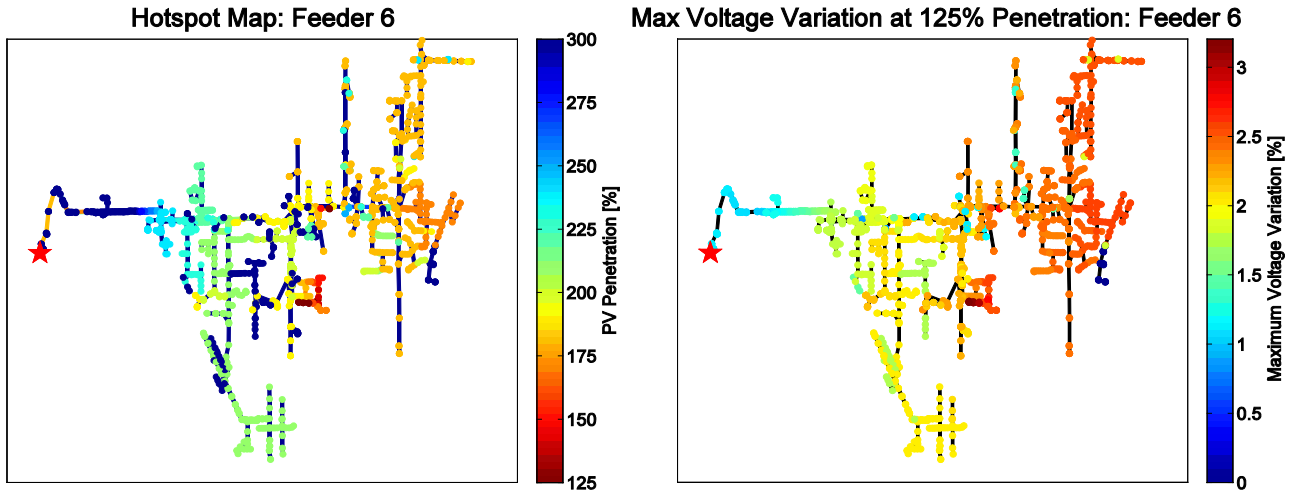


**Figure 19: Hotspot map for feeder 6. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 125%.**

The feeder can accommodate PV penetration below 125% without the need for network augmentation to mitigate thermal limits of the conductors and/or voltage violations exceeding ±5% of the nominal 12 kV. Both voltage violations and thermal limits of some conductor segments resulted in feeder hotspots. The hotspots associated with a PV penetration level of 250% were located on a small branch of the distribution feeder.

Figure 19 (right) shows maximum voltage variations along the feeder ranged from 0% to 3.2% for 125% PV penetration. Further, numerous load buses have voltage variations above the 2% threshold. Accordingly, for PV penetration of 125% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 3% is recommended.

Figure 20 (left) presents the average number of daily tap operations for the on-load tap changing transformers at the distribution substations for the 3 month period when increasing PV penetration levels. From Figure 20 shows a moderate increase (in most cases) in the number of daily tap operations as PV penetration increases.

Figure 20 (right) presents the daily average capacitor switching events for the 3 month period when increasing PV penetration levels. In Figure 20 (right) the number of switching events increases as PV penetration increases, because the capacitor reduces reactive power output as PV generation increases in the morning, and increases reactive power output as PV generation decreases and the load increases in the evening.

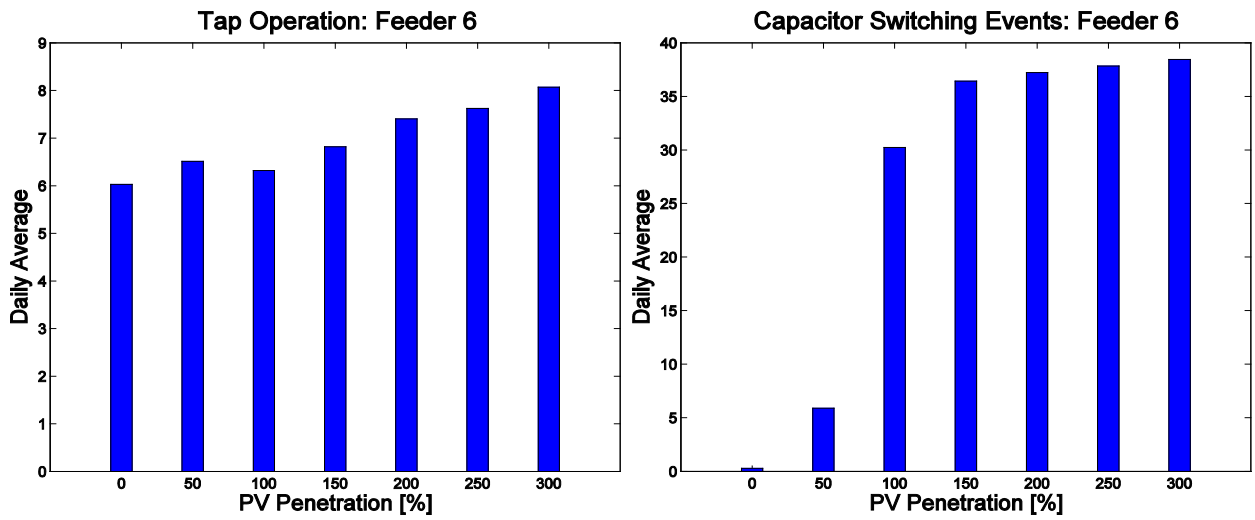


**Figure 20: Left, the average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Right, the daily average switching events for the capacitor located on feeder 6.**

## 4.7. Feeder 7

Feeder 7, operated at a nominal 12 kV, is characterized as urban with a length of 48.7 km, carries a peak load of 9.81 MVA, and connects 212 supply transformers. Further, 69 single-phase PV units are connected to the secondary side of the supply transformers, the majority of which are located on residential rooftops. Approximately 4 larger likely commercial PV units are connected to the secondary side of the supply transformer (Figure 21).

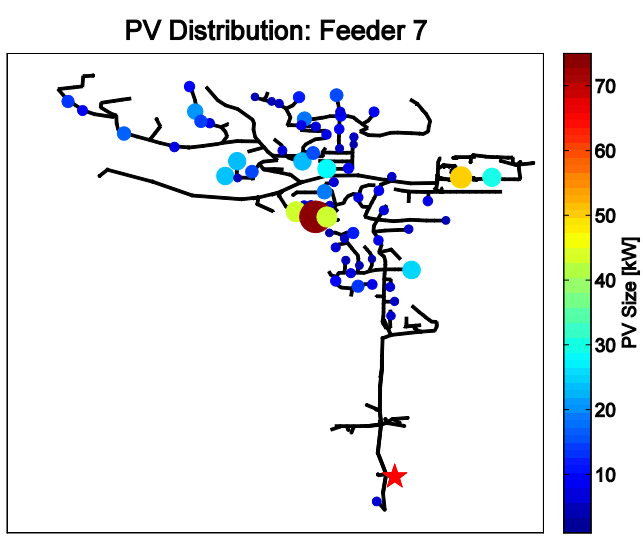


**Figure 21: PV distribution map for feeder 7, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located.**

Feeder 7 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.02 Vpu, operated for the purpose of improving voltages along the 12 kV

feeder. Feeder 7 also includes three 1.2 MVAr capacitor, however, in the simulations these capacitors are removed from the circuit because the hosting capacity of the distribution feeder improves when these capacitors are out of service.

Figure 22 presents geo-schematic single line diagrams of feeder 7. Figure 22 (left) presents feeder hotspots corresponding to various PV penetration levels, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding ±5% of the nominal 12kV. Figure 22 (right) presents the maximum voltage variability observed along each node of the feeder for a 125% PV penetration.

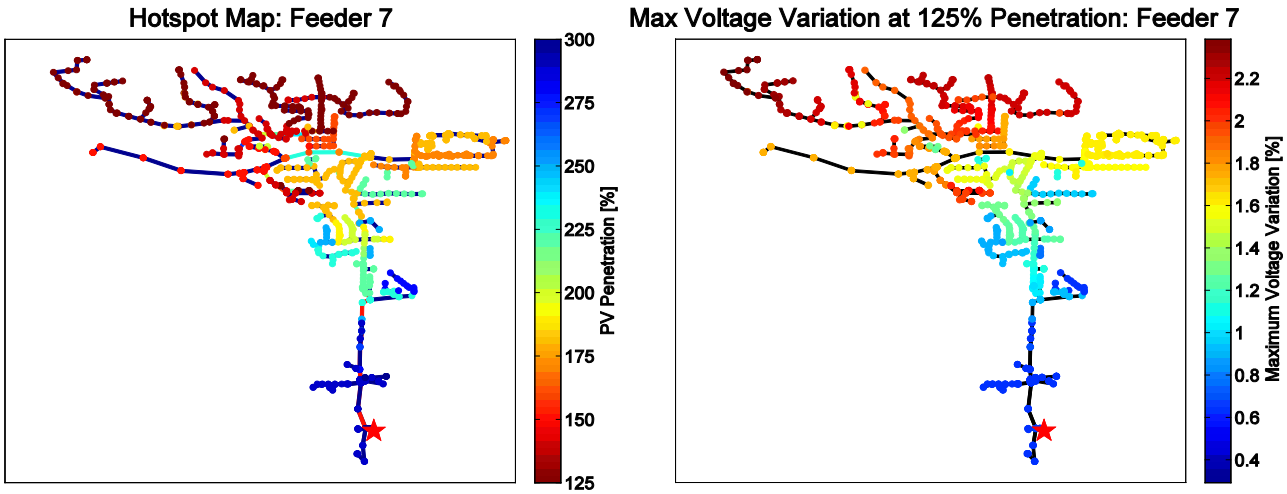


**Figure 22: Hotspot map for feeder 7. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 125%.**

Figure 22 (left) shows that the feeder can accommodate PV penetration below 125% without the need for network augmentation to mitigate thermal limits of the conductors and/or voltage violations exceeding ±5% of the nominal 12 kV. It was also observed that the feeder hotspots were a consequence of both over-voltage conditions and/or thermal limits of some conductors. That is, a number of conductors are insufficiently rated for PV penetration up to 300%. The hotspots associated with a PV penetration level of 125% were located towards the end of the distribution feeder.

Figure 22 (right) shows maximum voltage variations along the feeder ranged from 0.3% to 2.4% for 125% PV penetration. Further, numerous voltage variations are above the 2% threshold. Accordingly, for PV penetration of 125% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 2.4% is recommended. From Figure 23 a significant increase in the number of daily tap operations were observed for PV penetration above 200%.

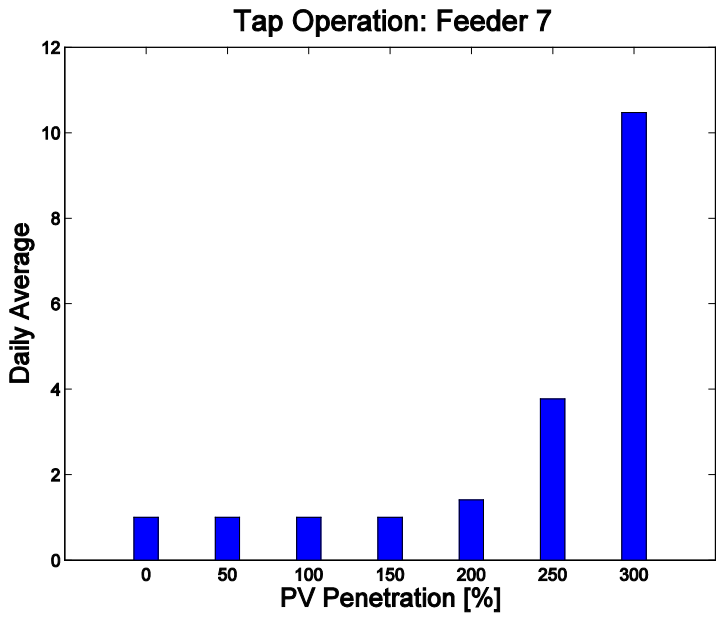


**Figure 23: The average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Note that capacitors were disabled to improve hosting capacity.**

## 4.8. Feeder 8

Feeder 8, operated at a nominal 12 kV, is characterized as urban with a length of 56.1 km, carries a peak load of 8.76 MVA, and connects 139 supply transformers. Further, 147 single-phase PV units are connected to the secondary side of the supply transformers, the majority of which are located on residential rooftops. Approximately 1 larger likely commercial PV unit is connected to the secondary side of the supply transformer (Figure 24).

