ELECTRIC POWER RESEARCH INSTITUTE

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# Alternatives to the 15% Rule

*Modeling and Hosting Capacity Analysis of 16 Feeders*

**3002005812**

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Technical Update, April 2015

EPRI Project Manager

J. Smith

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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**Electric Power Research Institute (EPRI)**

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The following organizations prepared this report:

Electric Power Research Institute (EPRI)
3420 Hillview Avenue
Palo Alto, CA 94304

Principal Investigators
M. Rylander
J. Smith

Sandia National Laboratories
1515 Eubank SE
Albuquerque, NM 87123

Principal Investigator
R. Broderick

National Renewable Energy Laboratory (NREL)
15013 Denver West Parkway
Golden, CO 80401

Principal Investigator
B. Mather

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# ABSTRACT

This project is part of the third solicitation of the California Solar Initiative (CSI3) Research, Development, Demonstration, and Deployment Program created by the California Public Utilities Commission (CPUC) in 2006 to support solar research in California. The program focuses on research to improve the utility application review and approval process for interconnecting distributed energy resources such as solar to the distribution system. The CSI3 program is supporting EPRI, National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL) in their collaboration on the process with Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E). At present, the application review and approval process is the most time-consuming of any step on the path to generating power for delivery through the distribution system.

Completed CSI3 project tasks include data collection from the three utilities, clustering of feeder characteristic data, detailed modeling of 16 feeders, and analysis of photovoltaic (PV) impacts on those feeders. The distributed PV impacts are being examined to determine gaps and limitations in the current California Rule 21screening process. Updates to Rule 21 supplemental review will also identify when higher levels of PV could be accommodated without initiating the detailed review process. The majority of these updates to the supplemental review originate directly from results of the detailed study. The updates will provide utilities with additional guidance on the information/data and equations needed to better determine the impact from aggregate levels of PV on a feeder. This report highlights the modeling, analysis, and results from the evaluation of PV impacts on the 16 feeders. A subsequent report will discuss suggested modifications to the current screening process and provide validation with additional feeder models developed under the CPUC CSI3 initiative.

**Keywords**

California Solar Initiative (CSI)
Distributed photovoltaic (PV) resources
Feeder analysis
Feeder modeling
Hosting capacity
Solar energy

# EXECUTIVE SUMMARY

This project is part of the third solicitation of the California Solar Initiative (CSI3) Research, Development, Demonstration, and Deployment Program created by the California Public Utilities Commission (CPUC) in 2006 to support solar research in California. This program focuses on research to improve the utility application review and approval process for interconnecting distributed energy resources such as solar to the distribution system. The CSI3 program is supporting EPRI, National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL) in their collaboration on the process with Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E). At present, the application review and approval process is the most time-consuming of any step on the path to generating power for delivery through the distribution system[1].

Completed CSI3 project tasks include data collection from the three utilities, clustering of feeders, detailed modeling of 16 feeders, and analysis of photovoltaic (PV) impacts on those feeders. The distributed PV impacts are being examined to determine gaps and limitations in the current screening process, California Rule 21[2]. This report highlights the modeling, analysis, and results from the evaluation of PV impacts on the 16 feeders. Previous reports have addressed the additional completed tasks. A subsequent report will discuss suggested modifications to the current screening process and provide validation with additional feeder models developed in the CPUC CSI3 initiative.

## Industry Challenge

Various incentive programs have increased the number of solar PV system interconnection requests to unprecedented levels. To ensure ongoing reliable grid operation, utilities must evaluate these interconnection requests. Certain screening techniques have been developed over the years that help utilities identify when interconnection issues may or may not arise. The most common screening method takes into account the ratio of solar PV to peak load (15%); however, the method does not take into account either the locational impact of PV or feeder-specific characteristics that can strongly factor into whether issues may occur. EPRI has shown that a feeder's hosting capacity for accommodating PV is strongly determined by PV location as well as feeder-specific characteristics.[3]

## Project Goal

The objective of this project—entitled *Screening Distribution Feeders: Alternatives to the 15% Rule*—is to develop a screening methodology that efficiently evaluates new interconnection requests while taking into account PV and feeder-specific factors. This method will not only consider peak load levels but also other critical factors as well, including PV

[1] *A State-Level Comparison of Processes and Timelines for Distributed Photovoltaic Interconnection in the United States*, NREL: January 2015. TP-7A40-63556.

[2] Electric Rule No. 21: Generating Facility Interconnections, Cal. P.U.C. 34818-E, January 2015.

[3] Smith, Jeff, "Alterative Screening Methods: PV Hosting Capacity in Distribution Systems." *DOE/CPUC High Penetration Solar Forum*, San Diego, California (February 13–14, 2013). http://calsolarresearch.ca.gov/Funded-Projects/solarforum.html

location, aggregate PV effects, and most importantly specific feeder characteristics such as voltage class, voltage regulation schemes, and operating criteria.

### Benefits

This effort will result in improved methods that will allow utilities to more quickly and accurately perform engineering screens for new interconnection requests of solar PV, thus reducing time and costs associated with interconnection studies.

### Approach

This project seeks to provide California (CA) utilities with usable, accurate methods to determine the available capacity for PV generation on existing distribution feeders. The overall project approach will be accomplished via a number of distinct tasks as outlined in Figure 1 and described below:

1. Document current practices for screening PV interconnections both inside and outside of CA.
2. Determine the range of feeder configurations for CA utilities and develop a database of feeder characteristics. Select feeders for modeling and simulation that will be used in developing and validating the proposed screening methodology.
3. Collect high-resolution solar output data for validation of feeder models, definition of scenarios for high-penetration PV output, and verification of screening methodology with empirical data.
4. Complete detailed feeder electrical modeling of a selected test group of feeders across CA.
5. Simulate a wide range of PV deployment scenarios and penetration levels on each feeder by utilizing EPRI's distributed PV (DPV) feeder analysis method for determining hosting capacity.
6. Develop practical screening criteria for evaluating new interconnection results.
7. Conduct a formal validation process to determine the accuracy of the screening methodology.

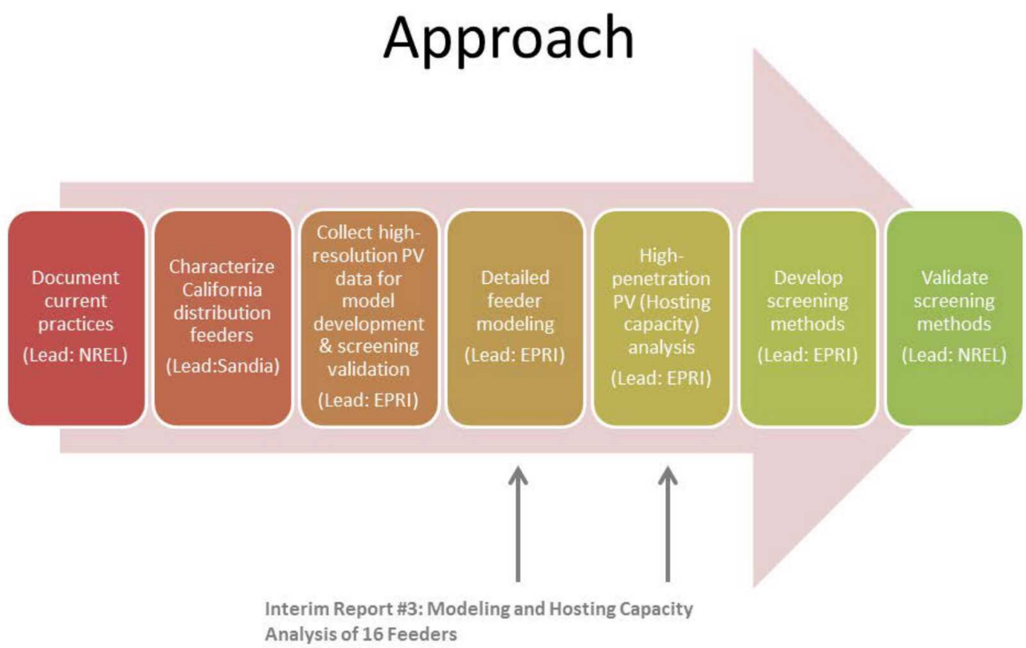



**Figure 1**
**Project Breakdown and Task Leads**

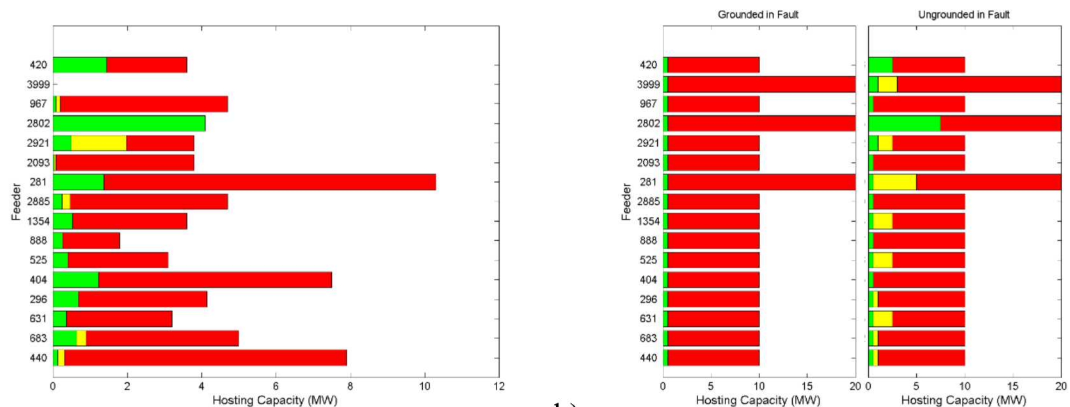
## Results

The feeders identified from each utility for analysis have been chosen based upon their various characteristics—a goal of the clustering analysis in this project. These characteristics inherently make each feeder more or less susceptible to significant impact from distributed generation. The range of impacts based on hosting capacity is shown in Figure 2 for both residential and commercial PV (combined) and utility-class PV. Each colored region represents no issues (green), issues dependent upon PV location (yellow), and issues regardless of PV location (red).

The residential and commercial PV analysis examines behind-the-meter PV, while the utility-class PV analysis examines large PV systems interconnected behind dedicated interconnect transformers. Separate scenarios in the utility-scale analysis examine two types of interconnect transformers that have different impacts during feeder faults. The contribution of ground fault zero sequence current from ground-source interconnect transformers (grounded wye-delta) significantly limits the hosting capacity. The maximum penetration analyzed in the residential and commercial PV scenario is limited by the total feeder load, while the maximum utility-class PV is based on the feeder voltage class (10 MW for 15-kV class and below, and 20 MW for above 15-kV class).

Hosting capacities for each feeder in the residential and commercial PV scenario and utility-scale PV scenario are different due to the possible PV locations. In the utility-scale analysis, the deployed PV could be located close to the start-of-circuit at the substation or in the feeder extremities. In the residential and commercial deployed PV scenario analysis, the PV location depends to a greater degree upon the customer location.

The key understanding from Figure 2 is that no two feeders have the same ability to accommodate PV interconnection without the need to modify the feeder or implement mitigation measures (for example, the initial PV hosting capacity of the feeder). This modification is expected based on the feeders chosen from clusters of different characteristics. The clustering analysis performed separately for each utility, however, has allowed several “similar” feeders to be analyzed across the different utilities. For example, two feeders with similar characteristics are identified in the study as No. 967 and No. 683. While these two feeders are each 12-kV class, ~6-MW peak load, ~35 conductor miles, and have one line regulator, Figure 2 shows that their hosting capacities are different. Only with a closer look at additional model-based data such as specific node voltage, electrical distance (impedance), and topology do the differences in hosting capacity become more evident.




a) b)

**Figure 2**
**Detailed Hosting Capacity for Analyzed Feeders a) Residential and Commercial PV* and b) Utility-Class PV**
***Note: Feeder 3999 is a solely industrial circuit and is not included in hosting capacity analysis for residential and commercial PV deployment.**

The detailed feeder model (incorporating knowledge of all feeder characteristics) and the detailed hosting capacity results obtained through this analysis have made it possible to determine gaps and methods for improvement in the current Rule 21 review and approval process. The aggregate hosting capacity limitations of each feeder derived from this analysis will not apply directly to modifying the current screening process. Rather, the hosting capacity limitation will only show where the current process can be improved.

Results of the analysis discussed in this report are instrumental in determining the necessary Rule 21 improvements. While the subsequent report will provide further information on these improvements, some preliminary findings follow:

- Additional fast track screens need to be applied alongside the 15% peak / 100% daytime minimum load screens.
- Additional key characteristics can also be used in shorthand formulas to better predict the true amount of PV that can be accommodated regardless of the feeder loading.
- The shorthand formulas would allow several inputs such as aggregate PV location, feeder voltage class, and feeder response limit before violation occurs.

Figure 3 shows an example of the hosting capacity based on shorthand estimation compared to the detailed hosting capacity for nine analyzed issues on one feeder. The asterisks represent the results from the shorthand calculations. The goal of the shorthand calculations is to better estimate when higher PV penetrations can be accommodated. This modification can help expedite approval of higher penetrations without performing a detailed review.

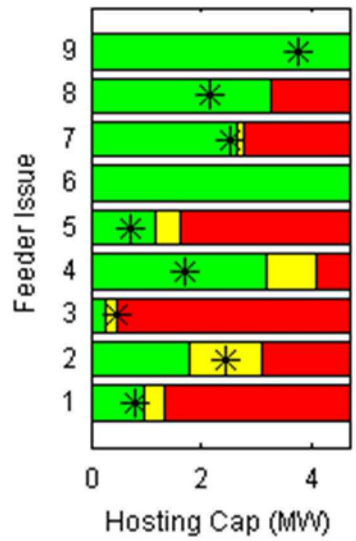



**Figure 3**
**Detailed Hosting Capacity Compared to Estimation (Asterisks) for Multiple Feeder Issues**

## Project Team

This CPUC/CSI project combines wide-ranging experience across the industry, including the following:

- EPRI – Project lead
- National Renewable Energy Laboratory
- Sandia National Laboratories
- Itron

Utility Partners:

- Southern California Edison (SCE)
- Pacific Gas & Electric (PG&E)
- San Diego Gas & Electric (SDG&E)

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# 1
# INTRODUCTION

The third California Solar Initiative (CSI3) established by the California Public Utility Commission is supporting EPRI, NREL, and SNL with collaboration from SDG&E, PG&E, and SCE in research to improve the Utility Application Review and Approval process of interconnecting distributed energy resources to the distribution system. Currently this process is the most time-consuming of any step on the path to generating power on the distribution system[4].

The process allows utilities approximately 15 business days to perform initial fast-track screens. From that initial review, the utility can determine if supplemental review is required. Twenty additional days are allowed for supplemental review. If the interconnection request is not granted after fast-track and supplemental review, detailed impact studies are preformed and to be completed in less than 120 calendar days. Interconnection requests primarily fall into one of the two following categories: (1) those that are granted based on fast-track screens and accepted within 10–15 business days, or (2) projects with significant delays 2–3 weeks beyond the allowed time. Among several reasons, the cause of longer application decisions can be attributed to utility-required supplemental reviews or impact studies beyond initial screens.

An outcome of this CSI3 project will improve the review and approval process in both the fast-track screening and supplemental review. The improvement to the fast-track screens comes with identifying gaps where incorrect approval could occur. The improvement to the supplemental review will provide suggested shorthand calculations to identify where the current method is overly conservative (supplemental review failure). Identifying overly-conservative failure would prevent more lengthy supplemental review or transfer to detailed analysis. All of the above will improve and expedite the application review and approval process.

The project has several steps that occur in the course of reaching this ultimate goal. The first has been to collect utility feeder characteristic data for the three California utilities: SDG&E, PG&E, and SCE. The characteristics of each utility's feeders have been clustered to identify approximately five feeder groups for each utility. A feeder from each group, best representing its constituent cluster, has been selected to perform detailed PV impact analysis. The impact analysis involved modeling the feeder in detail and performing millions of PV impact scenarios. The impact results from this analysis are included in this report and will formulate the additional screens and enhancement to current California P.U.C. Rule 21.

## Clustering

Data for more than 8,000 feeders have been received from the California utilities. After close examination, it is evident that there is a wide variation in feeder characteristics among the three utilities and even within each utility. The differences between feeder characteristics will have a direct impact on the hosting capacity of these feeders. Therefore, when selecting representative

[4] A State-Level Comparison of Processes and Timelines for Distributed Photovoltaic Interconnection in the United States, NREL, TP-7A40-63556, January 2015.

feeders for developing and validating the screening methods, it is crucial to select a set that are as representative as possible.

K Means clustering has been applied to select feeders representative of a cross-section of the known range of feeder types in California as well as representative of the characteristics known to be important to hosting capacity.

### *Approach*

Figure 1-1 depicts the general steps taken during the clustering approach for all three utilities. For several of these steps, a statistical analysis program called SAS JMP has been used[5].


**Figure 1-1**
**General steps in clustering approach**

### *Initial Data Review and Cleanup*

Data received differed between utilities due to availability and ease of retrieval. Once received, the data went through an initial review process. The review process consisted of the following steps:

- Histogram generation – to understand the distribution of all variables of interest (e.g. nominal voltage, total circuit miles, number of capacitors, etc.)
- Data clarification – to understand how certain data is defined, calculated, etc.
- Outlier identification – identify feeders that are obvious outliers, often excluded from the clustering approach
- Boundary definition – boundaries defined to exclude data due to scarcity/irrelevance
- Data anomaly documentation – identify anomalies
- Data set preparation – ensure consistent formatting and data population

#### Select Variables for Clustering

Initial variables are selected based on the impact they might have on differentiating feeder types and hosting capacity. These are varied among utilities to account for differences in availability of data from each utility. Because the optimum number of clusters is more accurately achieved when the chosen variables are independent of each other, correlation maps are used to examine pairs of highly correlated variables to determine if it is appropriate to remove some of the variables before clustering.

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[5] Clustering Method and Representative Feeder Selection for the California Solar Initiative, SAND2014-1443, 2014.

### Remove Outliers

The K-means clustering algorithms can be very sensitive to outliers. Removing outliers when using K-means as the clustering technique can help improve convergence speed and will make the clustering more reliable. Feeders labeled as outliers are not representative of the overall data set and are removed from the clustering process. Distance, a multivariate calculation that is a measure of how similar a particular feeder is to its closest neighbor, is used as the basis for outlier removal. A distance measure from each feeder to its twelve closest neighbors is computed and these distances are used to compute an average distance. If the average distance is above a certain threshold (different for all utilities) the feeder is considered an outlier and removed from the clustering process.

### Select the Number of Clusters

The K-means algorithms require the number of clusters to be specified in advance. Cubic Clustering Criterion (CCC) is used to determine the initial number of clusters for each of the three data sets. To help minimize the number of representative feeders for each utility given the project objectives and limitations, clusters that had similar characteristics are evaluated and the clusters that best captured the similar characteristics are retained while the other redundant clusters are eliminated.

### Final Feeder Selection

Biplots are created by reducing the multiple data dimensions using Principle Component Analysis (PCA) to the two dominant aspects of variation. Feeder selection from within the cluster is accomplished by sorting the feeders based on their distance from the center mean and selecting feeders that are closest to the center of the cluster, and therefore highly representative of the cluster. In addition to Biplots, other important parameters, such as significant PV system presence and the existence of feeder measurement data, are used for final feeder selection. A total of 22 feeders have been chosen for evaluation. From those 22, a control group of 6 feeders have been selected for testing/validating the screening methodology, while the remaining 16 are examined with the detailed PV impact analysis.

## Feeder Modeling

The modeling and analysis approach is performed entirely in the OpenDSS (Open-source Distribution System Simulator). The OpenDSS tool has been used for more than a decade in support of various research and consulting projects requiring distribution system analysis. Many of the features found in the program have been originally intended to support the analysis of distributed generation interconnected to utility distribution systems. Other features support analysis of such things as energy efficiency in power delivery and harmonic current flow. The OpenDSS is designed to be indefinitely expandable so that it can be easily modified to meet future needs.

The base electrical feeder model used in the analysis consists of all primary and secondary power delivery elements from the substation transformer to the individual customer. Control elements such as capacitors and regulators are included with fully implemented control algorithms using setpoints, delays, and bandwidths provided by the utility. Loads are based on SCADA or AMI measurements, and depending on the location of measurement, load is allocated to each individual customer. The complete model is usually derived from a number of data sources, including the simulation platform database (CYME or SynerGEE), field measurements, billing information, and GIS data.

## *Model Conversion*

The first step to create the feeder model needed for the analysis is to convert the model from the utilities distribution software platform into the OpenDSS platform. The model is converted without any modifications to verify the same electrical representation. The validation consists of several solution checks such as voltage profiles shown in Figure 1-2. Table 1-1 indicates the validation of the OpenDSS model with respect to the power flow and short circuit fault currents.

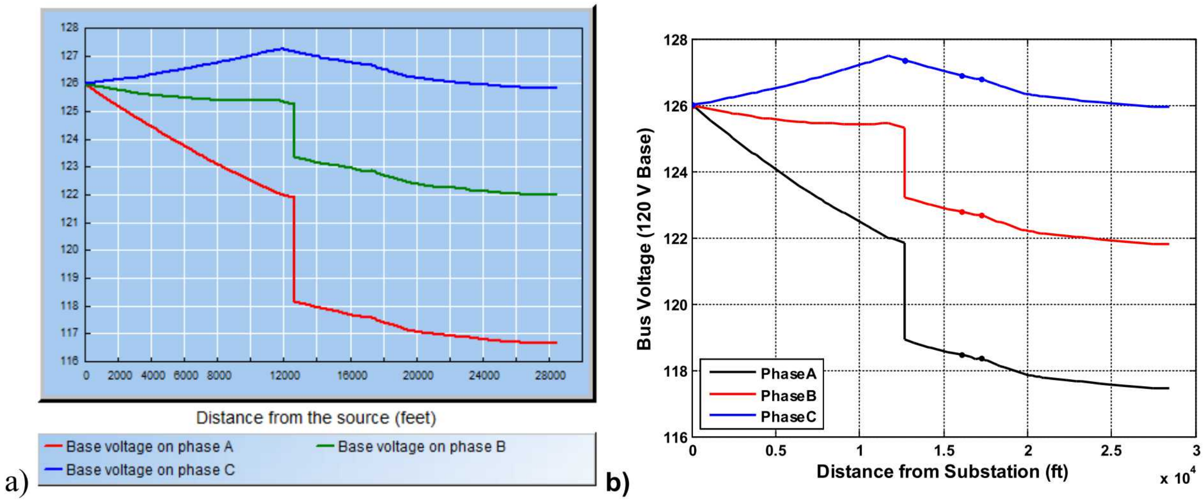


**Figure 1-2**
**Voltage Profile Validation a) Utility Model b) OpenDSS Model**

**Table 1-1**
**Power Flow and Short Circuit Validation**

| | Power (MVA) | Three-Phase Fault Current | Single-Phase Fault Current | Line-Line Fault Current |
|---|---|---|---|---|
| **OpenDSS** | 7.35 – j1.44 | 872 | 578 | 746 |
| **CYME** | 7.35 – j1.45 | 855 | 586 | 741 |

## *Modification of the Model*

The second step to create the feeder model needed for the analysis is to modify for a more detailed representation. This modification includes adding the substation transformer, voltage regulation controls, service transformers/conductors to individual customers, and load adjustments.

The substation transformer is added to the model as shown in Figure 1-3 to provide the appropriate voltages at the feeder head. This is especially necessary when the substation has voltage regulation such as a load tap changer. Since a new power flow element is replacing impedance previously modeled as the source impedance, a short circuit fault analysis is repeated for validation of the added element.

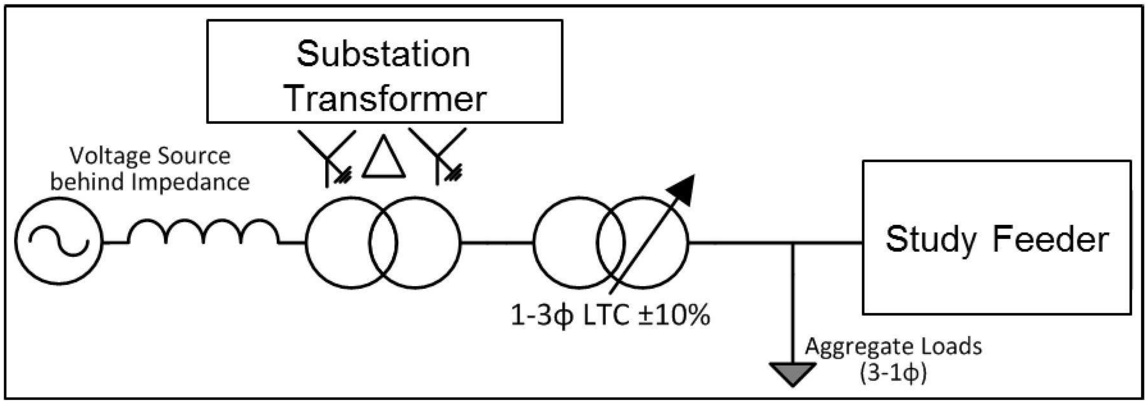


**Figure 1-3**
**Substation Transformer**

The controls of load tap changers, line drop compensation, line regulators, and/or capacitor banks must also be added. Those control settings are not always available in the utility model and may need to be acquired separately. Figure 1-4 shows the voltage profile based on control settings that exist in a utility model versus those based on updated control records.

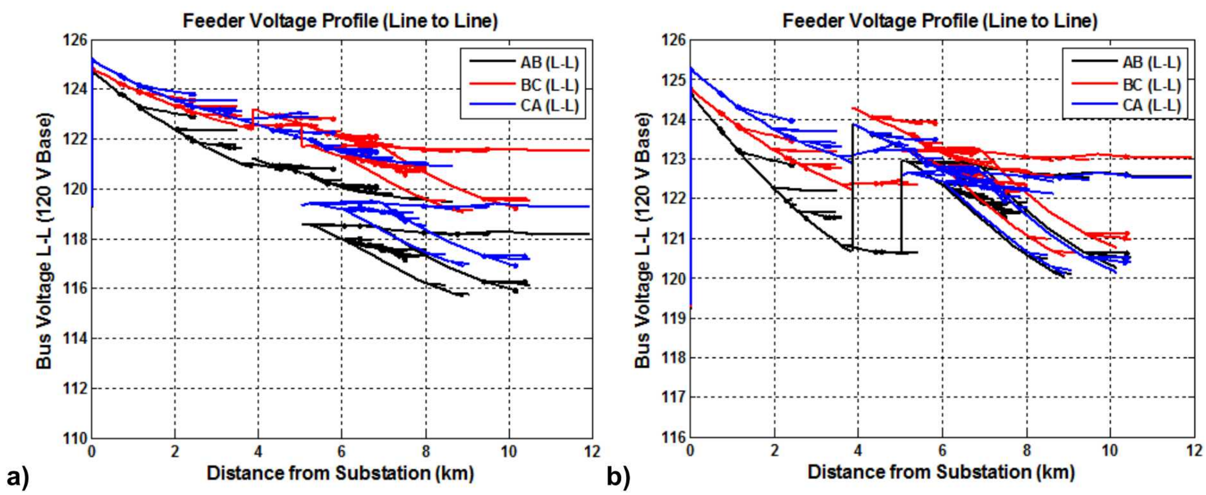


**Figure 1-4**
**Voltage Profile with Different Control Settings a) Utility Model b) OpenDSS Model**

Service transformers and services are not typically included in the utility model. Loads are typically lumped at a primary node on the feeder. The OpenDSS model adds service transformers and services to individual customers. Figure 1-5 illustrates the voltage drop to the individual customers by the dashed lines. The voltages at the individual customers will have a direct impact on the current flowing out of constant power inverters. These new power flow elements are validated with respect to preventing overloads and staying within voltage limits. Finally, customer loads can be reallocated based on measurements across the feeder. Load is additionally adjusted based on existing distributed generation.

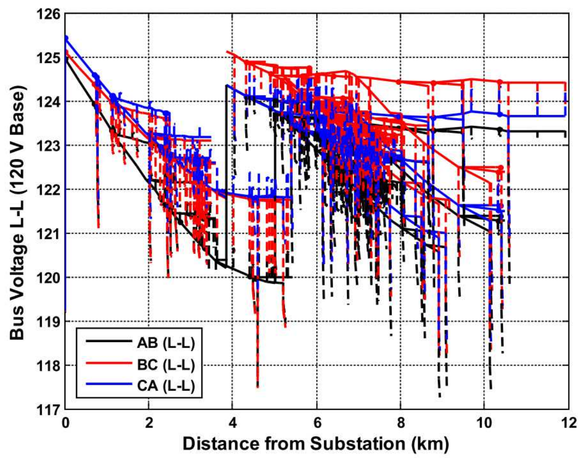


**Figure 1-5**
**Voltage Profile with Services Added to OpenDSS Model**

## *Final Feeder Validation*

The final validation of the OpenDSS model is made with respect to measurement data. The power flow data is compared to peak SCADA measurements as shown in Table 1-2. Additionally, validation is made with respect to a time series simulation. Figure 1-6 illustrates the validation of active and reactive power flow based on model and measured data.