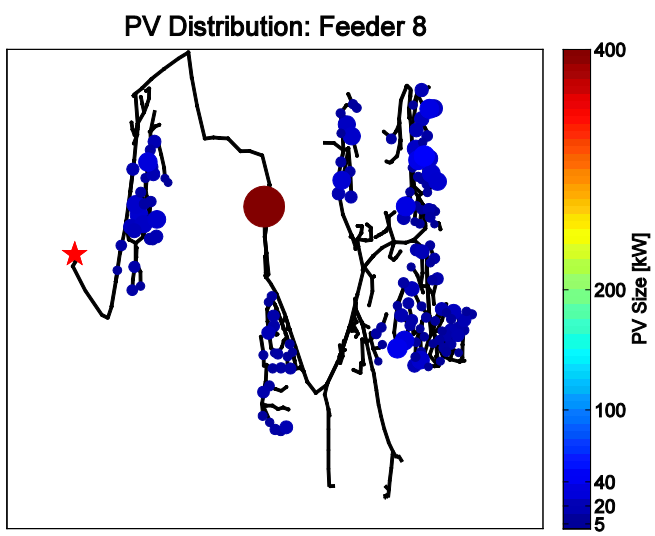


**Figure 24: PV distribution map for feeder 8, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located.**

Feeder 8 includes 2 three-phase 1.2 MVAr capacitor with assumed 60 kVAr steps located 7.45 km and 9.6 km, respectively, from the distribution substation, which are operated to improve voltages along the 12 kV feeder. Further, feeder 8 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.02Vpu, which is also operated to improve voltages along the 12kV feeder.

In Figure 25 geo-schematic single line diagrams of feeder 8 are presented. Figure 25 (left) presents feeder hotspots corresponding to various PV penetration levels, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding ±5% of the nominal 12 kV. Figure 25 (right) presents the maximum voltage variability observed along each node of the feeder for a 150% PV penetration level.

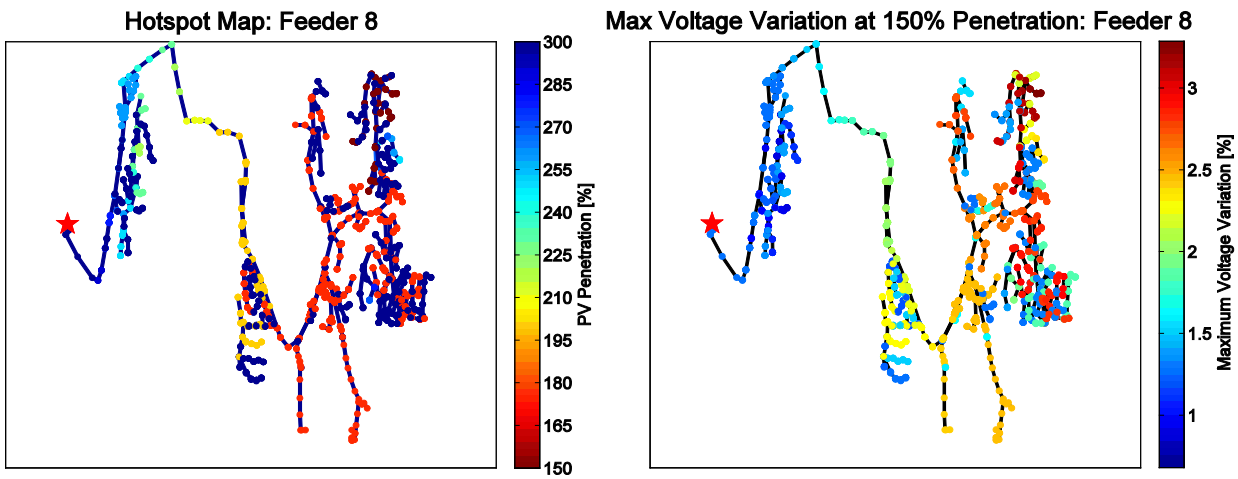


**Figure 25: Hotspot map for feeder 8. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 150%.**

Figure 25 (left) shows that the feeder can accommodate PV penetration below 150% without the need for network augmentation to mitigate thermal limits of the conductors and/or voltage violations exceeding ±5% of the nominal 12kV. Segments of the feeder can accommodate PV penetration up to or possibly above 300%, and voltage violations resulted in the majority of observed feeder hotspots. That is, only a few small segments of conductor were insufficiently rated for PV penetration up to 300%. The hotspots associated with a PV penetration level of 250% were located towards the end of the distribution feeder.

From Figure 25 (right) maximum voltage variations along the feeder ranged from 0.5% to 3.5% for the 150% PV penetration level. Further, a significant number of voltage variations are above the 2% threshold. Accordingly, for PV penetration of 125% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 3% is recommended.

Figure 26 (left) presents the average number of daily tap operations for the on-load tap changing transformers at the distribution substations for the 3 month period when increasing PV penetration levels. The number of daily tap operations increases moderately as PV penetration increases to 150%, and then a slight increase in tap operations occurs.

Figure 26 (right) shows the average daily capacitor switching events for the 3 month period when increasing PV penetration levels. In Figure 26 (right) the number of switching events increases as PV penetration increases, because the capacitor reduces reactive power output as PV generation increases in the morning, and increases reactive power output as PV generation decreases and the load increases in the evening.

Comparing Figure 26 (left) to Figure 26 (right) increased capacitor switching events as PV penetration increases to 150% correspond to decreasing in tap operations. Voltage regulation for the feeder is being dominated by the capacitor allowing for a reduction in transformer tap operations.

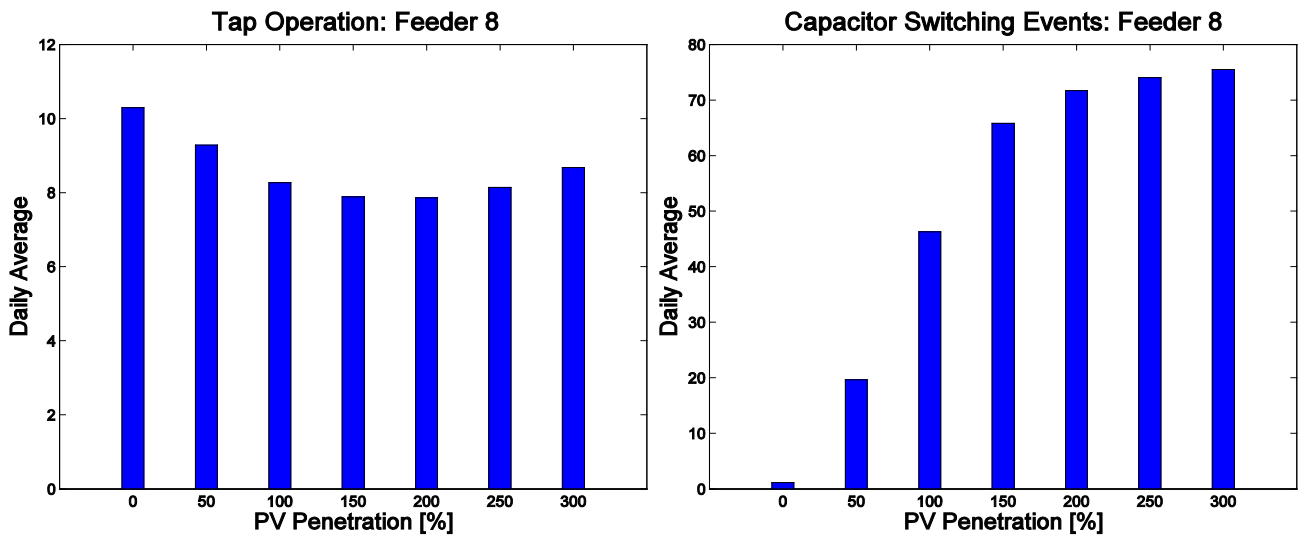


**Figure 26: Left, the average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Right, the daily average switching events for the capacitor located on feeder 8.**

## 4.9. Feeder 9

Feeder 9, operated at a nominal 12 kV, is characterized as urban with a length of 45.4 km, carries a peak load of 8.04 MVA, and connects 260 supply transformers. Further, 66 PV units are connected to the secondary side of the supply transformers, the majority of which are located on residential rooftops. Approximately 3 larger likely commercial PV units are connected to the secondary side of the supply transformer (Figure 27).

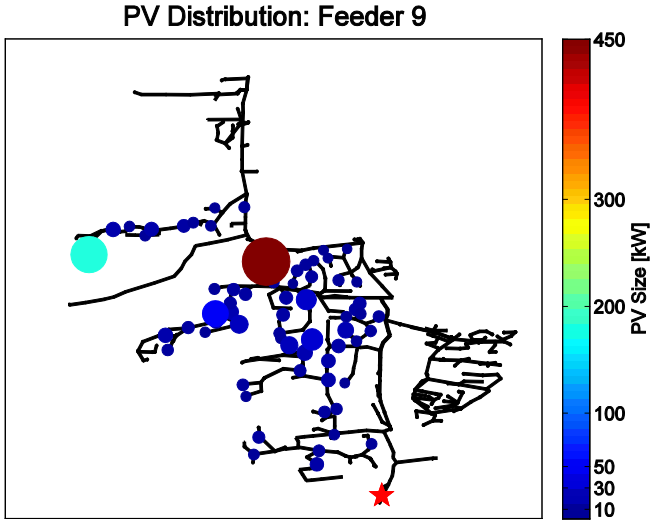


**Figure 27: PV distribution map for feeder 9, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located.**

Feeder 9 includes a single three-phase 1.2 MVAr capacitor with assumed 60 kVAr steps located 4.33 km from the distribution substation, which is operated to improve voltages along the 12 kV feeder. Further, feeder 9 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.02 Vpu, which is also operated to improve voltages along the 12 kV feeder.

In Figure 28, geo-schematic single line diagrams of feeder 9 are presented. Figure 28 (left) presents feeder hotspots corresponding to various PV penetration levels, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding ±5% of the nominal 12 kV. Figure 28 (right) presents the maximum voltage variability observed along each node of the feeder for a 100% PV penetration level.

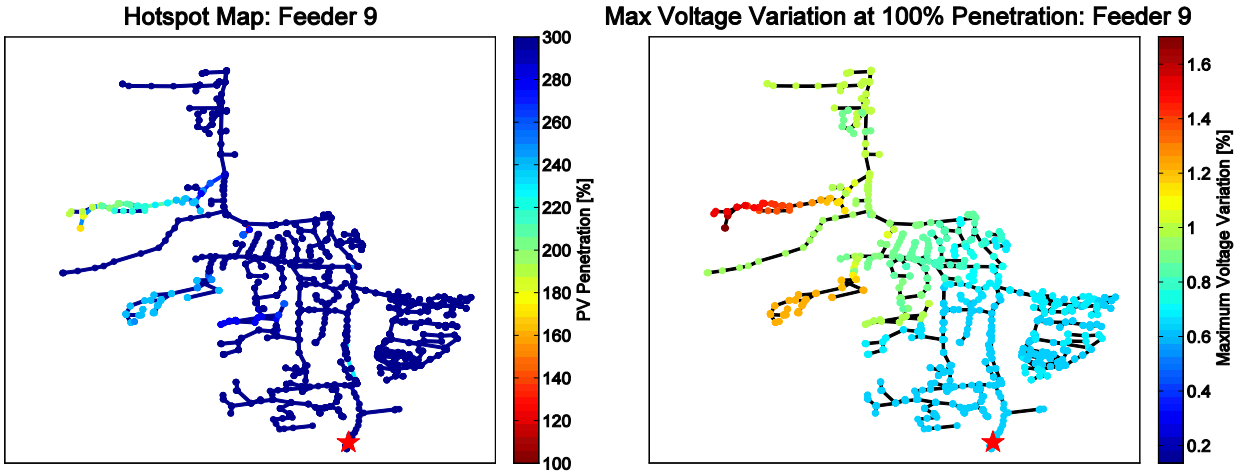


**Figure 28: Hotspot map for feeder 9. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 100%.**

Figure 28 (left) shows the feeder can accommodate PV penetration below 100% without the need for network augmentation to mitigate thermal limits of conductors and/or voltage violations exceeding ±5% of the nominal 12 kV. The majority of the feeder can accommodate PV penetration up to or possibly above 300%, and both voltage violations and thermal constraints of the conductors resulted in the observed feeder hotspots. That is, some conductors were insufficiently rated for PV penetration up to 300%. The hotspot associated with a PV penetration level of 100% was located on a small branch of the distribution feeder that was rated for 130A, and there was a larger PV unit located along this branch that produced up to 1500 kW.

Figure 28 (right) presents maximum voltage variations along the feeder ranging from 0.2% to 1.7% for 100% PV penetration. Further, the voltage variations observed are below the 2% threshold. The customer impact of voltage variations below the 2% threshold might be investigated by a utility on a case-by-case basis with an instrument based on IEC 61000-4-15 (IEEE Power Engineering Society, 2005).

Figure 29 (left) presents the average number of daily tap operations for the on-load tap changing transformers at the distribution substations for the 3 month period when increasing PV penetration levels. The number of daily tap operations decreased slightly as the PV penetration level increases to 150%.

Figure 29 (right) presents the average daily capacitor switching events for the 3 month period when increasing PV penetration levels. In Figure 29 (right) the number of switching events increases as PV penetration increases, because the capacitor reduces reactive power output as PV generation output increases in the morning, and increases reactive power output as the load increases in the evening,.

Comparing Figure 29 (left) to Figure 29 (right) increased capacitor switching events as PV penetration increases to 200% correspond to a decrease in tap operations. Voltage regulation for the feeder is being dominated by the capacitor allowing for a reduction in transformer tap operations.

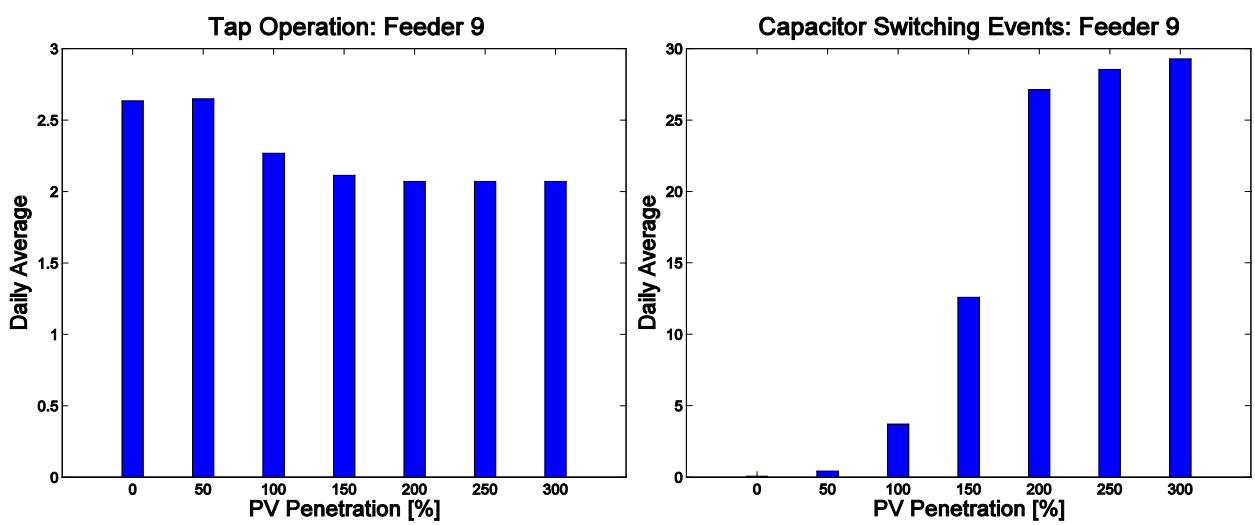


**Figure 29: Left, the average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Right, the daily average switching events for the capacitor located on feeder 9.**

### 4.10. Feeder 10

Feeder 10 is operated at a nominal 12 kV, is characterized as urban with a length of 51.8 km, carries a peak load of 13.61 MVA, and connects 376 supply transformers. Further, 71 single-phase PV units are connected to the secondary side of the supply transformers, the majority of which are located on residential rooftops. Approximately 6 larger likely commercial PV units are connected to the secondary side of the supply transformer (Figure 30).

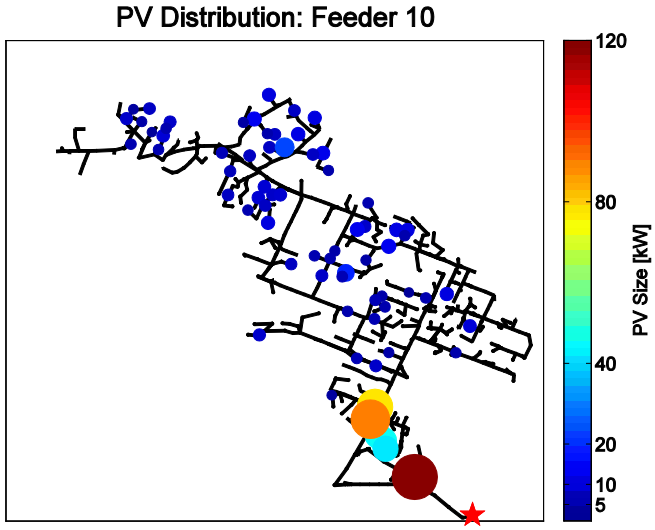


**Figure 30: PV distribution map for feeder 10, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located.**

Feeder 10 includes 4 three-phase 1.2 MVAr capacitors with assumed 60 kVAr steps located 6.86 km, 8.08 km, 5.31 km, and 3.04 km, respectively, from the distribution substation. The capacitors are operated to improve voltages along the 12 kV feeder. Further, feeder 10 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.02 Vpu that is also operated to improve voltages along the 12 kV feeder.

In Figure 31 geo-schematic single line diagrams of feeder 10 are presented. Figure 31 (left) presents feeder hotspots corresponding to various PV penetration levels, where hotspots along an edge arises due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding $\pm 5\%$ of the nominal 12 kV. Figure 31 (right) presents the maximum voltage variability observed along each node of the feeder for a 100% PV penetration level.

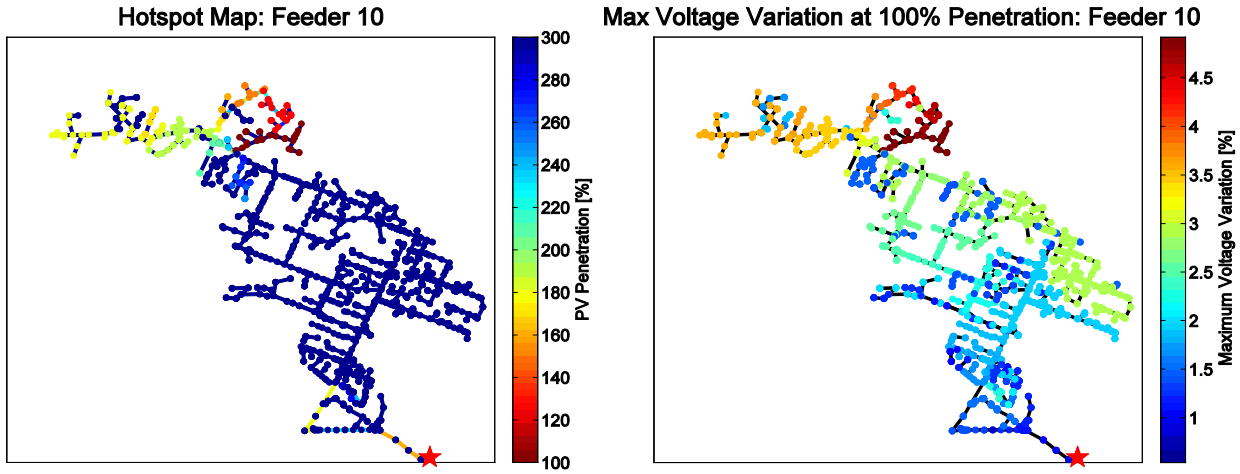


**Figure 31: Hotspot map for feeder 10. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 100%.**

Figure 31 (left) shows the feeder can accommodate PV penetration below 100% without the need for network augmentation to mitigate thermal limits of the conductors and/or voltage violations exceeding ±5% of the nominal 12 kV. The majority of the feeder can accommodate PV penetration up to or possibly above 300%. Further, both voltage violations and thermal constraint of the 12 kV conductors resulted in all observed feeder hotspots. That is, some of the observed feeder hotspots were a result of conductors that were insufficiently rated for PV penetration up to 300%. The hotspots associated with a PV penetration level of 250% were located towards the end of the distribution feeder.

From Figure 31 (right) maximum voltage variations along the feeder ranged from 0.5% to 5% for 100% PV penetration. Also, a significant proportion of the voltage variations presented in Figure 32 (right) are above the 2% threshold. Accordingly, for PV penetration of 100% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 5% is recommended.

Figure 32 (left) presents the average number of daily tap operations for the on-load tap changing transformers at the distribution substations for the 3 month period when increasing PV penetration levels. A small reduction in the number of daily tap operations can be observed as PV penetration increases to 150%, and then an increase in the number of daily tap operations as PV penetration increases further to 300%.

Figure 32 (right) presents the daily average capacitor switching events for the 3 month period when increasing PV penetration levels. In Figure 32 (right) the number of switching events increases as PV penetration increases, because the capacitor reduces reactive power output as PV generation output increases in the morning, and increases reactive power output as the load increases in the evening.

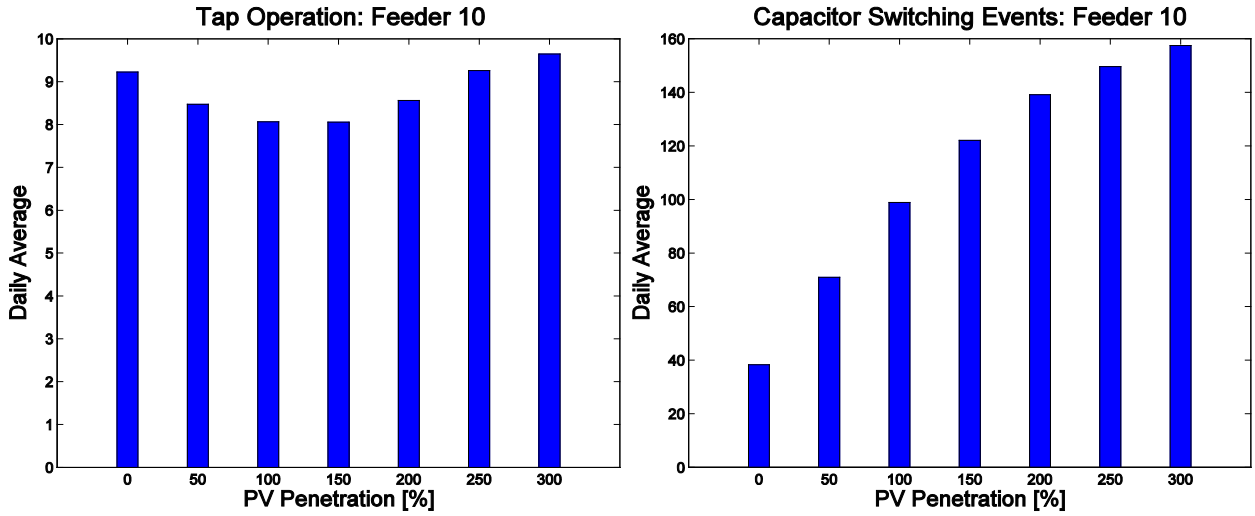


**Figure 32: Left, the average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Right, the daily average switching events for the capacitor located on feeder 10.**

## 4.11. Feeder 11

Feeder 11, operated at a nominal 12 kV, is characterized as urban with a length of 39.6 km, carries a peak load of 8.38 MVA, and connects 322 supply transformers. Feeder 11 is modelled with a combination of existing PV units and some artificial PV units, as described in (Nguyen, et al., 2016). In total, 340 PV units are connected to the primary side of the supply transformers, the majority of which are sized for residential rooftops (Figure 33).