**Table 1-2**
**Power Flow Validation**

| | Feeder (MVA) | Substation (MVA) | Phase A (Amps) | Phase B (Amps) | Phase C (Amps) |
|---|---|---|---|---|---|
| **OpenDSS** | 9.200 + j0.417 | 20.777 + j1.626 | 429.265 | 429.975 | 415.093 |
| **SCADA** | 9.269 + j0.423 | 20.407 + j1.565 | 429.468 | 429.313 | 415.521 |

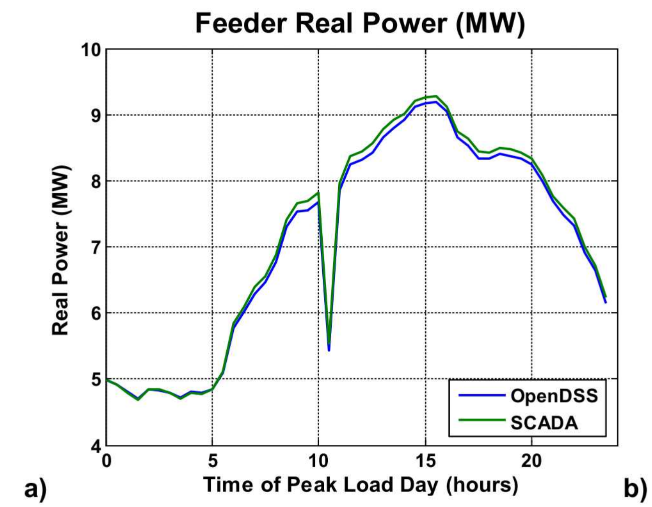


**Figure 1-6**
**Time-Series Validation a) Active Power b) Reactive Power**

## Analysis

The analysis[6] approach is broken down into two categories: small-scale PV (residential/commercial) and large-scale PV (utility-class). Small-scale PV is based on individual customer loading with typical residential PV systems in the range of 2-5 kW. Large-scale PV is based on 500 kW systems interconnecting to the three-phase feeder primary through a step-up transformer. Small-scale and large-scale PV are stochastically deployed and simulated to determine the feeder response. The stochastic nature of the analysis develops thousands of potential distributed PV deployments that capture the unpredictability of 'where' and 'how much' PV will eventually be installed. The feeder response is determined for voltage, protection, harmonic, and loading concerns in a static analysis.

Each feeder response is addressed by determining a hosting capacity for PV. The hosting capacity is determined when a stochastically created PV deployment causes the feeder-wide response to exceed established thresholds. At this point, the feeder has met the limit for maximum total amount of PV that can be hosted for that particular deployment. However, the analysis is not complete at this point. Since feeder hosting capacity can widely vary based upon the size and location of solar PV, thousands of different PV deployment scenarios are simulated to determine the range in hosting capacity values that might occur.

### *Stochastic Deployment Development*

A key component in accurately assessing the PV impact on the distribution system is accurately representing the nature of the PV systems themselves. This includes not only sufficiently accounting for the electrical characteristics of the distributed generation, but also the array size and solar irradiance which inherently drives the PV output. Other research efforts in this area utilize satellite imagery to evaluate potential roof tops for possible PV locations and determine PV sizes based upon available space and roof orientation. While this approach may provide a

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[6] Analysis of High-Penetration Solar PV Impacts for Distribution Planning: Stochastic and Time-Series Methods for Determining Feeder Hosting Capacity. EPRI, Palo Alto, CA: 2012. 1026640

better estimate of PV at any given location, the approach outlined and utilized in this study is based primarily on market-based information that represents a larger range of existing PV system installation sizes as well as a wider range of possible PV locations along the feeder. This approach can more effectively provide information relative to the overall goal of the project of understanding when and where solar PV significantly impacts feeder performance.

Penetration of distributed PV onto a feeder is influenced by many different market conditions and customer variables. In the analysis, market conditions are assumed favorable and non-restrictive on customer PV system purchases and all customers are assumed to have equal opportunity to acquire a PV system. Weighting customers to be more likely to acquire PV in a particular area due to factors such as socioeconomics is possible within the developed modeling framework, however, is not applied in this analysis.

The amount of installed PV (in kilowatts) by the individual customer is dependent on customer constraints such as available space and system price. These factors are not readily accessible, so detailed market distributions[7] are used to randomly determine PV size each time a customer is assigned a PV system. These distributions can be seen in Figure 1-7 and Figure 1-8. Each PV system is assumed to operate at 100% of rated AC output, irrespective of solar panel orientation and/or tilt. This approach for considering full output capability is in line with well-established transmission and distribution planning practices. Each PV system's power factor is set to unity (zero reactive power), which is considered standard "off-the-shelf" setting for PV systems available in the US.

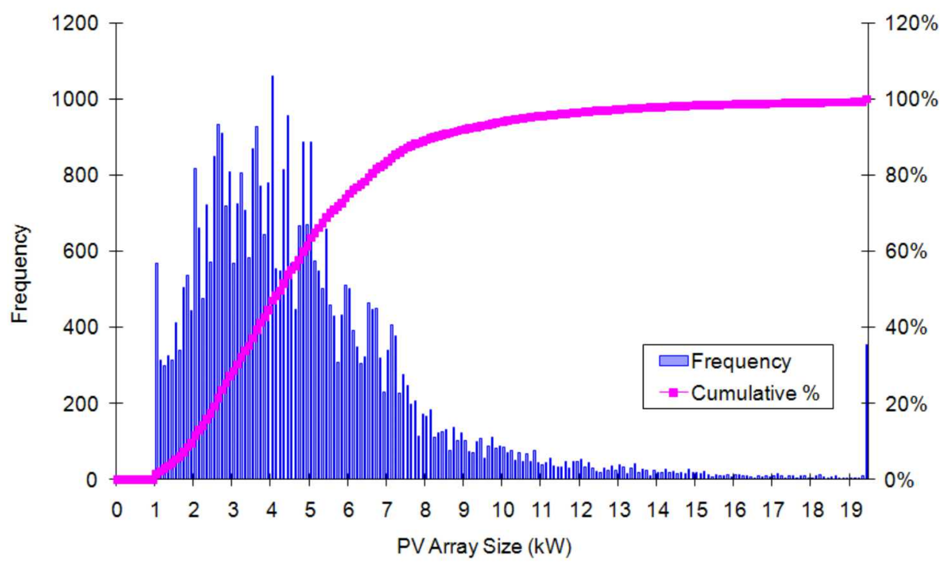


**Figure 1-7**
**California Residential PV Distribution**

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[7] California Solar Statistics, http://www.californiasolarstatistics.org

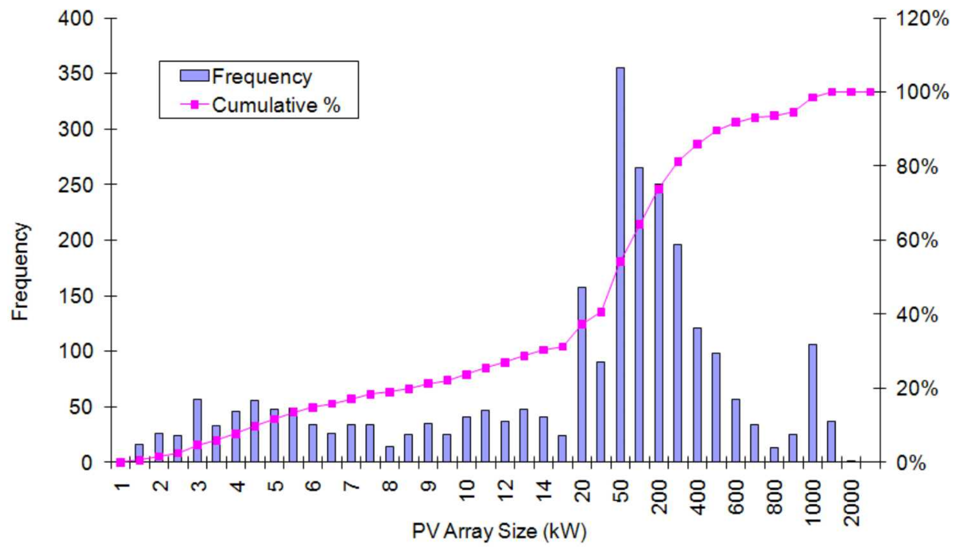



**Figure 1-8**
**California Commercial PV Distribution**

In order to reasonably represent the impact of large- and small-scale PV, the analysis is split into the two deployment routines:

- Small-scale PV
- Large-scale PV

Each deployment routine serves as a tool for examining system response from a different conditional perspective. Results from the separate deployment routines can be used to provide a complete picture concerning the nature and relationship between PV generation and system impacts.

Small-scale PV deployment uses the customer service as the most probable point of coupling for each individual PV (behind the meter). Customer class is used to distinguish between using a residential or commercial PV distribution for randomly selecting installed PV size. In the analysis, the maximum PV size is restricted by the customer peak load and size of the service transformer. The peak loading of the individual customers is used as a metric to gauge 'likely' maximum PV size, while the total PV arrays on an individual service transformer is ultimately limited by the kVA rating of the service transformer.

The allocation of PV is performed for multiple scenarios and penetration levels as shown in Figure 1-9. As penetration increases for a specific scenario, further PVs accrued are in addition to those existing in the same scenario at the previous penetration level. Penetration is increased until all customer locations have been deployed with PV. Each scenario is unique in the order that customers are selected to acquire PVs. Thousands of PV deployments are created.

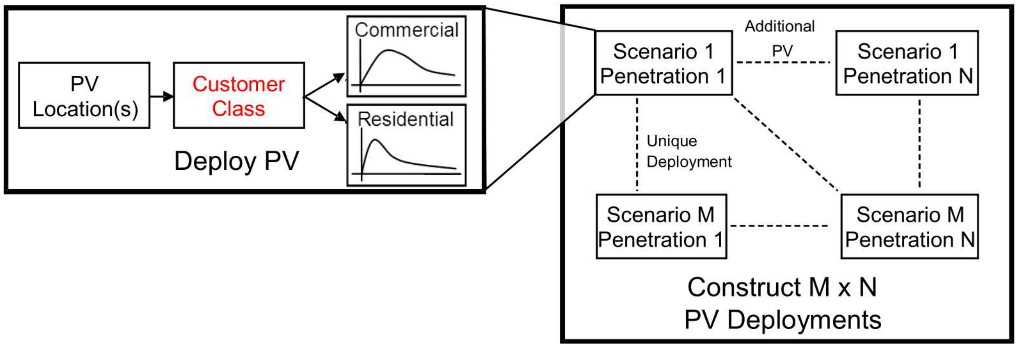



**Figure 1-9**
**Small-Scale PV Deployment Routine**

Large-Scale PV deployment uses a select number of three-phase primary line locations as probable points of interconnection. At each penetration level, one ungrounded 500 kW PV system is interconnected at a randomly selected location behind a 480 V three-phase step-up transformer. The PV penetration level is increased until 10 MW of PV has been deployed (20 MW for feeders above 15 kV). Again, each penetration level builds upon the previous penetration level for a given scenario. Figure 1-10 illustrates the Large-Scale PV deployment.

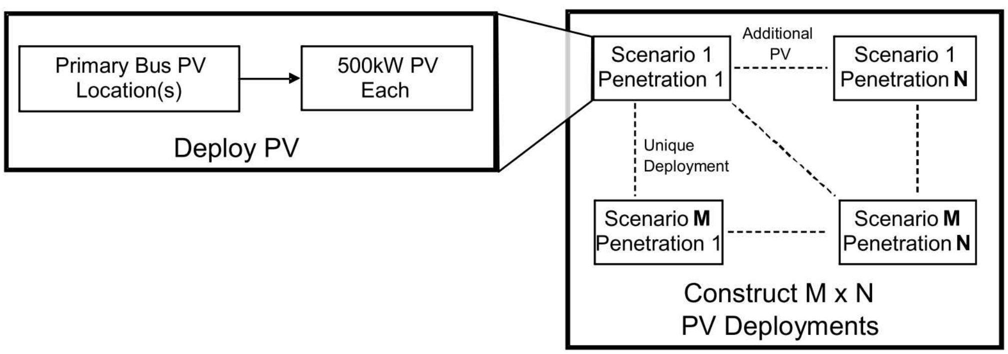



**Figure 1-10**
**Large-Scale PV Deployment Routine**

In the study, residential and commercial PVs are interconnected at the customer service level, while large-scale PV systems are connected directly to the primary distribution system via a Wye Grounded-Wye Grounded step-up transformer. Customer service conductor is included in the model using detailed or default data. As default, a 100 ft or 125 ft run of 1/0 aluminum triplex is assumed for individual customer's service connection depending on the maximum service length provided by each utility included in the study.

## *Framework*

The PV impact analysis is a combination of power flow, fault, and harmonic studies. These studies examine a large variation of PV deployment scenarios, load levels, fault locations/types, and resonance. The analysis determines the 'worst case' feeder response that would occur in any condition.

The power flow analysis is conducted for the four base load levels:

- Absolute maximum – maximum feeder load level derived from 8760 feeder measurement data; irrespective of time-of-day
- Absolute minimum – minimum feeder load level derived from 8760 feeder measurement data; irrespective of time-of-day
- Midday maximum – maximum feeder load level derived from 8760 feeder measurement data; 11am-1pm local time considered only
- Midday minimum – minimum feeder load level derived from 8760 feeder measurement data; 11am-1pm local time considered only

The absolute maximum and minimum loads are used to derive a bounding envelope for the worst-case conditions. The midday maximum and minimum loads determine more probable bounds for the feeder response. These midday load levels occur when PV can produce full output.

### *Issues to Analyze*

Distributed generation planning criteria and limits have been identified by both North American and European practices. Table 1-3 shows a summary of criteria used in the analysis to identify potential issues. The flags in this table are applied for study purposes and are not necessarily planning limits currently applied in the industry. These values are used across all feeders to allow uniform comparisons to be made.

The criteria that have been identified fall into the following general categories of potential concern:

- Voltage
- Loading
- Protection
- Harmonics

**Table 1-3**
**Monitoring Criteria and Flags for Distribution PV Analysis**

| Category | Criteria | Basis | Flag |
|---|---|---|---|
| Voltage | Overvoltage | Feeder voltage | ≥ 1.05 Vpu at primary<br>≥ 1.05 Vpu at secondary |
| | Voltage Deviation | Deviation in voltage from no PV to full PV | ≥ 3% at primary<br>≥ 5% at secondary<br>≥ ½ bandwidth at regulators |
| | Unbalance | Phase voltage deviation from average | ≥ 3% of phase voltage |
| Loading | Thermal | Element loading | ≥ 100% normal rating |
| Protection | Element Fault Current | Deviation in fault current at each sectionalizing device | ≥ 10% increase |
| | Sympathetic Breaker Tripping | Breaker zero sequence current due to an upstream fault | ≥ 150A |
| | Breaker Reduction of Reach | Deviation in breaker fault current for feeder faults | ≥ 10% decrease |
| | Breaker/Fuse Coordination | Fault current increase at fuse relative to change in breaker fault current | ≥ 100A increase |
| | Anti-Islanding | Percent of minimum load | ≥ 50 % |
| Harmonics | Individual Harmonics | Harmonic magnitude | ≥ 3% |
| | THDv | Total harmonic voltage distortion | ≥ 5% |

## Voltage

The analysis examines the voltage impact to the entire modeled feeder. This includes all nodes (buses) modeled along primary and secondary lines. Flags for the voltage category are applied separately to primary nodes, secondary nodes, and voltage regulation nodes. The flags are adjusted for nodes with control elements to account for control actions. The modified flag allows better approximation of the PV penetration when the controls may begin to operate.

Overvoltage issues are a concern for both primary and secondary nodes due to reliability and power quality. Voltage deviation issues are examined for customer power quality, protection of equipment, and to know the potential voltage drop that could occur if PV is suddenly lost on the feeder. Voltage unbalance impacts power quality and equipment health.

## Loading

Thermal loading limits are an important factor that can restrict the capacity of PV on a given feeder. Typically, the deployment of PV reduces the net forward (downstream) power flow on the system; however, PV systems can potentially cause high reverse power flow and in some cases could cause overloads and increased losses if not located near other loads for local consumption. Element loading issues are a concern for reliability of the distribution system.

### Protection

The chief means of fault detection on utility distribution systems is series overcurrent relaying. The presence of PV systems has the potential to disrupt the coordination of the series overcurrent devices by essentially turning the radial distribution system into a meshed network system. The fault current contribution from the PV systems is used to judge whether a single or aggregation of PV will interfere with the detection and clearing of faults. Protection impacts are examined at the sectionalizing elements. These elements include breakers, reclosers, fuses, and switchgear. Three-phase to ground, line-line, and single-phase to ground faults are examined at all sectionalizing devices.

Element fault current contribution, sympathetic breaker tripping, and fuse coordination issues are a concern due to inadvertent operation. The reduction in breaker reach is a concern due to loss of breaker sensitivity to faults on the feeder. Islanding issues are determined as a percent of minimum load. As the generation to load ratio approaches one, the chance for islanding to occur increases. Besides other inverter-based function to prevent islanding, maintaining a low generation to load ratio would also help.

### Harmonics

Voltage harmonic impacts from distributed PV are analyzed by the change in harmonics with and without PV on the feeder. The feeder response includes load harmonics, minimum and maximum load levels, all possible capacitor configurations, and maximum penetration PV deployments. Harmonic issues are a concern due to the decrease in power quality and adverse impact on sensitive equipment.

## *Calculating Hosting Capacity*

The calculation of Hosting capacity is best explained via illustration as shown in Figure 1-11. The figure shows the maximum primary feeder voltage versus total PV penetration. Recall that when applying the hosting capacity method, a wide range of possible PV sizes and locations are simulated. For each simulation, the feeder response is recorded and then post-processed to determine if and when any criteria from Table 1-3 is violated. When analyzing overvoltage, the absolute highest voltage anywhere on the feeder is determined. Each marker in Figure 1-11 shows the absolute maximum primary feeder voltage for each unique PV deployment. Once the maximum voltages are determined, the results are then broken down into three regions (A-green, B-yellow, C-red) identified in the figure.

Region A includes PV deployments, regardless of individual PV size or location, that do not cause maximum primary voltages to rise above the ANSI 105% voltage threshold (threshold shown by horizontal red line).

At the start of Region B, the first PV deployment exceeds the voltage threshold. This PV penetration level is termed the **Minimum Hosting Capacity** because the total PV in the deployment is the lowest of those analyzed that cause adverse impact. At the same penetration level there are many PV deployments that do not cause an adverse impact due to more optimal sizes/locations of individual PV systems. Perhaps most of these PV systems are located in areas of the feeder where the voltage is low and there is more headroom, or closer to the substation where the feeder is stronger. As penetration increases further, more and more scenarios begin to cause further impact and eventually result in a violation. It is likely in these PV deployment scenarios that the PV is located further from the substation where the feeder is weak, or near a line regulator or capacitor bank and therefore has less headroom. The rightmost side of Region B defines the **Maximum Hosting Capacity** where all PV deployments, regardless of individual PV sizes or locations, cause primary voltages to exceed the threshold. This is the maximum penetration level that can be accommodated under the given feeder conditions.

Region C identifies PV deployments that exceed the threshold regardless of individual PV sizes or locations. Aggregate PV of this magnitude will be problematic.

Feeder hosting capacity is the range indicated by Region B (yellow). This hosting capacity range depicts more/less optimal PV deployments. The minimum and maximum hosting capacity are metrics for determining the range of aggregate PV that can be accommodated on a feeder. The hosting capacity is similarly calculated for all issues shown in Table 1-3.

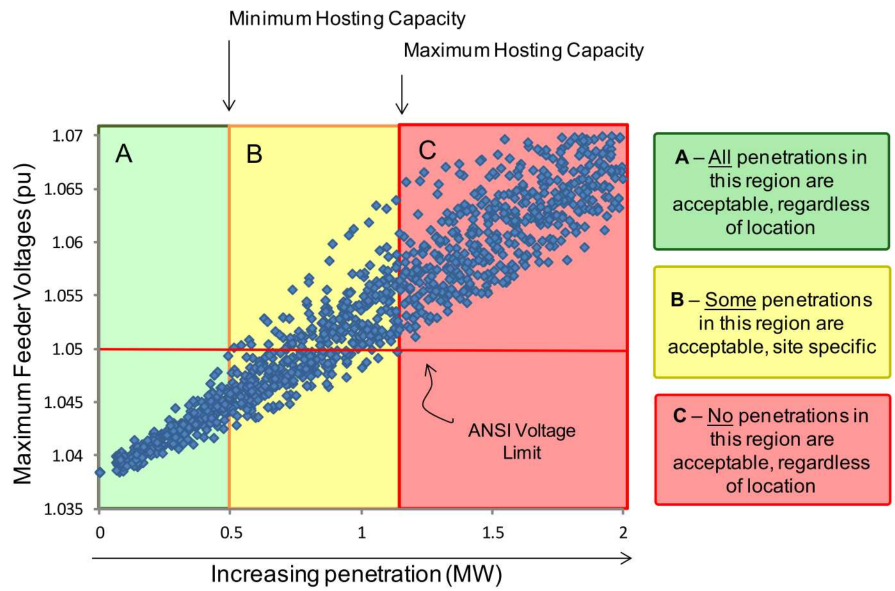



**Figure 1-11**
**Example Calculation of Hosting Capacity**

# 2

# FEEDER MODELING AND ANALYSIS

There are 16 feeders modeled in detail and thoroughly analyzed. The characteristics of all 16 feeders and the description and results from one are provided in this section. The description and results for the remaining 15 are included in the appendix.

## Characteristics

How a feeder responds to photovoltaic generation is dependent on the individual feeder's characteristics. Although feeder characteristics are a key factor in the feeder response from distributed PV, additional factors include the PV size, location, and output. The distribution system connected PV will ultimately mold the overall feeder response. The main characteristics of each feeder analyzed are shown in Figure 2-1. The characteristics cover a range in values as indicated by the maximum and minimum values. All characteristics have an impact on feeder hosting capacity, however, not all are equally important.

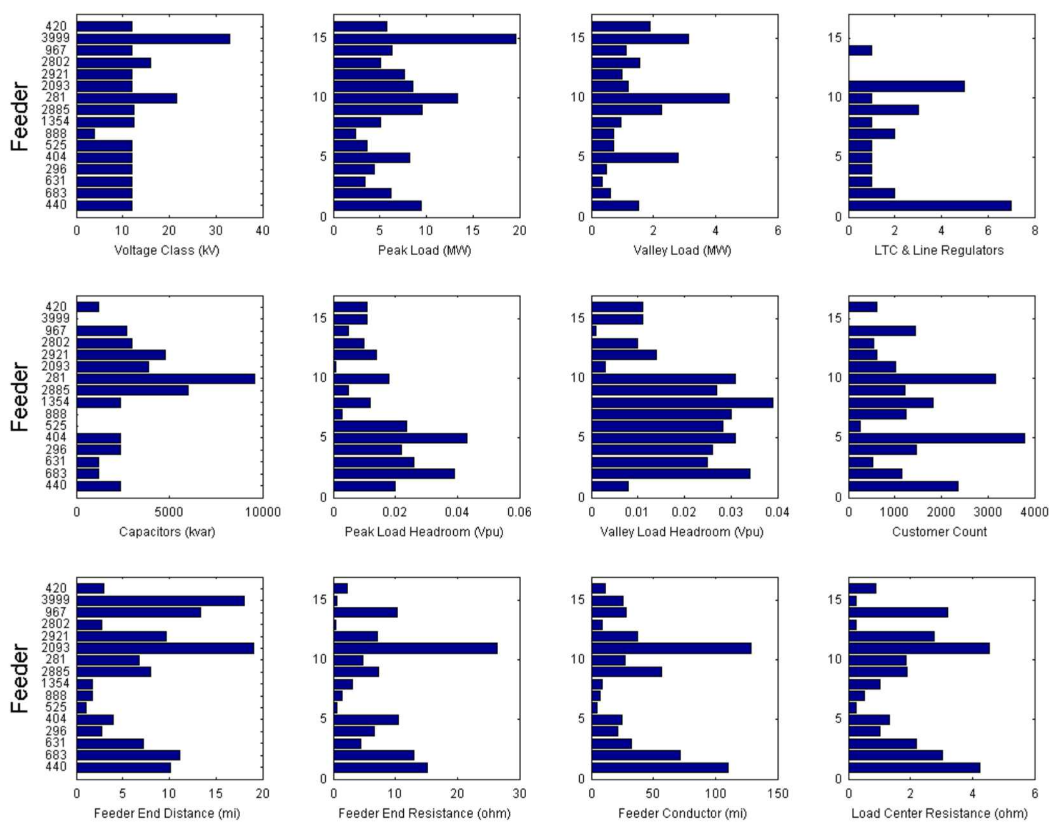



**Figure 2-1**
**Characteristics of Analyzed Feeders**

### *Feeder Voltage*

Feeder voltage class is an important characteristic due to the effect primary voltage has on primary line currents and overall electrical strength of the feeder. The sampled feeders primarily cover the 12 kV class. There are two high voltage class feeders and one low voltage class feeder.

### *Load Level*

The sampled feeders cover a wide range in feeder loading. The peak and valley load shows the variability in customer demand among the sampled feeders. The load levels directly impact the voltage along the feeder. Both load levels are important to the analysis because some feeder responses to distributed generation are more adverse during specific load conditions.

### *Voltage Regulation*

Utilizing a substation load tap changer will have a direct impact on the feeder voltages. Additional line regulation also affects the voltage along the feeder. Feeders with voltage regulation include a wide variety of setpoints, bandwidths, and line drop compensation.

### *Reactive Compensation*

The number of capacitor banks and their reactive compensation (kvar) are important in the power quality and harmonic impact on the feeders. The reactive compensation also influences the feeder voltage.

### *Voltage Headroom*

The minimum voltage headroom is also calculated for each feeder. This value is the difference between maximum feeder voltage and 105% of nominal voltage. An illustration of this is shown in Figure 2-2. The minimum headroom can occur at any location on the feeder. The headroom is dependent on the load level on the feeder. Often, the headroom is less in the valley load case, but utilization of line drop compensation can cause the headroom to be less at peak load.

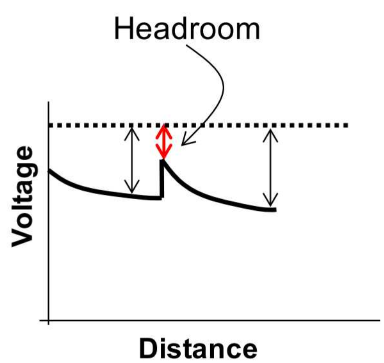



**Figure 2-2**
**Minimum Feeder Voltage Headroom Indicated by Red Arrow**

### *Customer Count*

The customer count on the feeder indicates the number of potential PV customers. These are the total residential, commercial, and industrial customers. The customers impact the potential location small-scale PV, whereas large-scale PV can be sited regardless of customer location.

### Feeder Topology

Conductor length is the aggregated length of all primary lines. This includes single-phase, two-phase, and three-phase lines. Total conductor length can potentially be an indication of how strong or weak a particular feeder might be. A drawback of the total length characteristic, however, is that it does not indicate the type of conductor or if the feeder is a short urban feeder with many laterals or a long radial feeder with minimal taps.

The feeder-end distance conveys additional information on feeder topology. It indicates the maximum distance to the last customer. This characteristic can also be an indication of how weak/strong a feeder might be.

### Feeder Impedance

The electrical characteristic of the conductors are pulled in by characterizing the feeder by primary line resistances. Resistance is used since the majority of PV systems installed are at unity power factor. The feeder-end resistance gives a good indication of the electrical strength of the feeder, but does not indicate if there are customers at that location. The load center location describes the electrical location of the aggregate load on a feeder. The characterization is based on the weighted average primary resistance to all loads. The weighted average resistance value ($R_{avg}$) for a specific feeder is determined as

$$R_{avg} = \left( \sum_{i=1}^{k} R_i \cdot kW_i \right) \Big/ \sum_{i=1}^{k} kW_i \,, \qquad \textbf{Eq. 2-1}$$

where $i$ defines the individual characteristics for load size ($kW$) and primary short circuit resistance ($R$) to each load and $k$ is the number of loads on the feeder.

The load center location is an electrical characteristic of the feeder that can help approximate the electrical location of PV deployments on each feeder. Several illustrations of this calculation are shown in Figure 2-3. The black arrows indicate location and magnitude of individual loads while the green arrows indicate the aggregate load magnitude and location based on the weighted average impedance.

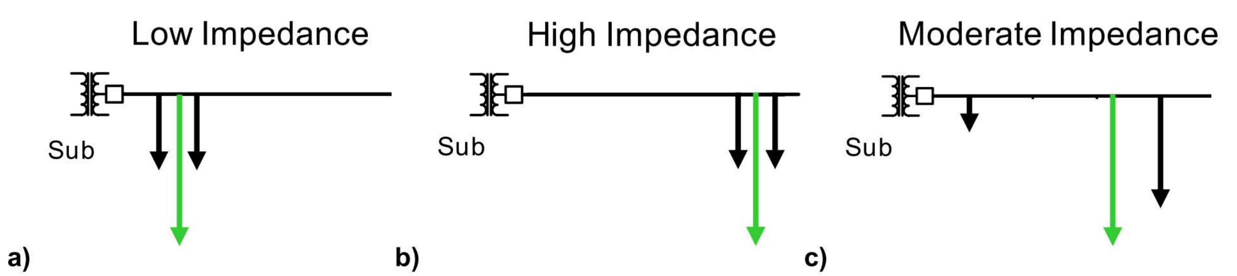



**Figure 2-3**
**Weighted Average Impedance shown by Green Lines and Black Lines Indicate Individual Loads. a) Low Impedance b) High Impedance and c) Moderate Impedance**

## Feeder Description and Detailed Results for Feeder 631

The studied 12 kV feeder peak load is 3.4 MW with 23.9 MW at the substation. There are 32 primary feeder miles that extend a maximum length of 7.2 miles from the substation. There are approximately 363 residential customers and 152 commercial customers on the feeder. The substation three-phase LTC regulates voltage on the feeder. The LTC is modeled in a co-generation mode to maintain the 123 V setpoint and 4 V band at the low side tap. There is one feeder capacitor with 1200 kvar total compensation. The bank is voltage controlled with 119/123V on/off settings. A feeder voltage profile plot at peak load is shown in Figure 2-4a, while a schematic illustrating system impedance is shown in Figure 2-4b.