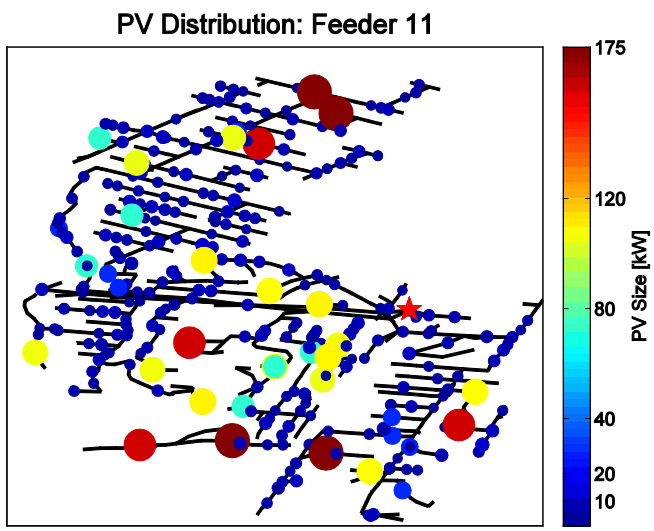


**Figure 33: PV distribution map for feeder 11, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located.**

Feeder 11 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.01 Vpu, operated to improve voltages along the 12 kV feeder. Feeder 11 also includes two 1.2 MVAr capacitor, however, in the simulations these capacitors are removed from the circuit because the hosting capacity of the distribution feeder improves when these capacitors are out of service.

In Figure 34 geo-schematic single line diagrams of feeder 11 are presented. Figure 34 (left) presents feeder hotspots corresponding to various PV penetration levels, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding ±5% of the nominal 12 kV. Figure 34 (right) presents the maximum voltage variability observed along each node of the feeder for a 100% PV penetration level.

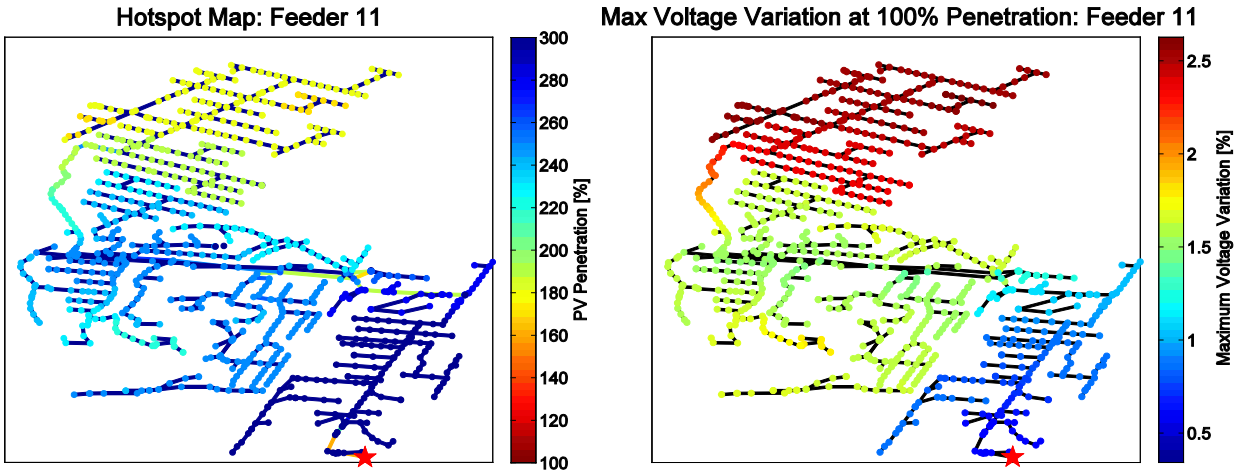


**Figure 34: Hotspot map for feeder 11. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 100%.**

The feeder can accommodate PV penetration below 100% without the need for network augmentation to mitigate thermal limits of conductors and/or voltage violations exceeding ±5% of the nominal 12 kV. Some segments of the feeder can accommodate PV penetration up to or possibly above 300%. Further, both voltage violations and thermal constraints of the conductors resulted in the observed feeder hotspots. That is, some of the conductors were insufficiently rated for PV penetration up to 300%. The hotspot associated with a PV penetration level of 100% was the result of a thermal capacity constraint on the trunk section of the feeder near the distribution substation.

Figure 34 (right) shows that maximum voltage variations along the feeder ranged from 0.4% to 2.6% for a 100% PV penetration level. Further, numerous voltage variations are above the 2% threshold. Accordingly, for PV penetration of 100% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 2.6% is recommended. Figure **35** shows an increase in the number of daily tap operations as the PV penetration level increases from 200%.

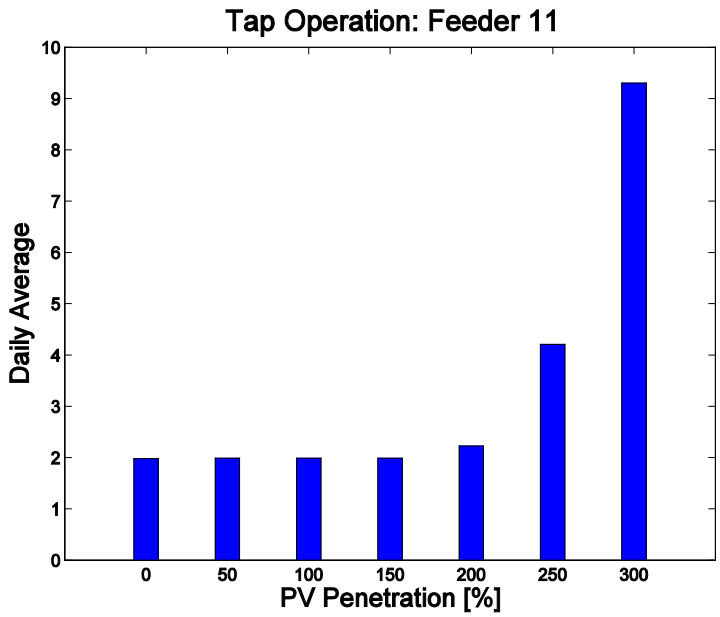


**Figure 35: The average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Note that the capacitors were disabled to improve hosting capacity.**

### 4.12. Feeder 12

Feeder 12, operated at a nominal 12 kV, is characterized as rural with a length of 34.7 km, carries a peak load of 4.92 MVA, and connects 281 supply transformers. Feeder 12 is modelled with a combination of existing PV units and some artificial PV units, as described in (Nguyen, et al., 2016). In total, 364 PV units are connected to the primary side of the supply transformers, the majority of which are sized for residential rooftops (Figure 36).

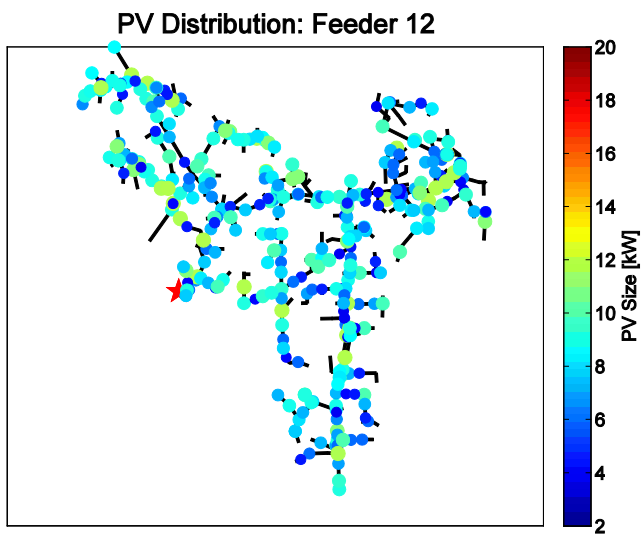


**Figure 36: PV distribution map for feeder 12, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located.**

Feeder 12 includes an on-load tap changing transformer at the distribution substation with a setpoint of 0.98 Vpu, operated to improve voltages along the 12 kV feeder. Feeder 12 also

includes two 1.2 MVAr capacitors, however, in the simulations these capacitors are removed from the circuit because the hosting capacity of the distribution feeder improves when these capacitors are out of service.

In Figure 37 geo-schematic single line diagrams of feeder 12 are presented. Figure 37 (left) presents feeder hotspots corresponding to various PV penetration levels, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding ±5% of the nominal 12kV. Figure 37 (right) presents the maximum voltage variability observed along each node of the feeder for a 260% PV penetration level.

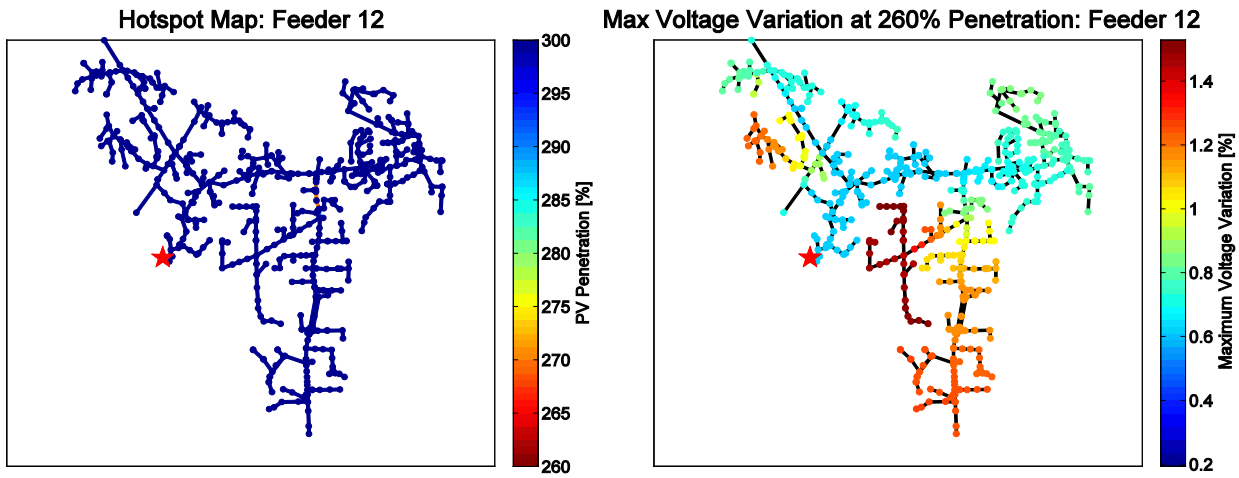


**Figure 37: Hotspot map for feeder 12. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 260%.**

Figure 37 (left) shows the feeder can accommodate PV penetration below 260% without the need for network augmentation to mitigate thermal limits of conductors and/or voltage violations exceeding ±5% of the nominal 12 kV. Thermal constraints of some conductors resulted in the observed feeder hotspots. That is, some of the 12 kV conductors were insufficiently rated for PV penetration up to 300%. In contrast, voltage violations exceeding ±5% of the nominal 12 kV were not observed in Figure 37 (left). The hotspots associated with a PV penetration level of 260% was the result of a thermal rating limit on a small section of conductors.

Figure 37 (right) shows maximum voltage variations along the feeder ranged from 0.2% to 1.5% for 260% PV penetration. Further, the voltage variations observed are below the 2% threshold. The customer impact of voltage variations below the 2% threshold might be investigated by a utility on a case-by-case basis with an instrument based on IEC 61000-4-15 (IEEE Power Engineering Society, 2005). Figure 38 shows an increase in the number of daily tap operations as the PV penetration level increases.

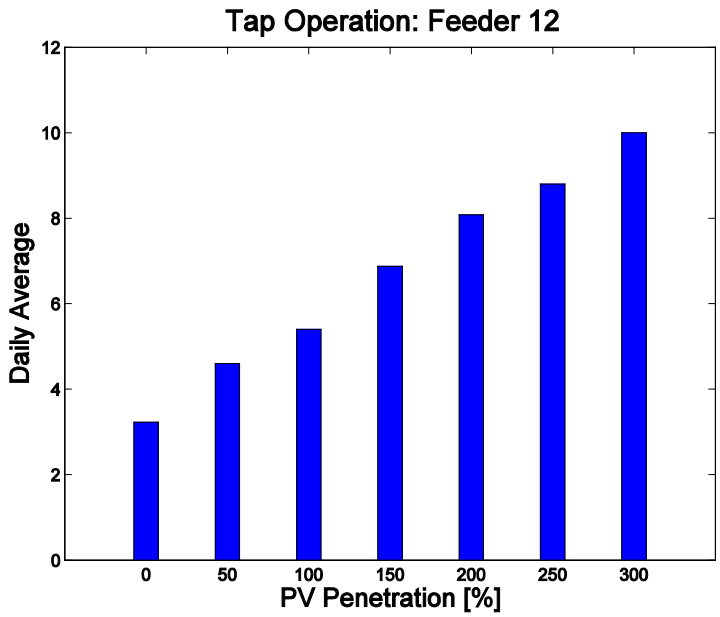


**Figure 38: The average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Note that the capacitors were disabled to improve hosting capacity.**

### 4.13. Feeder 13

Feeder 13, operated at a nominal 12 kV, is characterized as rural with a length of 51.5 km, carries a peak load of 3.86 MVA, and connects 276 supply transformers. Feeder 13 is modelled with a combination of existing PV units and some artificial PV units, as described in (Nguyen, et al., 2016). In total, 104 PV units are connected to the primary side of the supply transformers, the majority of which are sized for residential rooftops (Figure 39).

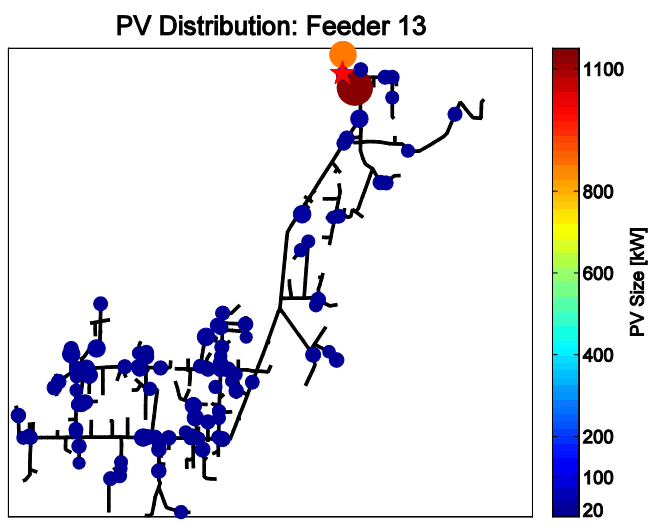


**Figure 39: PV distribution map for feeder 13, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located.**

Feeder 13 includes an on-load tap changing transformer at the distribution substation with a setpoint of 0.99 Vpu, operated to improve voltages along the 12 kV feeder. Feeder 13 also

includes a 1.2 MVAr capacitor, however, in the simulations this capacitor is removed from the circuit because the hosting capacity of the distribution feeder improves when this capacitor is out of service.

In Figure 40 geo-schematic single line diagrams of feeder 13 are presented. Figure 40 (left) presents feeder hotspots corresponding to various PV penetration levels, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding ±5% of the nominal 12kV. Figure 40 (right) presents the maximum voltage variability observed along each node of the feeder for a 250% PV penetration level.

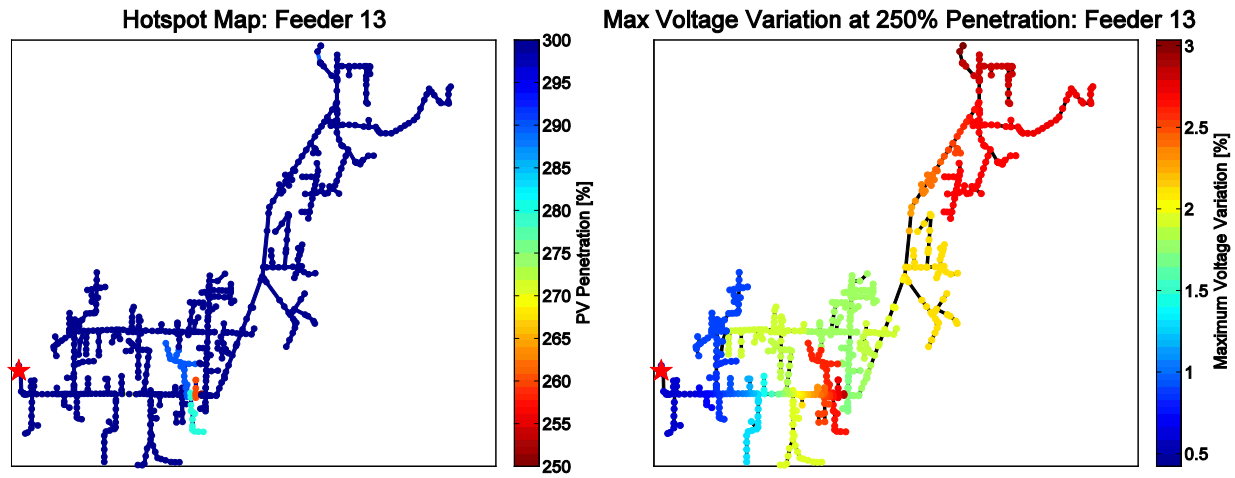


**Figure 40: Hotspot map for feeder 13. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 250%.**

The feeder can accommodate PV penetration below 250% without the need for network augmentation to mitigate thermal limits of conductors and/or voltage violations exceeding ±5% of the nominal 12 kV. A significant portion of the feeder can accommodate PV penetration up to or possibly above 300%. Further, both voltage violations and thermal constraints of the conductors resulted in the observed feeder hotspots. That is, some of the 12 kV conductors were insufficiently rated for PV penetration up to 300%. The hotspots associated with a PV penetration level of 250% were located on small branches off the feeder trunk section that were rated for 130A, and there were a few smaller PV units located along this branch.

From Figure 40 (right) maximum voltage variations along the feeder ranged from 0.5% to 3% for 250% PV penetration. Further, numerous voltage variations are above the 2% threshold. Accordingly, for PV penetration of 250% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 3% is recommended. Figure 41 shows that the number of daily tap operations increases as the PV penetration level increases.

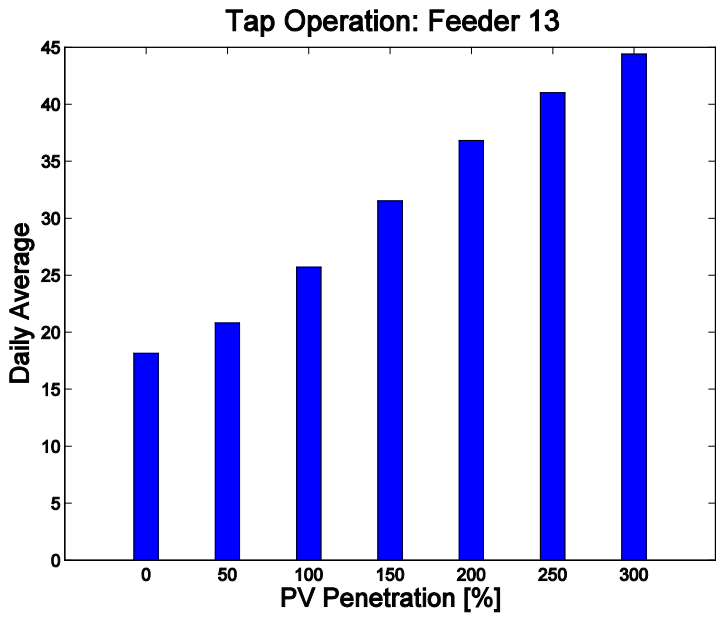


**Figure 41: The average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. The right graph is missing as capacitors were disabled to improve hosting capacity.**

### 4.14. Feeder 14

Feeder 14, operated at a nominal 12 kV, is characterized as rural with a length of 115.5 km, carries a peak load of 6.34 MVA, and connects 649 supply transformers. Feeder 14 is modelled with a combination of existing PV units and some artificial PV units. In total 387 PV units are connected to the primary side of the supply transformers, the majority of which are sized for residential rooftops (Figure 42).

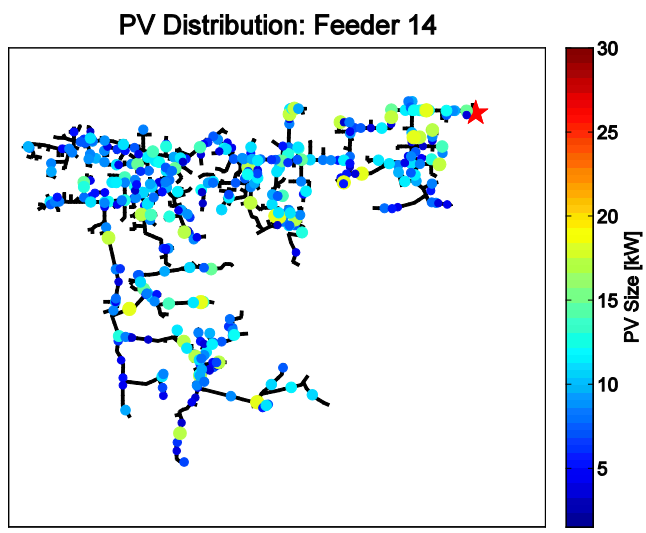


**Figure 42: PV distribution map for feeder 14, with circles proportional to the size of the system. The star indicates the distribution substation where the on-load tap changing transformer is located.**

Feeder 14 includes an on-load tap changing transformer at the distribution substation with a setpoint of 1.01 Vpu, operated to improve voltages along the 12 kV feeder. Feeder 14 also

includes a 1.2 MVAr capacitor, however, in the simulations this capacitor is removed from the circuit because the hosting capacity of the distribution feeder improves when this capacitor is out of service.

In Figure 43 geo-schematic single line diagrams of feeder 12 are presented. Figure 43 (left) presents feeder hotspots corresponding to various PV penetration levels, where hotspots along an edge arise due to thermal limits of electrical conductors and hotspots at a node arise due to voltages exceeding ±5% of the nominal 12 kV. Figure 43 (right) presents the maximum voltage variability observed along each node of the feeder for a 100% PV penetration level.

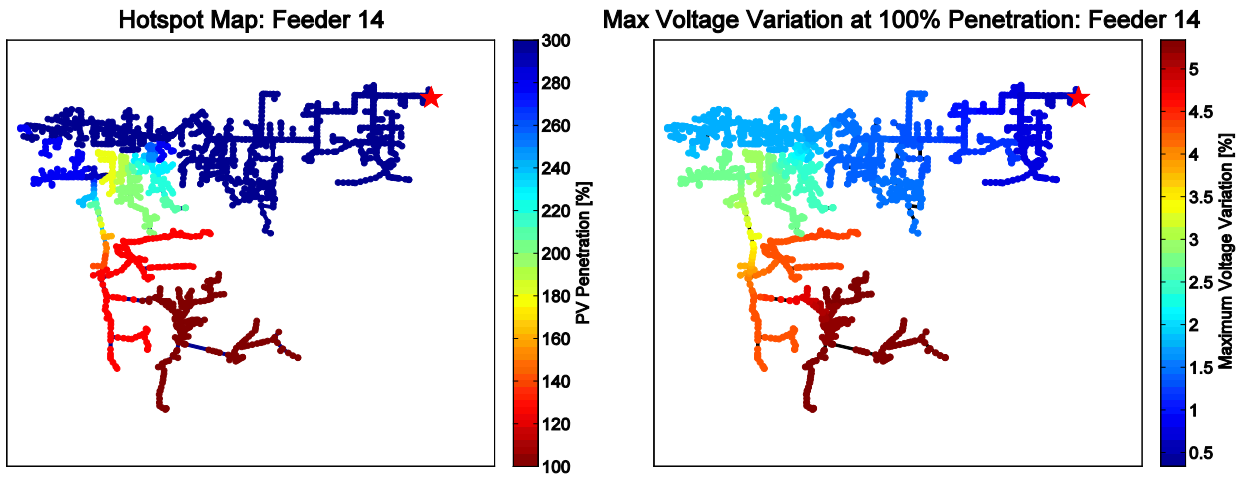


**Figure 43: Hotspot map for feeder 14. The star indicates the distribution substation where the on-load tap changing transformer is located, and each node represents a device or an interconnection point along the 12kV feeder. Left, hosting capacity limit of feeder 1, where the color bar indicates PV penetration levels that correspond to a thermal over-load (line color) and/or voltage exceedance. Right, the maximum absolute voltage change observed over a 30 second interval at each node of the feeder for a PV penetration of 100%.**

Figure 43 (left) shows the feeder can accommodate PV penetration below 100% without the need for network augmentation to mitigate thermal limits of conductors and/or voltage violations exceeding ±5% of the nominal 12 kV. Numerous segments of the feeder can accommodate PV penetration up to or possibly above 300%. Further, both voltage violations and thermal constraints of the conductors resulted in the observed feeder hotspots. That is, some of the 12 kV conductors were insufficiently rated for PV penetration up to 300%. The hotspots associated with a PV penetration level of 100% were located towards the end of the distribution feeder.