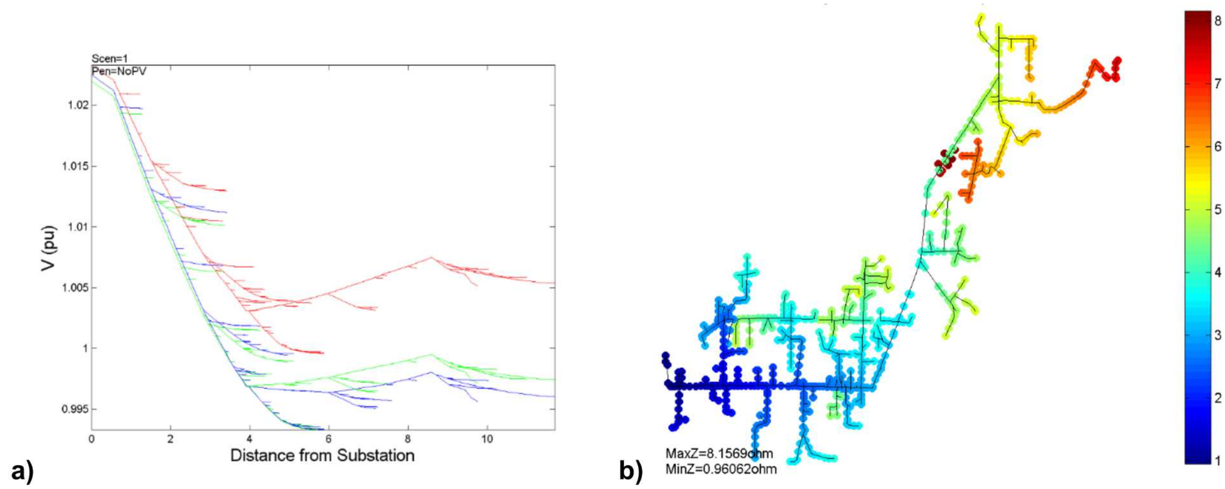
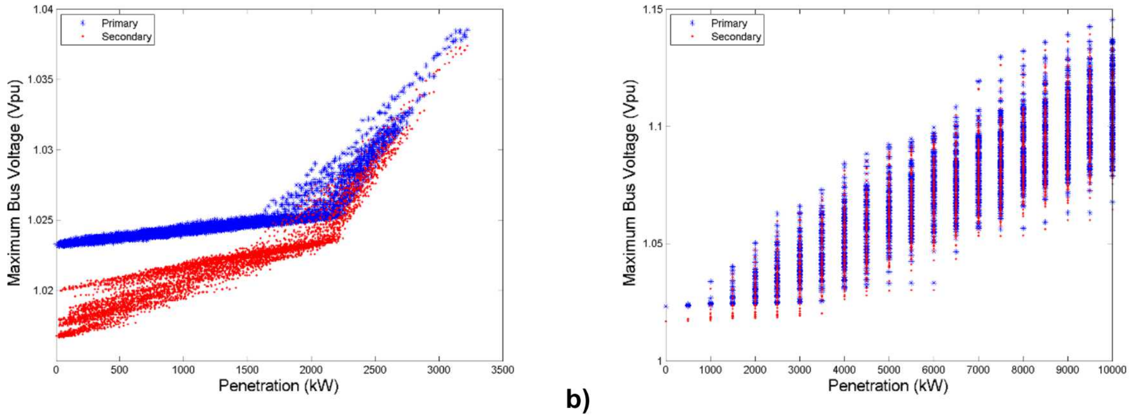



**Figure 2-4**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

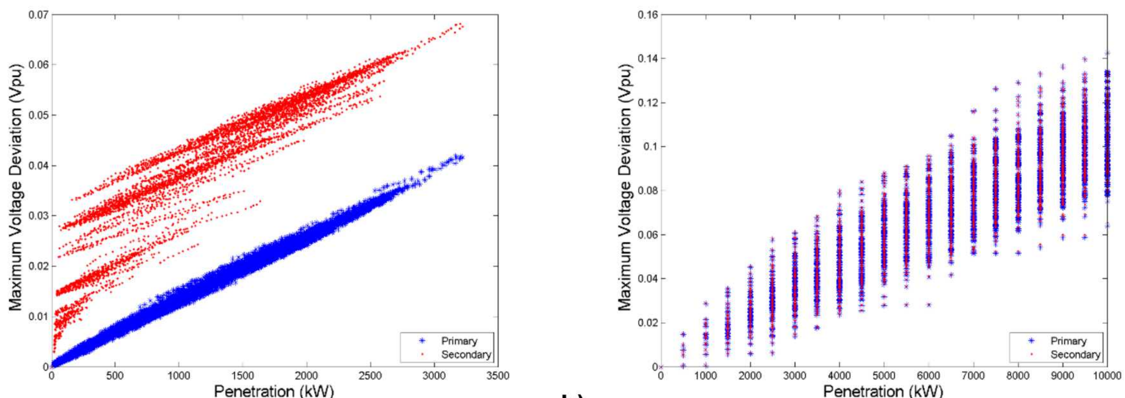
The following figures illustrate trends in feeder response from increased penetration of PV on the feeder. These trends are shown for peak load and small/large-scale PV. Slightly different trends occur for other load conditions. These other trends may be more/less limiting on feeder hosting capacity.

Overvoltage trends are shown in Figure 2-5. Trends for secondary voltage correlate closely to primary voltage for large-scale PV. This occurs because the large-scale PV system is connected directly behind a dedicated interconnect transformer, whereas in the small-scale PV scenario, the PV is connected at the end of the customer service. At peak load, the secondary voltage is typically lower than the primary at high penetration because the PV is smaller or equal to the size the load. During minimum load, there can be greater voltage rise across the service since there can be net power injection to the feeder. Figure 2-6 shows the voltage deviation trends. At peak load, lower voltages at the service cause the voltage deviation to be greater at those locations than on the primary. Again, large-scale deviations are closely correlated for primary and secondary nodes. Figure 2-7 shows the worst-case voltage deviations that occur at a voltage regulation point on the feeder. High voltage deviation could cause a regulator to operate excessively as voltage moves consistently out of its bandwidth.



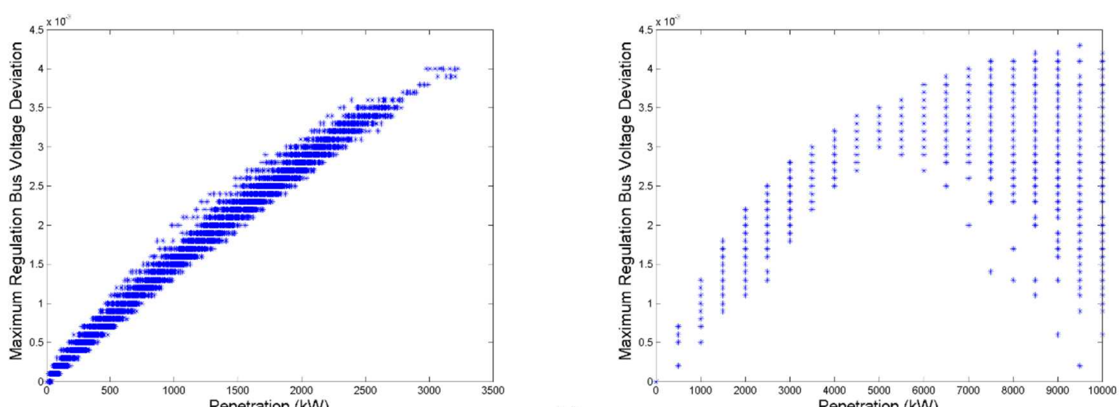

a) b)

**Figure 2-5**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

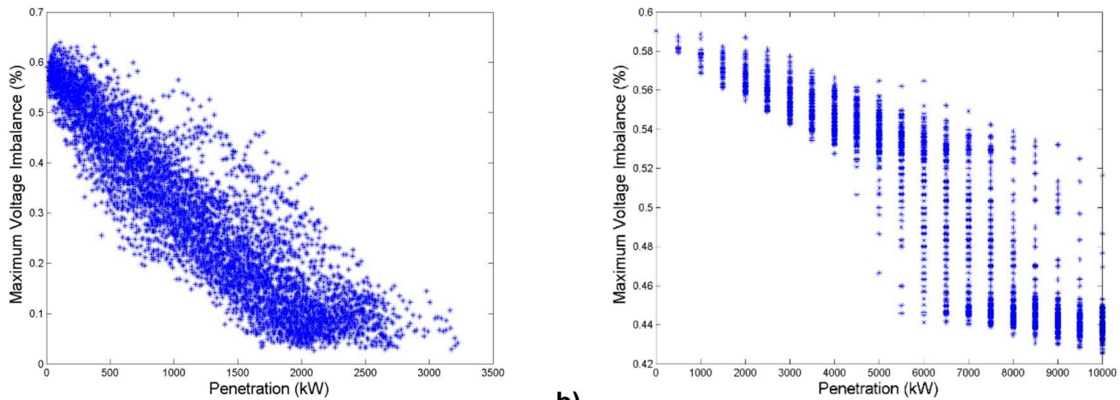
**Figure 2-6**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure 2-7**
**LTC Voltage Deviation (Vpu) Trends a) Small-Scale PV b) Large-Scale PV**

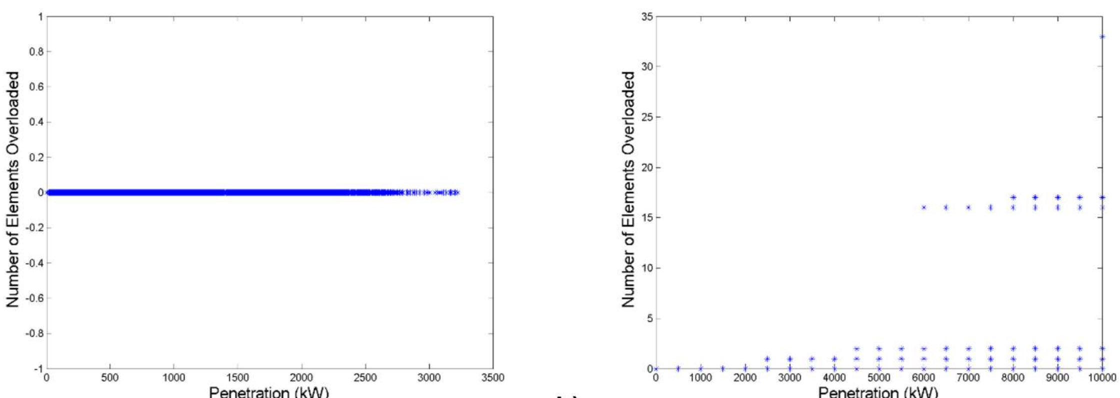
The voltage imbalance on the feeder generally decreases as the PV compensates demand on highly loaded phases. There is still the chance that PV can exist on lightly loaded phases at low penetration which causes the chance for increased imbalance as shown in Figure 2-8.




a) b)

**Figure 2-8.**
**Primary Voltage Imbalance Trends a) Small-Scale PV b) Large-Scale PV**

Overloads do not exist in the base case as shown for this feeder in Figure 2-9. Additional overloads in the small-scale analysis do not occur because the PV is sized smaller than the peak load in the analysis. Only in the large-scale analysis is the PV placed on the feeder unrestricted by location. In this deployment, the PV can be placed at locations that cause greater reverse power flow and additional overloads at high penetration.




a) b)

**Figure 2-9.**
**Overload Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*

The following figures illustrate trends in feeder protection impacts from increased penetration of PV. These trends are shown for small/large-scale PV using a reduced set of potential PV deployments. The large-scale PV analysis examines the impacts from using a ground-source interconnect transformer (Grounded Wye-Delta) and one that is not a ground source (Grounded Wye-Grounded Wye).

Figure 2-10 shows the maximum percent increase of any protection element due to any type of fault on the feeder for each PV deployment scenario. Trends for large-scale PV interconnected with a ground source transformer show the significant impact even at low penetration due to zero-sequence ground fault current contribution. Small-scale PV and large-scale ungrounded have more linear trends from no impact at 0 kW penetration.

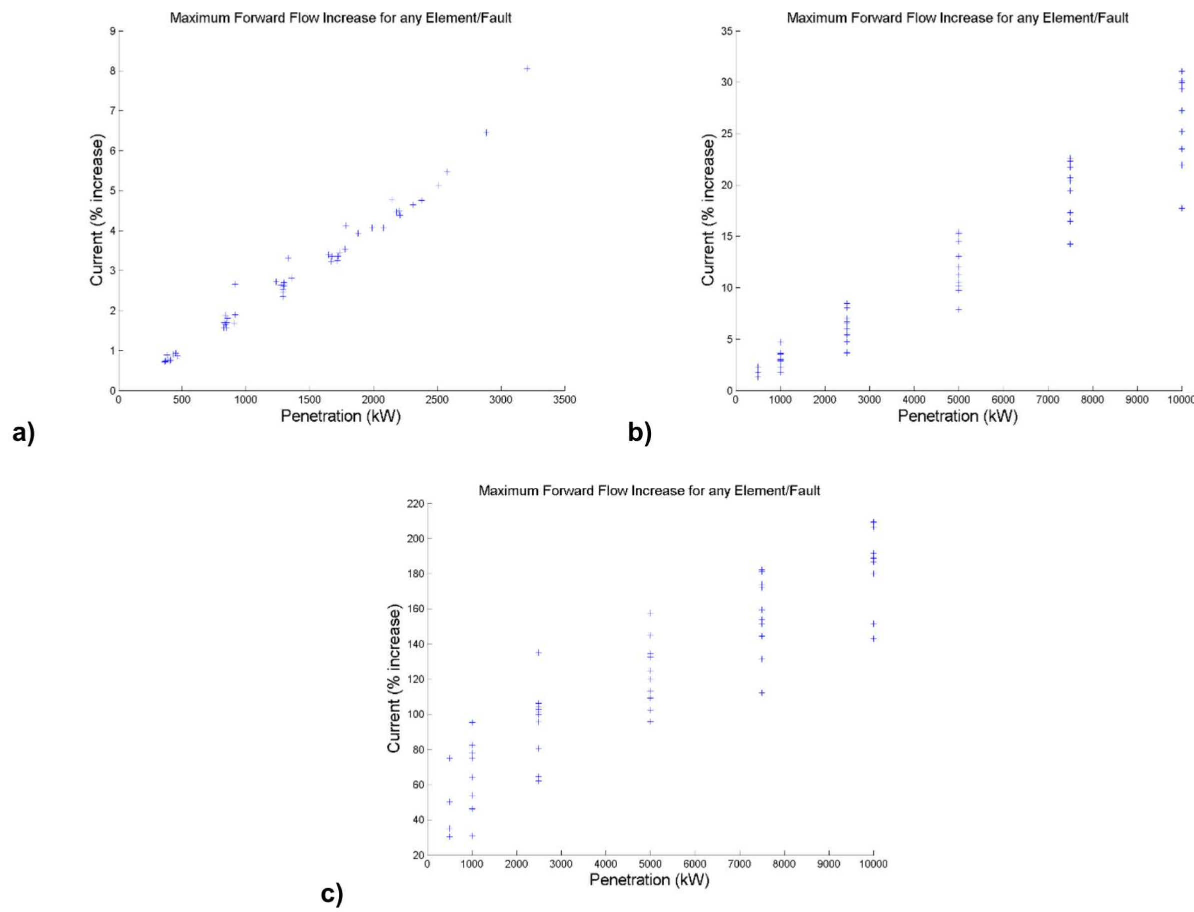



**Figure 2-10**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV Ungrounded Transformer c) Large-Scale PV Grounded Transformer**

Figure 2-11 shows the potential increase in ground (zero-sequence) fault current due to a fault upstream from the breaker or on a parallel feeder. The ground fault current is recorded as the residual current (unbalance) between the three primary phases. This is especially problematic when there are ground source transformers with PV on the feeder. Large-scale PV that does not contribute to ground faults is not problematic. The impact from small-scale PV is also dependent on the customer service transformers. Whether a three-phase system contributes depends on the customer's transformer. A single-phase system will only contribute if connected line-neutral. Line-line connected transformers have a negligible impact.

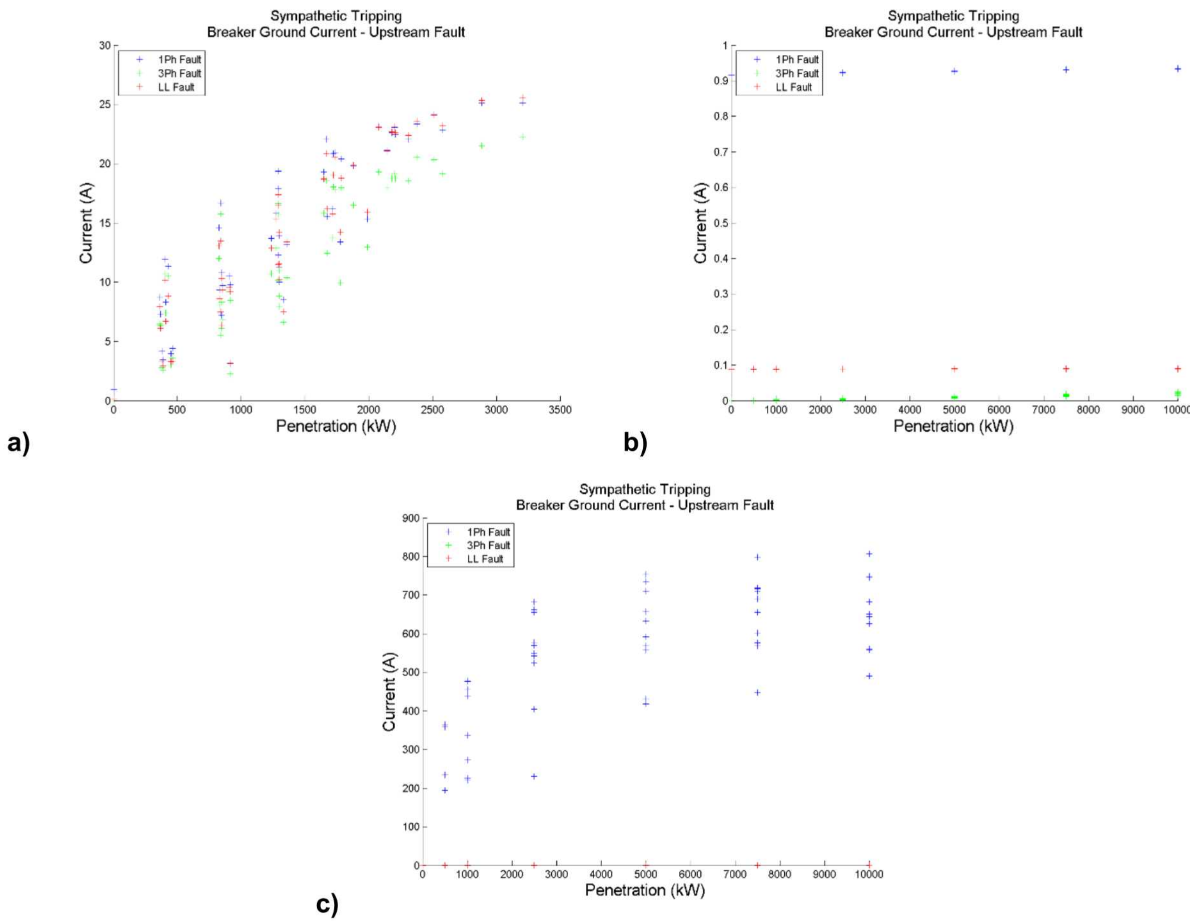



**Figure 2-11**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV Ungrounded Transformer c) Large-Scale PV Grounded Transformer**

Figure 2-12 shows the breaker reduction in reach (sensitivity). Higher penetration of PV makes it more difficult for the breaker to sense remote feeder faults. The ground source large-scale scenario is the most problematic. The small-scale impact is tightly correlated indicating independence from PV location. Large-scale PV is more dependent on PV location due to the more remote locations of systems analyzed.

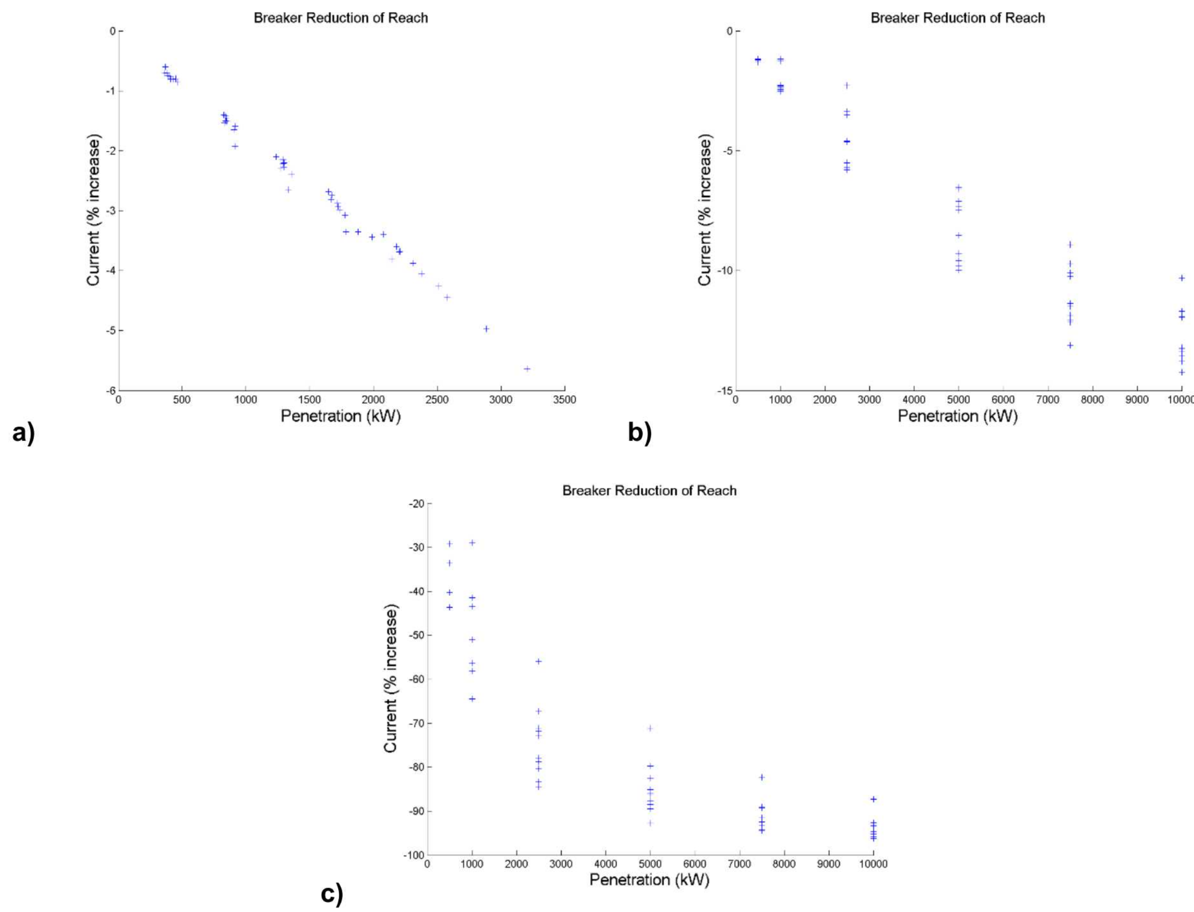
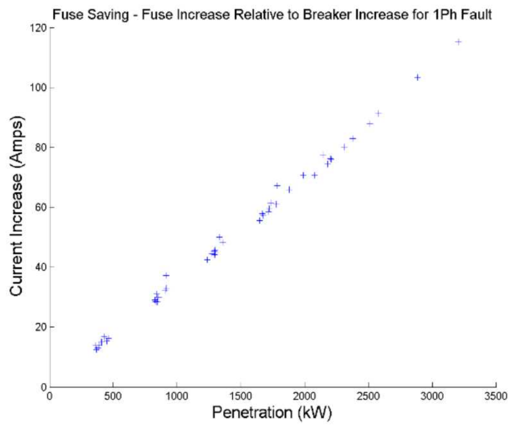
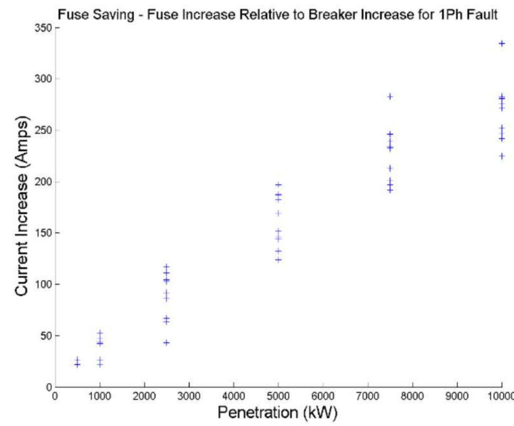



**Figure 2-12**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV Ungrounded Transformer c) Large-Scale PV Grounded Transformer**

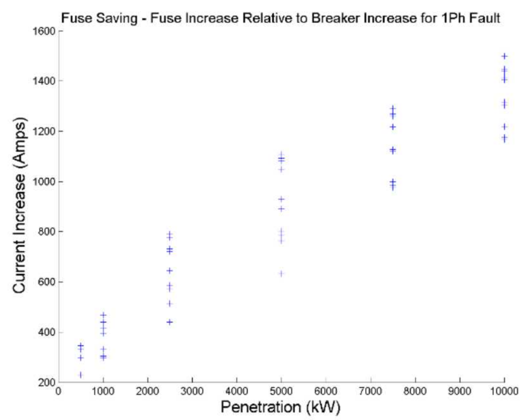
Figure 2-13 shows the fuse coordination impact from distributed PV. Higher penetration increases the potential current flowing through fuses, which could potentially cause those elements to operate more quickly than originally designed based on their time-current curves. There is a tight trend in small-scale impact while large-scale can be more location dependent.




a)




b)




c)

**Figure 2-13.**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV Ungrounded Transformer c) Large-Scale PV Grounded Transformer**

# 3

# AGGREGATED RESULTS

Hosting capacity is calculated separately for each potential issue on each feeder. The summary of hosting capacity for each feeder and correlations to feeder characteristics are provided in this section. The primary issues used to identify hosting capacity include:

- Overvoltage
- Voltage deviation
- Element fault current
- Breaker reduction of reach
- Sympathetic breaker tripping
- Breaker/fuse coordination

Several additional metrics have been removed from the hosting capacity summary due to significant impact that would immediately limit hosting capacity. These metrics include:

- Anti-islanding
- Large-scale PV protection issues with grounded wye-delta interconnect transformer

Anti-islanding hosting capacity in this analysis is only a function of line loading, thus the aggregate PV hosting capacity varies from near zero on lightly loaded sections to 50% of minimum load if located just below the feeder head. Large-scale PV connected through a grounded wye-delta transformer causes all fault current-based issues to be problematic at very low penetration levels. Therefore, the hosting capacity based on these issues is not shown.

The additional metrics found have low impact to hosting capacity include:

- Voltage imbalance
- Overloads
- Harmonics

Based on the method for PV deployment, voltage imbalance typically decreases and overloads seldom occur. This is strongly influenced by limiting the PV size to the customer peak load in the small-scale analysis. For balance large-scale PV, voltage imbalance seldom occurs, however, the PV systems do have a slight potential to cause overloads. Harmonic issues are strongly influenced by load and existing resonance rather than PV penetration.

## Small-Scale PV Hosting Capacity

The issue specific results shown in Figure 3-1 illustrate the range in hosting capacity across the three utilities. The feeders chosen for each utility had been selected based on different feeder clusters. The result of choosing feeders with different characteristics is a reason why there is a range of low to high impact across each utilities set of feeders. Hosting capacities are more PV location dependent for voltage issues (identified by greater yellow region).

The results also show that even though high impact feeders can be identified with the clustering analysis, two feeders that are highly susceptible to impact can accommodate different levels of PV. This is easily ascertained from the results for 440 and 2093. The issue specific hosting capacities are considerably different for several issues. Additionally, the high impact feeder 967 has low impact from PV with regards to protection.

A similar comparison between two feeders that have similar characteristics (967 and 683) shows that the hosting capacities are also different. These two feeders each have one line regulator, 12 kV class, ~6 MW peak load, and ~35 conductor miles. However, a closer look at additional model-based characteristics such as voltage headroom, resistance, and topology start to explain the differences in hosting capacity.

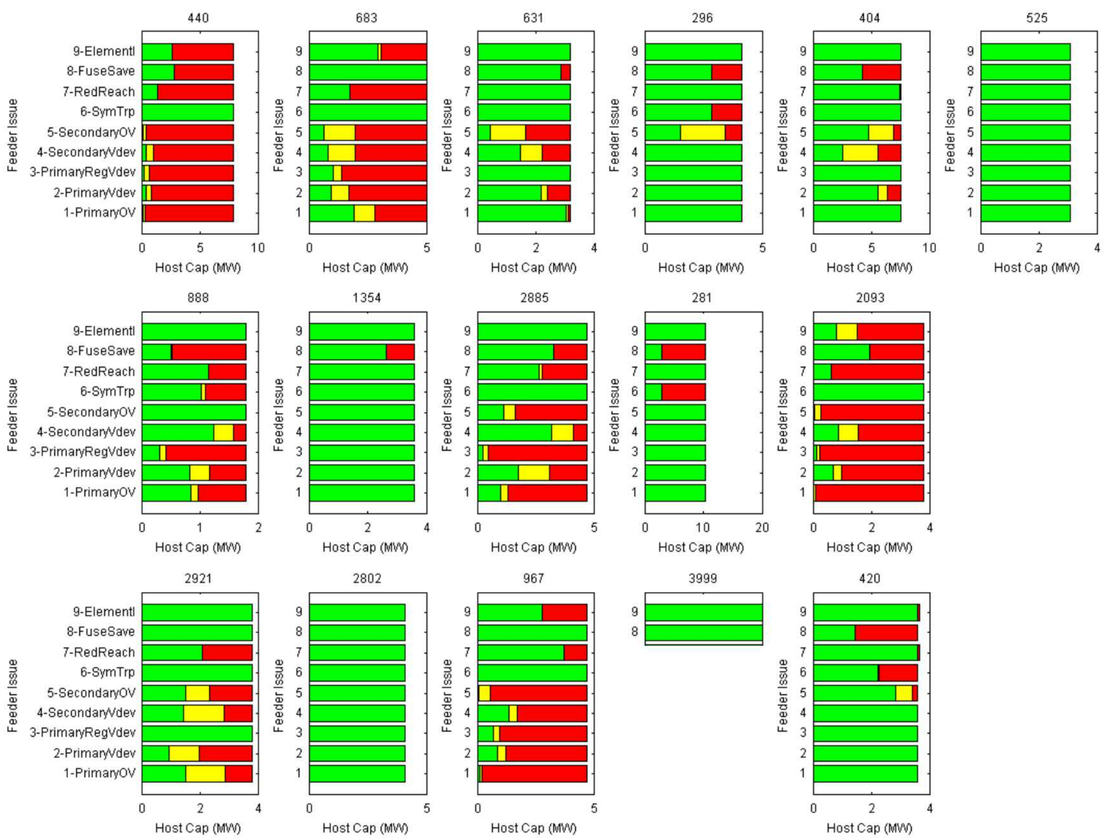



**Figure 3-1**
**Issue Specific Small-Scale PV Hosting Capacity**

*Note: Feeder 3999 is a solely industrial circuit and is not included in hosting capacity analysis for residential/ commercial PV deployment.