Figure 43 (right) shows maximum voltage variations along the feeder ranged from 0.5% to 5.2% for 100% PV penetration. Also, a significant proportion of the voltage variations presented in Figure 43 (right) are above the 2% threshold. Accordingly, for PV penetration of 100% further investigations into the customer impacts (e.g., perceptibility of flicker) of voltage variations on 30 sec timescales of 5.2% is recommended. Figure 44 shows that the number of daily tap operations increases as the PV penetration level increases.

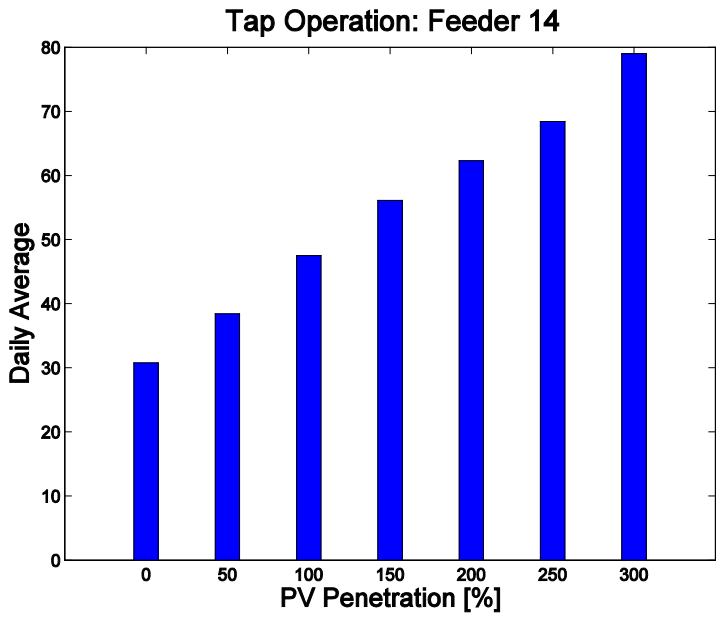


**Figure 44: The average number of daily tap operations corresponding to the on-load tap changing transformer located at the distribution substation. Note that the capacitors were disabled to improve hosting capacity.**

## 5. *Summary of the Feeder Hotspot Analysis for 14 Distribution Feeders*

Table 2 summarizes the feeder hotspots arising from high PV penetration levels based on OpenDSS simulation results for each of the 14 SDG&E feeders. Feeder hotspots associated with the lowest PV penetration level were typically observed towards the end of a distribution feeder and/or along small branches of the feeder that did not carry the trunk sectional load. In all cases PV units were located at these respective hotspots. Table 2 includes the conductor rating at the location of each feeder hotspot together with the trunk sectional rating of the feeder as a proxy for conductor impedances that may contribute to voltage-based hotspots.

**Table 1: Summary of the feeder hotspots for each of 14 SDG&E feeders. The maximum entries in each category / row are in bold.**

| Feeder ID | Existing PV Penetration[6] | Lowest PV Penetration Coinciding with a Hotspot | Max Voltage Variability at Lowest PV Penetration Coinciding with a Hotspot | Daily Average Transformer Tap Changes at 0% PV Penetration | Daily Average Transformer Tap Changes at 300% PV Penetration | Rating of conductor/s creating a feeder hotspot at lowest PV penetration | Trunk Section Rating |
|---|---|---|---|---|---|---|---|
| 1 | 23.5% | 280% | 2% | 3.7 | 3.7 | 130 A | 700 A |
| 2 | 11.6% | 250% | 4.2% | 4.5 | 4.5 | 500 A[7] | 580 A |
| 3 | 6.9% | 125% | 3% | 4 | 5.6 | 180 A | 700 A |
| 4 | 13.1% | 200% | 2.2% | 1.6 | 2.8 | 180 A | 770 A |
| 5 | 8.48% | 150% | 2.4% | 4.7 | 4.2 | 130 A | 770 A |
| 6 | 6.08% | 125% | 3.2% | 6 | 8 | 115 A | 700 A |
| 7 | 8.29% | 125% | 2.4% | 1 | 11 | 180 A | 580 A |
| 8 | 21.9% | 150% | 3.25% | 10.5 | 9 | 130 A | 700 A |
| 9 | 13.8% | 100% | 1.7% | 2.7 | 2.2 | 130 A | 770 A |
| 10 | 9.17% | 100% | 4.75% | 9.2 | 9.7 | 180 A | 580 A |
| 11 | 60.4% | 100% | 2.6% | 2 | 9.5 | 15 A | 520 A |
| 12 | 51.4% | 260% | 1.5% | 3.5 | 10 | 180 A[8] | 520 A |
| 13 | 71% | 250% | 3% | 18 | 44 | 130 A | 520 A |
| 14 | 38.0% | 100% | 5.2% | 31 | 78 | 180 A | 770 A |

## 6. *Conclusions*

The results of the case study highlighted that significant increases in PV penetration levels across all of the 14 feeders are feasible without the need for network augmentation. Further, the increase in PV penetration levels varied from feeder to feeder, as it was dependent on the feeder topology. Feeder hotspots associated with the lowest PV penetration level were typically observed towards the end of a distribution feeder and/or along small branches of the feeder that did not carry the trunk sectional load. Consequently, PV generation sites closer to the trunk sectional load where the conductor has been sufficiently rated would improve the hosting capacity in most cases.

The findings of this report are consistent with a 2012 NREL report (Coddington, et al., 2012) that found PV penetration levels substantially above 15% could be accommodated in many distribution feeders without necessitating systems upgrades. The existing 15% screen first established by the California Public Utilities Commission (Rule 21) is conservative and not an accurate indicator of the PV hosting capacity of a distribution feeder.

Future work will investigate improvements to the voltage regulation and capacitor control schemes to alleviate some feeder hotspots. Approaches that quantify power quality impacts

[6] Feeders 11-14 have some addition artificial PV deployments.

[7] Thermal hotspot.

[8] Thermal hotspot.

of high PV penetration levels for low voltage customers could also be considered in future work (Kim, Rylander, Powers, & Grady, 2008). The significance of secondary side impedances and losses with regard to the reported voltage variability on each SDG&E feeder studied could also be explored.

## 7. *Acknowledgements*

The authors would like to thank William Torre for his comments on the draft report, advice and helpful discussions, Dr. Andu Nguyen for the support in extending his previous work, and Ben Kurtz for the helpful OpenDSS visualization tools and insightful discussions.

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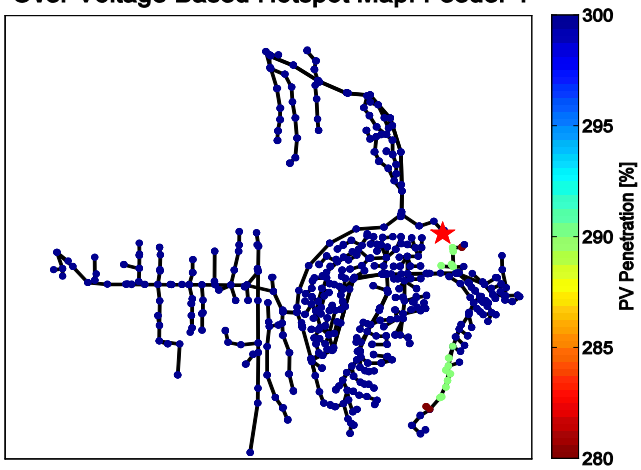
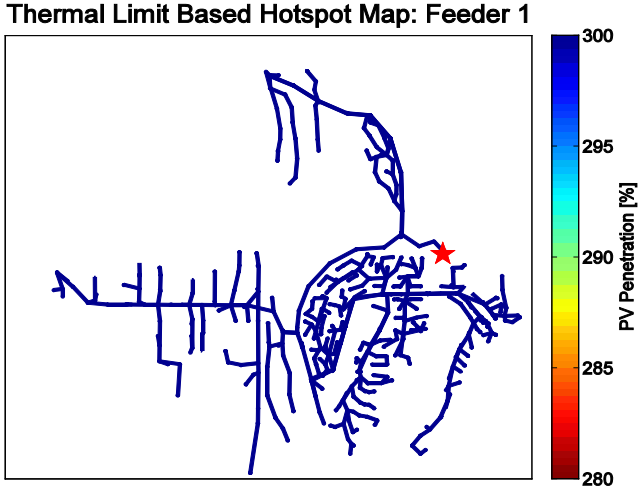
# 9. *Appendix*

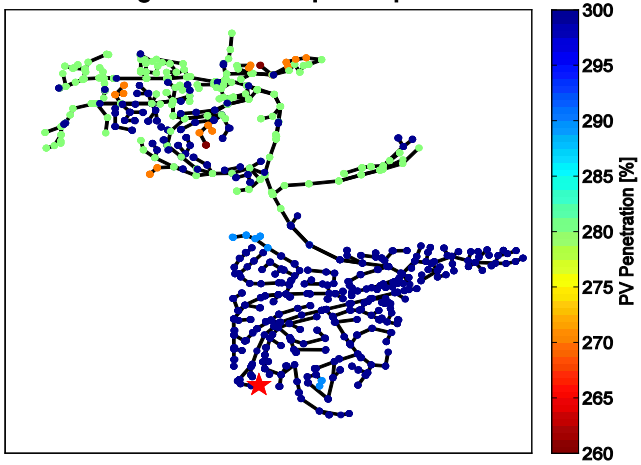
Over Voltage Based Hotspot Map: Feeder 1




Thermal Limit Based Hotspot Map: Feeder 1

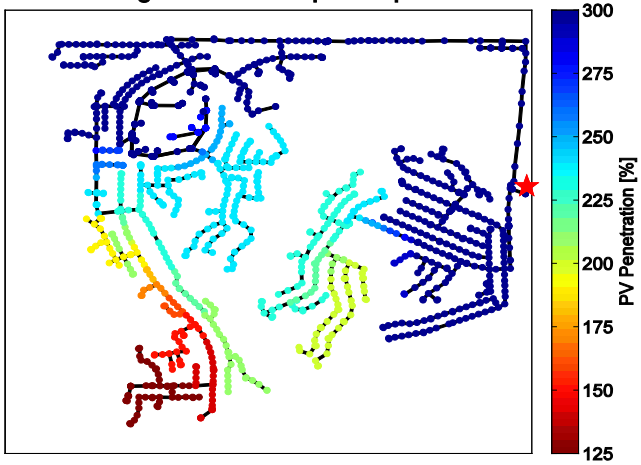



Over Voltage Based Hotspot Map: Feeder 2

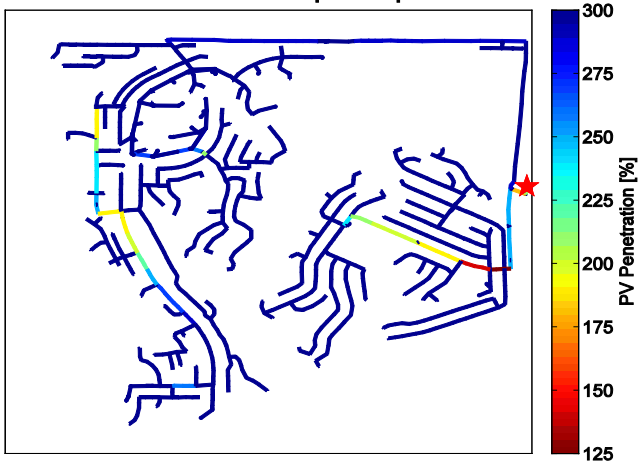



Thermal Limit Based Hotspot Map: Feeder 2

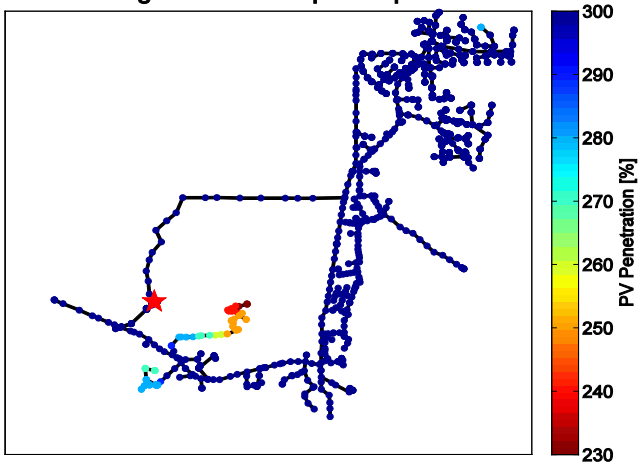
Over Voltage Based Hotspot Map: Feeder 3



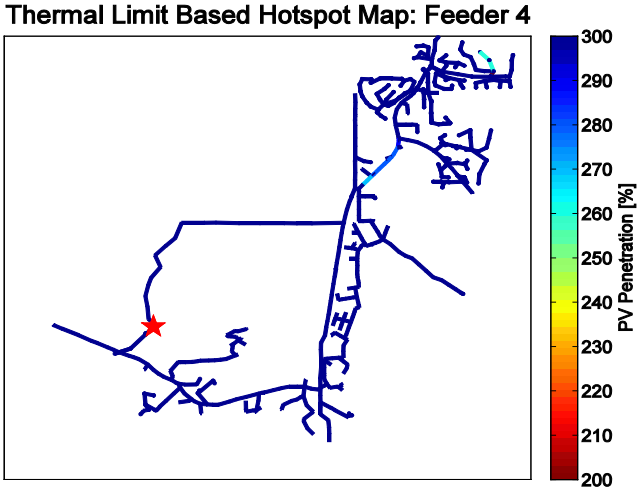

Thermal Limit Based Hotspot Map: Feeder 3



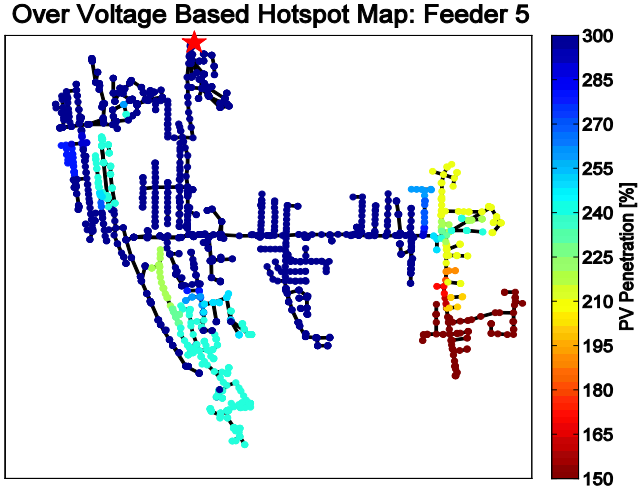
Over Voltage Based Hotspot Map: Feeder 4



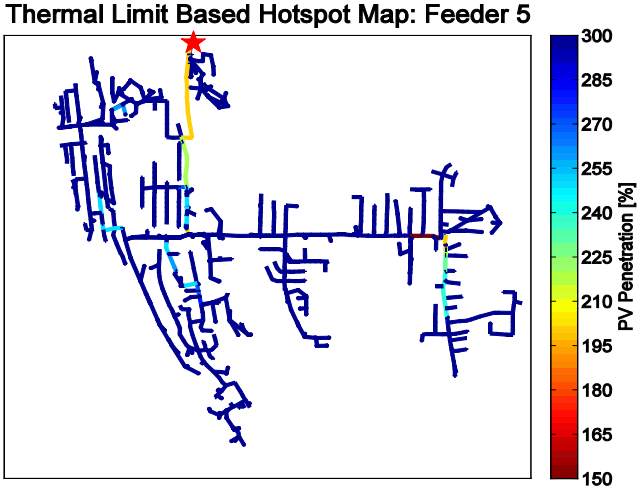

Thermal Limit Based Hotspot Map: Feeder 4



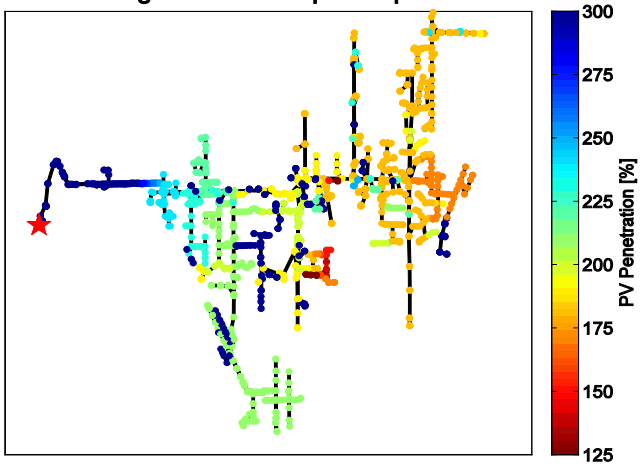

Over Voltage Based Hotspot Map: Feeder 5



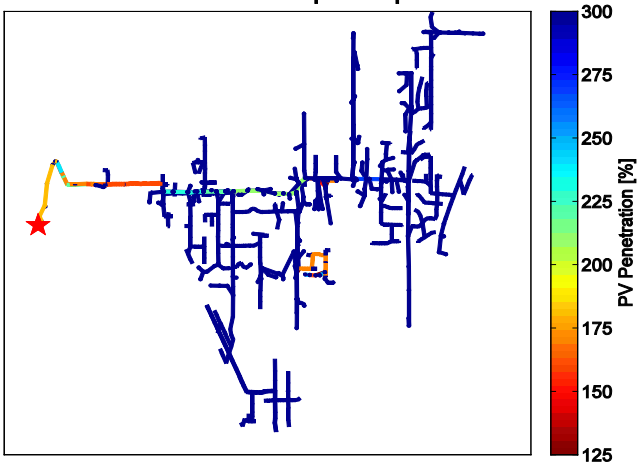

Thermal Limit Based Hotspot Map: Feeder 5

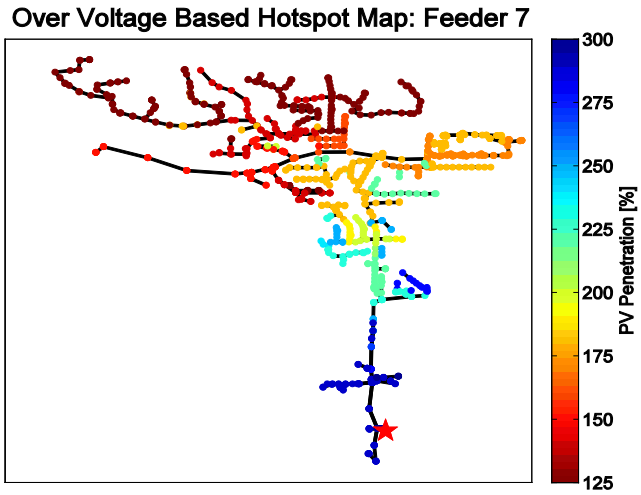


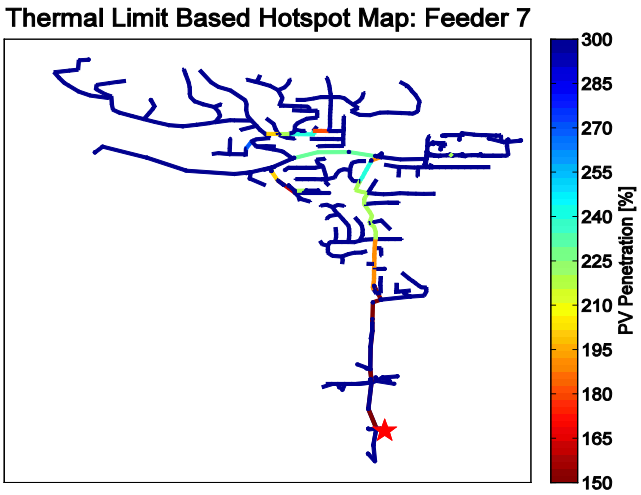

Over Voltage Based Hotspot Map: Feeder 6

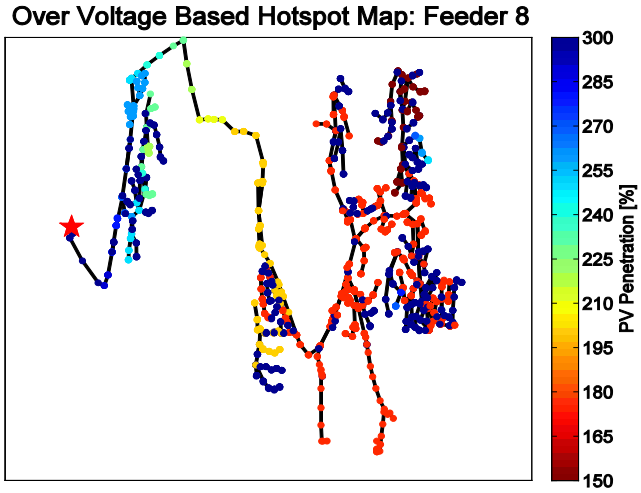


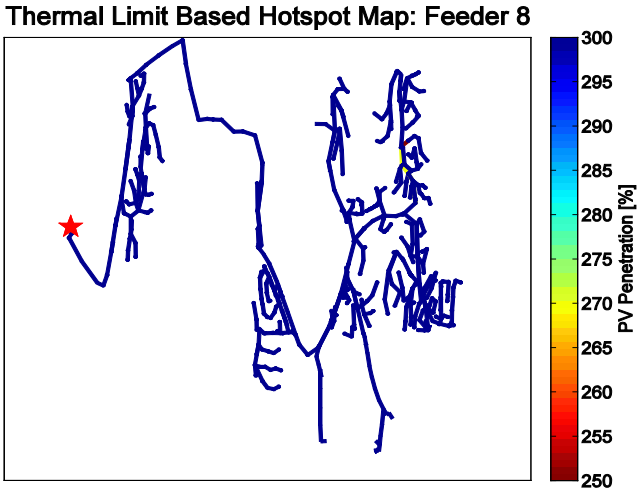

Thermal Limit Based Hotspot Map: Feeder 6

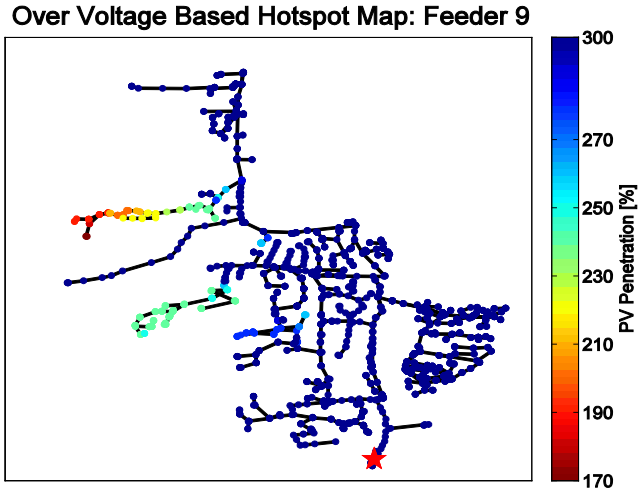


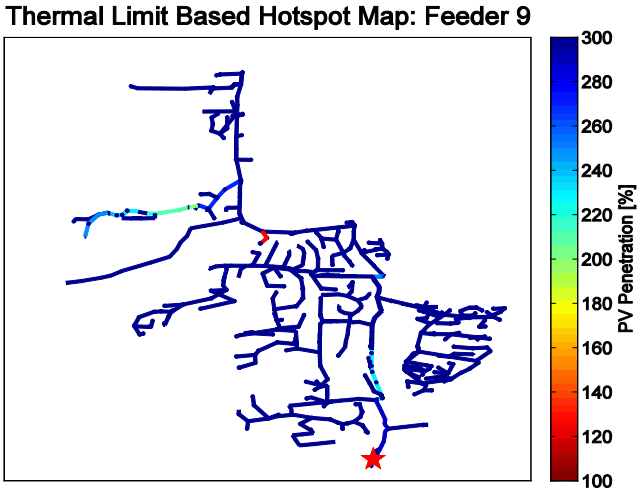

Over Voltage Based Hotspot Map: Feeder 7
PV Penetration [%]
300
275
250
225
200
175
150
125