Figure 3-2 illustrates the minimum of minimum hosting capacities for all issues and the minimum of maximum hosting capacity for all issues. Feeder 3999 only has several industrial customers, so there are no results in the small-scale PV analysis. Again, all feeders have different hosting capacities and issues that arise with higher penetration.

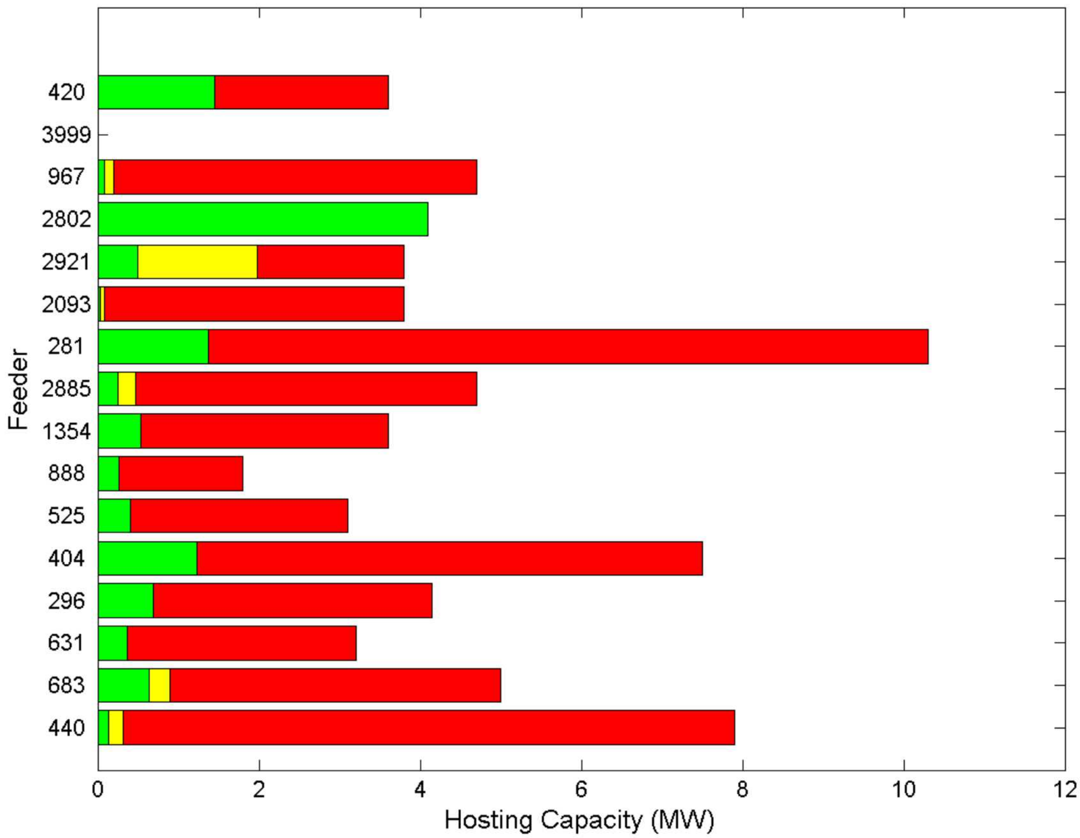



**Figure 3-2**
**Small-Scale PV Hosting Capacity**

*Note: Feeder 3999 is a solely industrial circuit and is not included in hosting capacity analysis for residential/ commercial PV deployment.

### *Hosting Capacity with Respect to Feeder Characteristics*

All hosting capacities are compared to each feeder characteristic. This helps identify strong correlations and trends in hosting capacity based on specific characteristics. All characteristics impact the feeder operation and ultimately have an impact on hosting capacity. The strongest of correlations occur for voltage class and resistance. Figure 3-3 illustrates the minimum hosting capacity of each feeder/issue with respect to the voltage class. If no hosting capacity limit occurred, no marker is shown for the feeder/issue. The blue, red, and green markers indicate results for the three different utilities. Lower voltage class generally has lower hosting capacity for primary node voltage and protection issues. Voltage class has less of an impact on secondary node voltage issues.

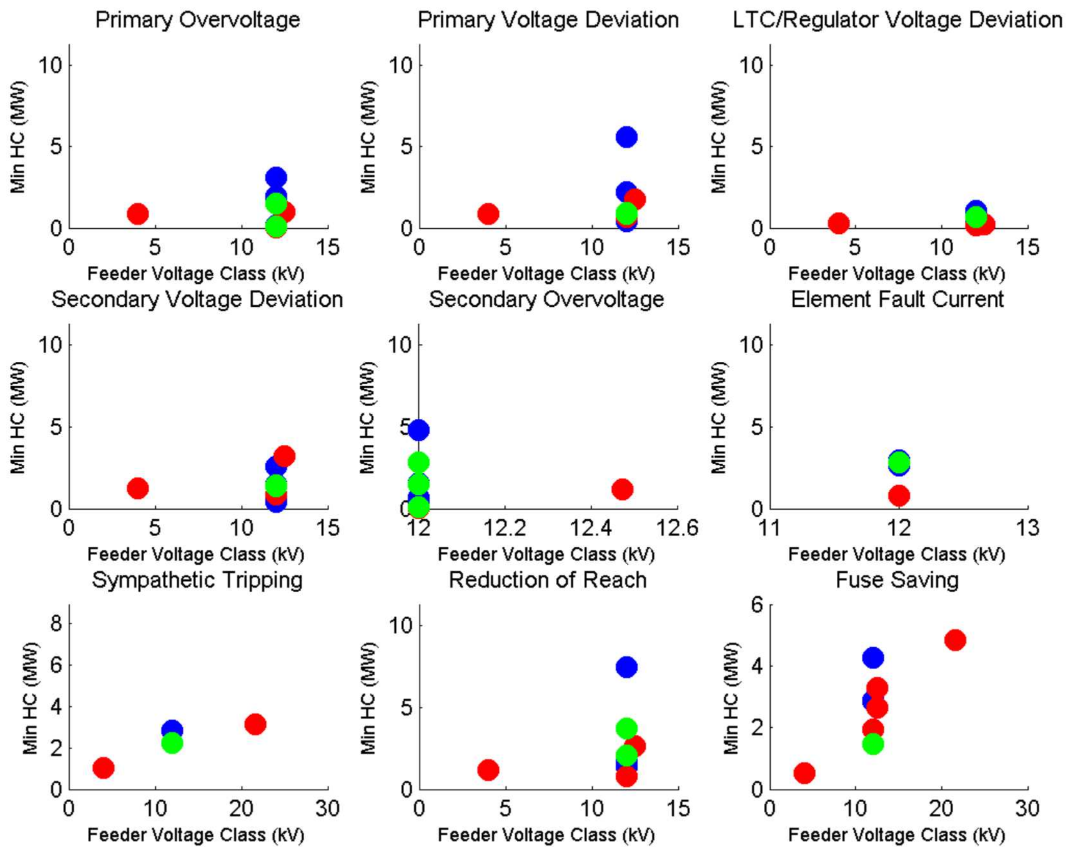



**Figure 3-3**
**Minimum Hosting Capacity with Respect to Feeder Voltage Class**

Figure 3-4 illustrates the minimum hosting capacity of each feeder/issue with respect to the PV location (resistance). Other feeder resistance characteristics can also show correlations, but the PV location is the strongest. The correlation is also dependent on voltage class. The evident trends are based on the large number of analyzed 12 kV class feeders. The trends are best for voltage-based issues, while the correlation is weaker for protection-based issues. Another significant factor reducing LTC/Regulator Voltage Deviation hosting capacity is the use of line drop compensation.

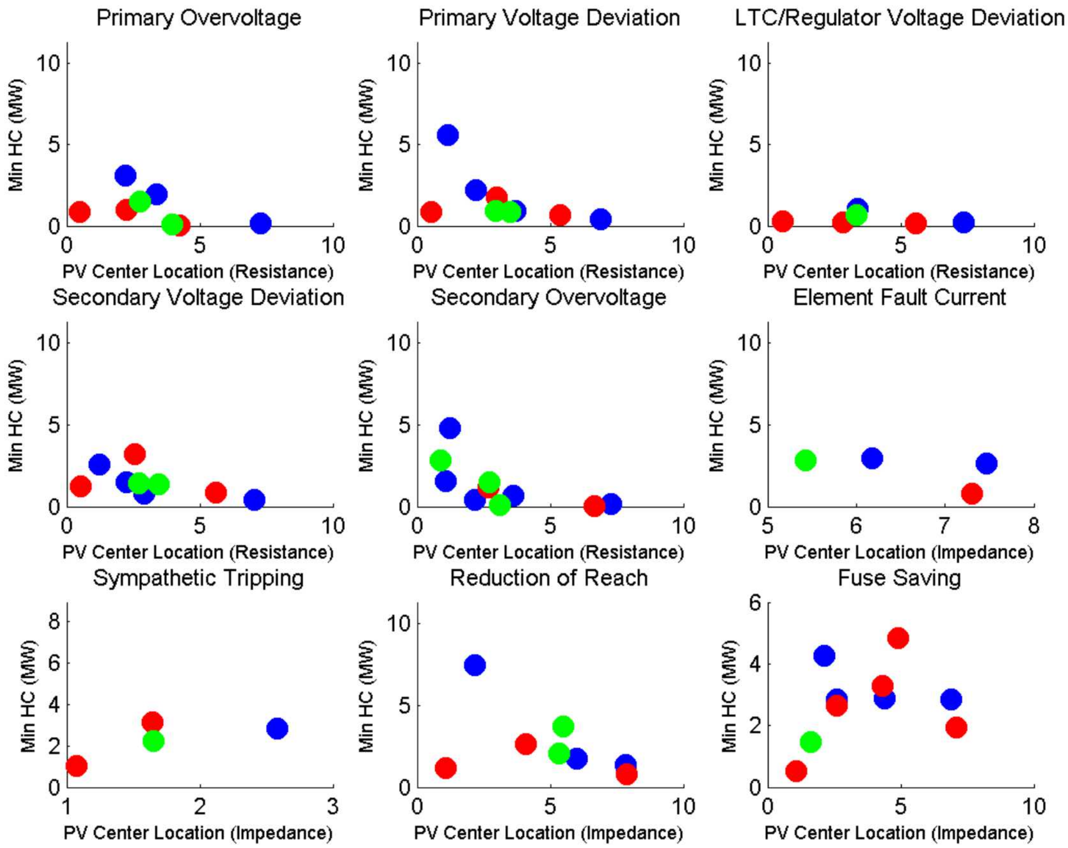



**Figure 3-4**
**Minimum Hosting Capacity with Respect to PV Location**

Figure 3-5 and Figure 3-6 are shown to illustrate the independence of hosting capacity based on feeder head 15% peak and 100% minimum load, respectively. The lines in the figures illustrate the theoretical hosting capacity based on the set percent of load. The load screens can both over- and under-estimate the feeder's ability to accommodate PV.

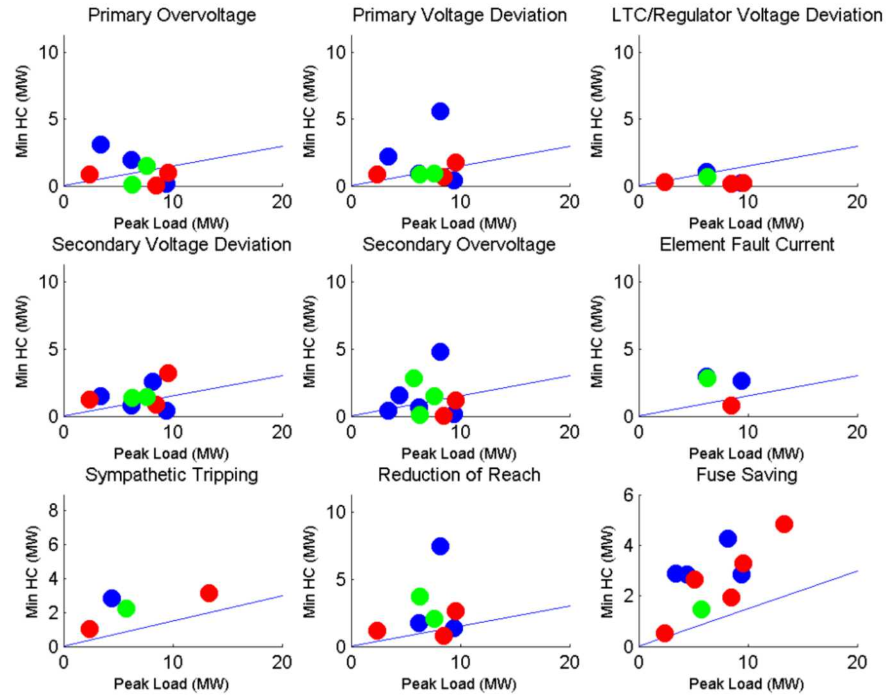



**Figure 3-5**
**Minimum Hosting Capacity with Respect to 15% Peak Load**

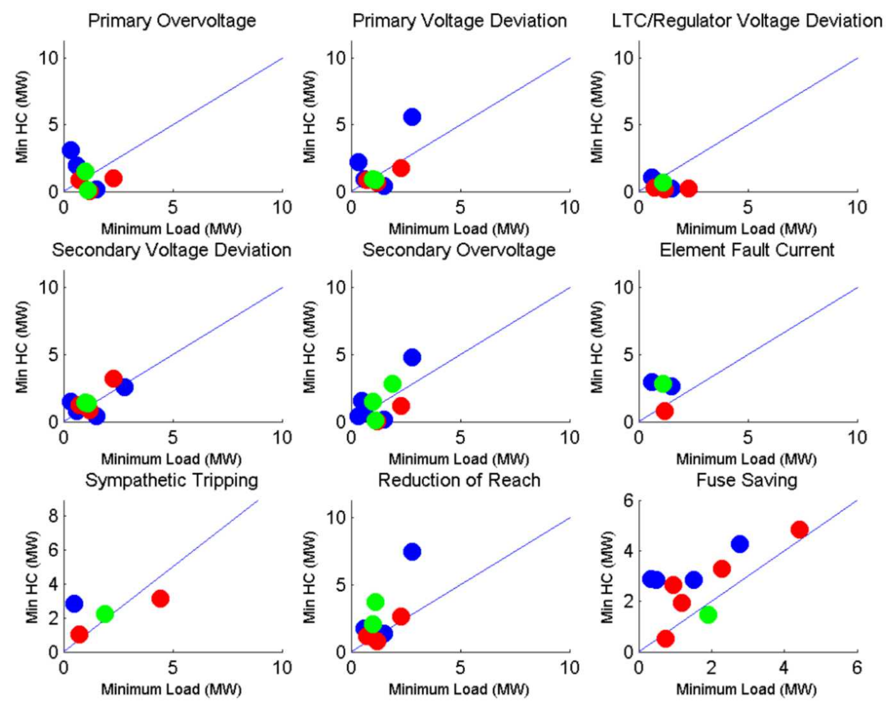



**Figure 3-6**
**Minimum Hosting Capacity with Respect to 100% Minimum Load**

### *Voltage Deviation Hosting Capacity with Respect to PV Location*

Figure 3-7 further illustrates the hosting capacity dependence on PV location. Connected lines indicate the maximum/median/minimum hosting capacity on a feeder for primary voltage deviation. When any of the hosting capacities do not exist, no points are displayed. There is a general exponential decrease in hosting capacity as PV location increases. There is one general trend indicating the most common voltage class. The outlying red markers occur for the 4 kV class feeder.