Thermal Limit Based Hotspot Map: Feeder 7
PV Penetration [%]
300
285
270
255
240
225
210
195
180
165
150

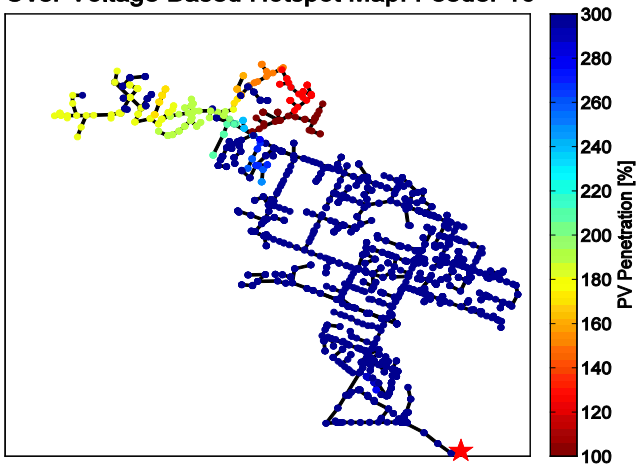

Over Voltage Based Hotspot Map: Feeder 8
PV Penetration [%]
300
285
270
255
240
225
210
195
180
165
150


Thermal Limit Based Hotspot Map: Feeder 8
PV Penetration [%]
300
295
290
285
280
275
270
265
260
255
250

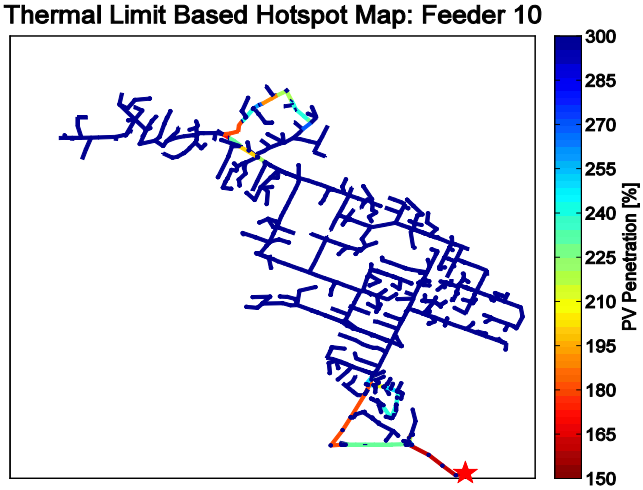

Over Voltage Based Hotspot Map: Feeder 9
PV Penetration [%]
300
270
250
230
210
190
170


Thermal Limit Based Hotspot Map: Feeder 9
PV Penetration [%]
300
280
260
240
220
200
180
160
140
120
100

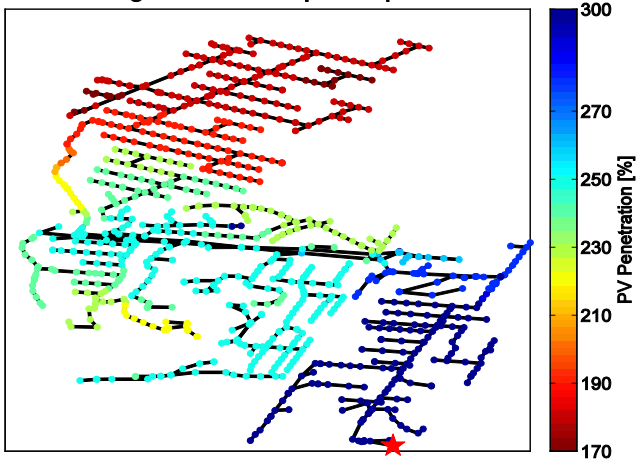
Over Voltage Based Hotspot Map: Feeder 10



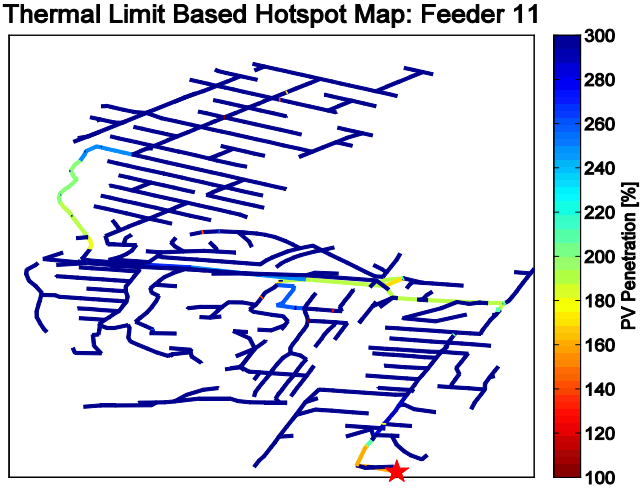

Thermal Limit Based Hotspot Map: Feeder 10



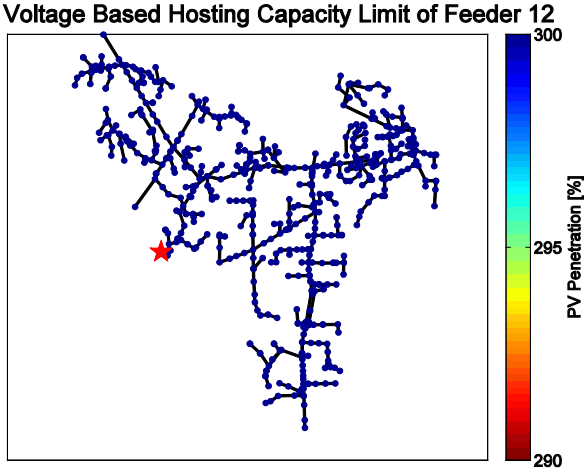

Over Voltage Based Hotspot Map: Feeder 11



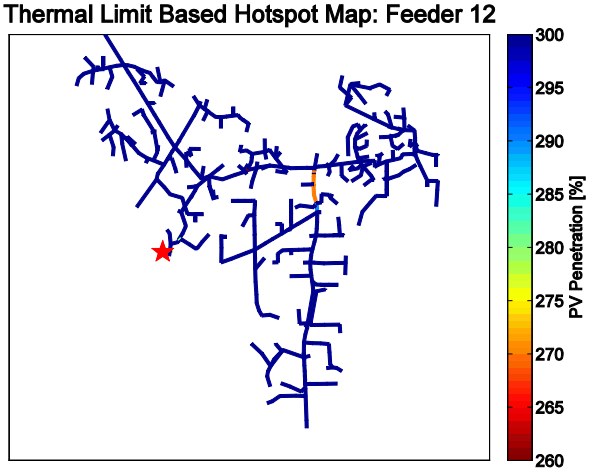

Thermal Limit Based Hotspot Map: Feeder 11

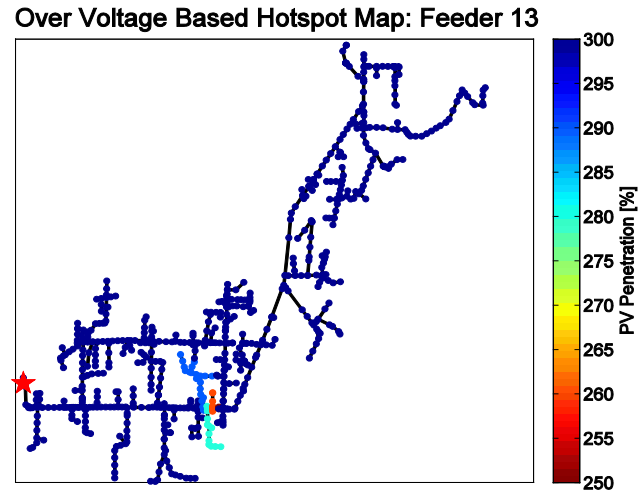


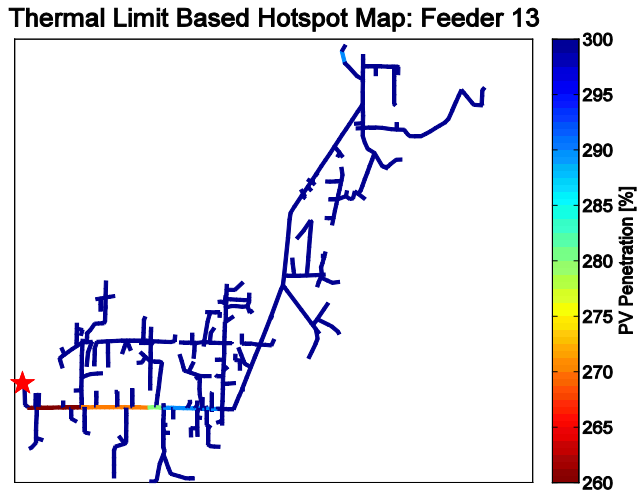

Over Voltage Based Hosting Capacity Limit of Feeder 12

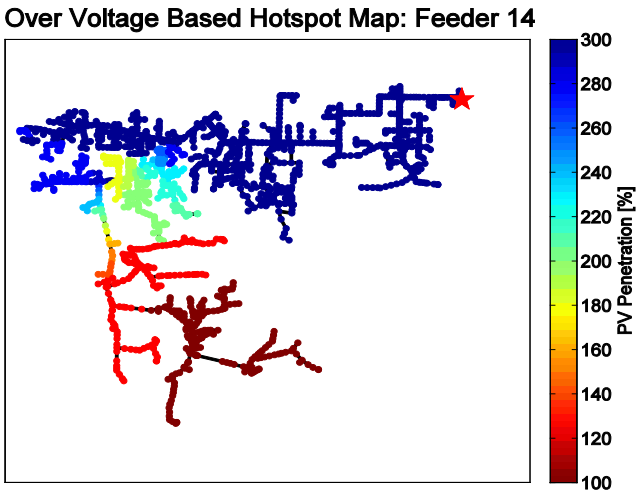


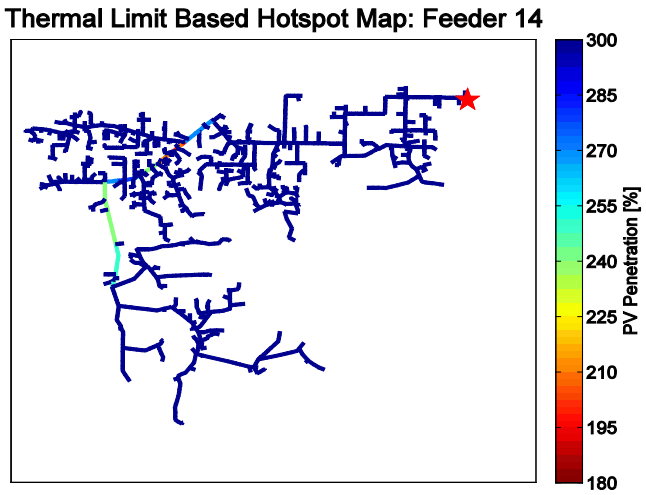

Thermal Limit Based Hotspot Map: Feeder 12




Over Voltage Based Hotspot Map: Feeder 13
PV Penetration [%]
300
295
290
285
280
275
270
265
260
255
250


Thermal Limit Based Hotspot Map: Feeder 13
PV Penetration [%]
300
295
290
285
280
275
270
265
260


Over Voltage Based Hotspot Map: Feeder 14
PV Penetration [%]
300
280
260
240
220
200
180
160
140
120
100


Thermal Limit Based Hotspot Map: Feeder 14
PV Penetration [%]
300
285
270
255
240
225
210
195
180