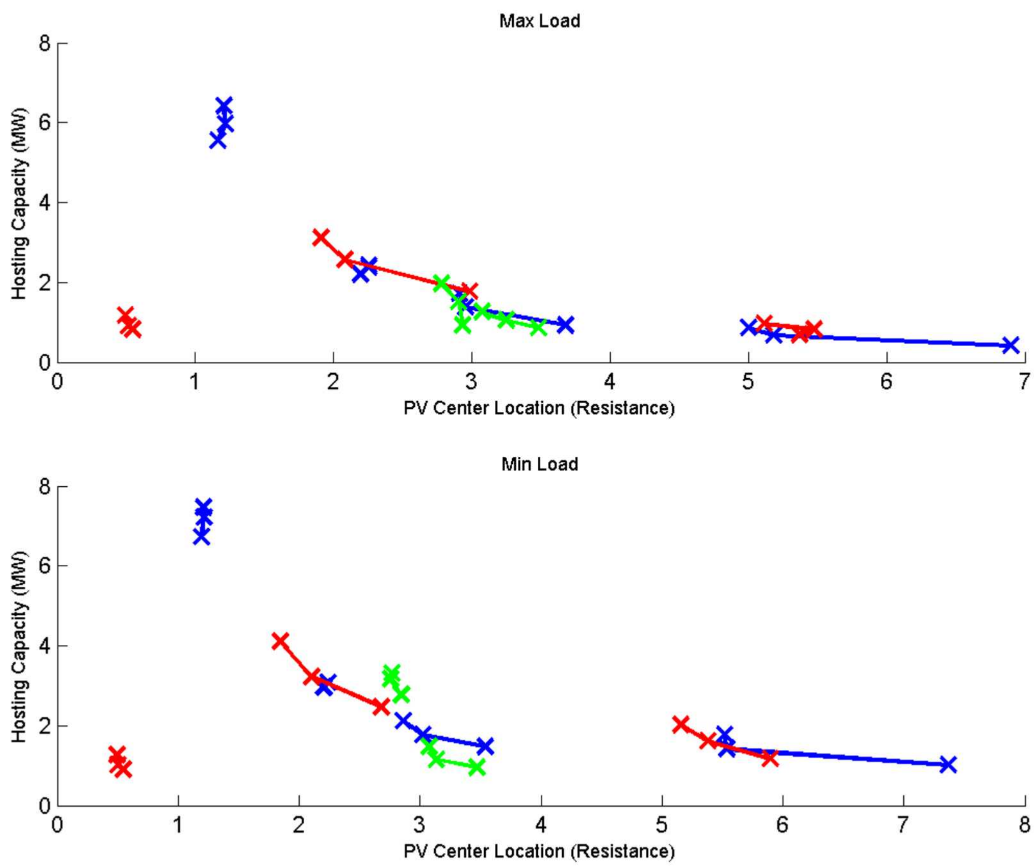



**Figure 3-7**
**Minimum/Median/Maximum Primary Voltage Deviation Hosting Capacity with Respect to PV Location**

### *Violation Location with Respect to PV Location*

Violation locations for minimum hosting capacity can be correlated to the location of the PV on the feeder as shown in Figure 3-8. The violation is typically electrically close to the PV location for voltage related issues. However, since the PV location is a value calculated based on many individual systems, the violation location can be influenced by one or more individual systems in specific areas. Element fault current violations are typically close to the aggregate PV location since the aggregate location can effectively identify where 50% of the PV is closer-in/further-out. Reach violations are further-out on the feeders than the PV center. Fuse violations are typically closer-in to the substation where all PV can contribute fault current.

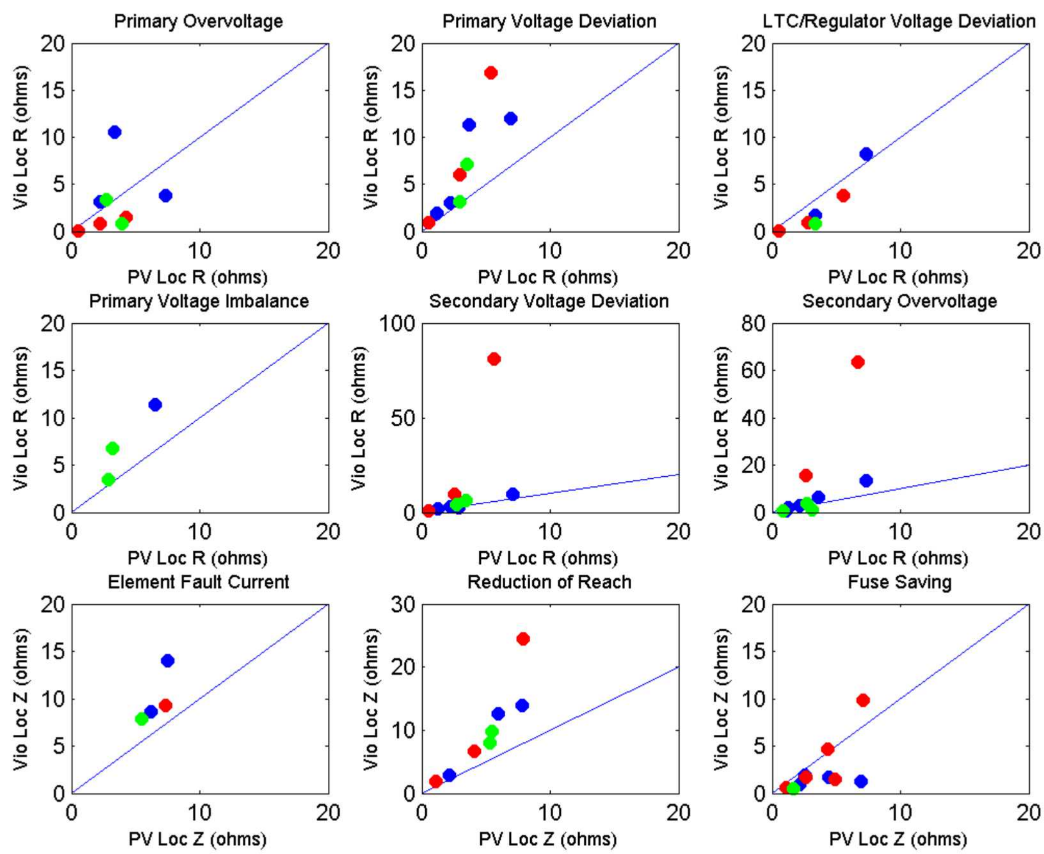



**Figure 3-8**
**Violation Location with Respect to PV Location**

### *Loading Level Impact on Hosting Capacity*

The load level does not have a direct correlation to hosting capacity, but as shown in Figure 3-9, the load does have an influence. Connected lines indicate the minimum hosting capacity of a feeder at the four load levels analyzed. Generally, voltage deviation-based hosting capacity decreases with higher load. At higher load, voltages on the feeders are typically lower and thus the constant power PV current output will be slightly elevated. Conversely, overvoltage-based hosting capacity typically increases with increased load due to lower feeder voltages and more voltage headroom. However, when line drop compensation exists, the overvoltage-based hosting capacity decreases with higher load since regulator voltages are higher during peak load. This commonly occurs for feeders with results colored red.

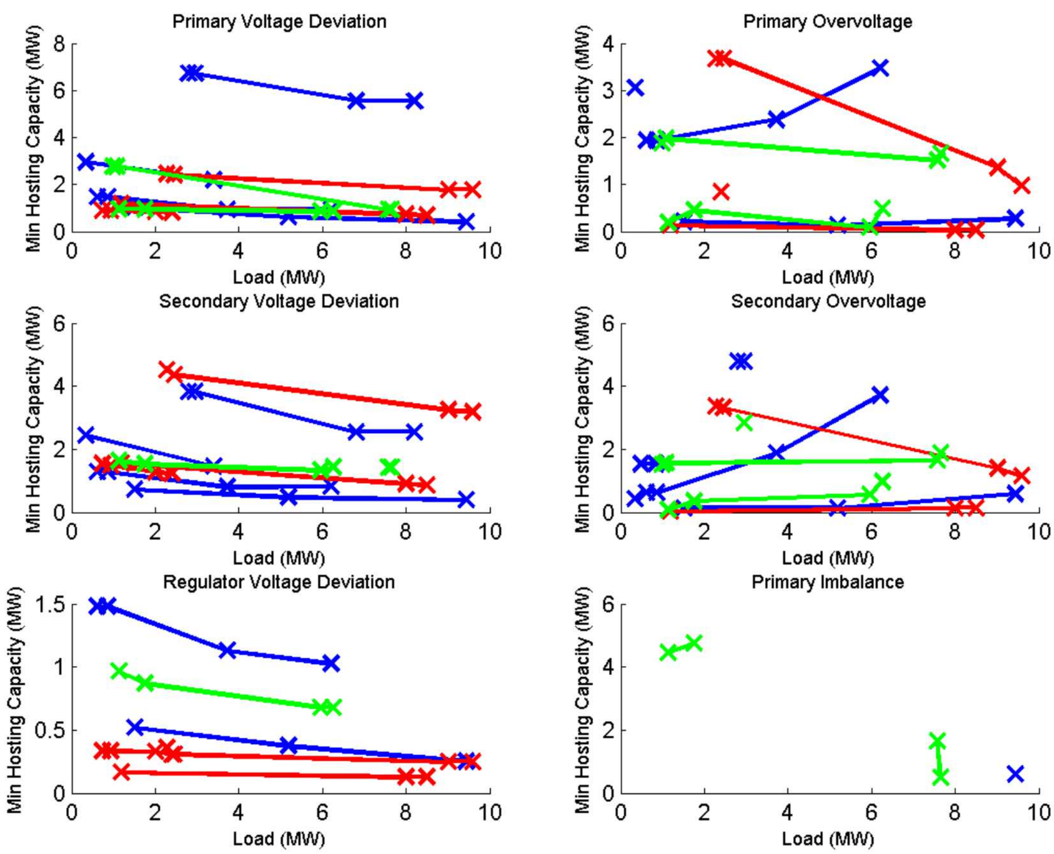



**Figure 3-9**
**Load Level Impact on Voltage-Based Hosting Capacity**

### *Harmonics*

The harmonics on a feeder can be impacted by the addition of PV. The change in harmonics and total harmonic distortion are shown in Figure 3-10. The impact is generally low, in some instances beneficial, but can be adverse during low loading or when there are more resonant conditions. The occurrence of these resonant conditions at low load is less likely since capacitors typically are offline at those times.

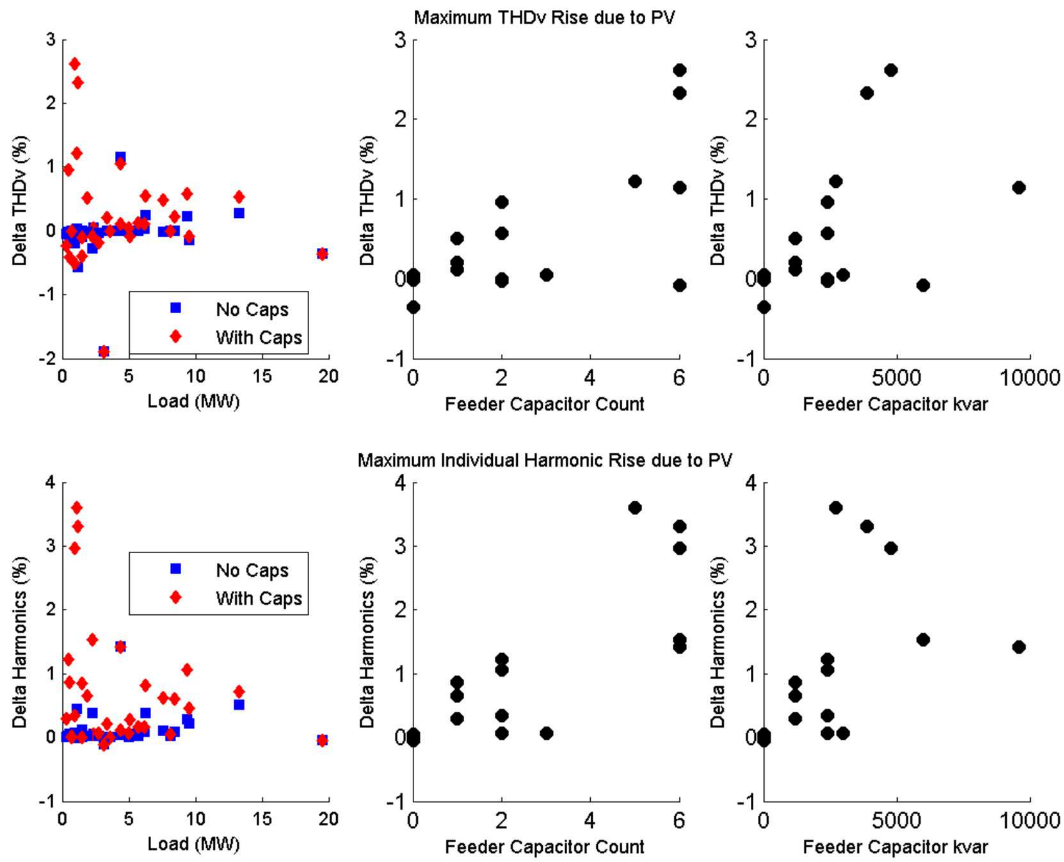



**Figure 3-10**
**Harmonics Impacted by Load/Capacitor Count/Reactive Compensation**

## Large-Scale PV Hosting Capacity

The issue specific large-scale PV hosting capacity results are shown for all feeders in Figure 3-11. The protection related issues shown are based on Grounded Wye-Grounded Wye interconnect transformers. The different feeders have drastically different hosting capacities. Across the different utilities, analyzed feeders such as 683 and 967 would fall into a similar cluster, however, the hosting capacities are still different.

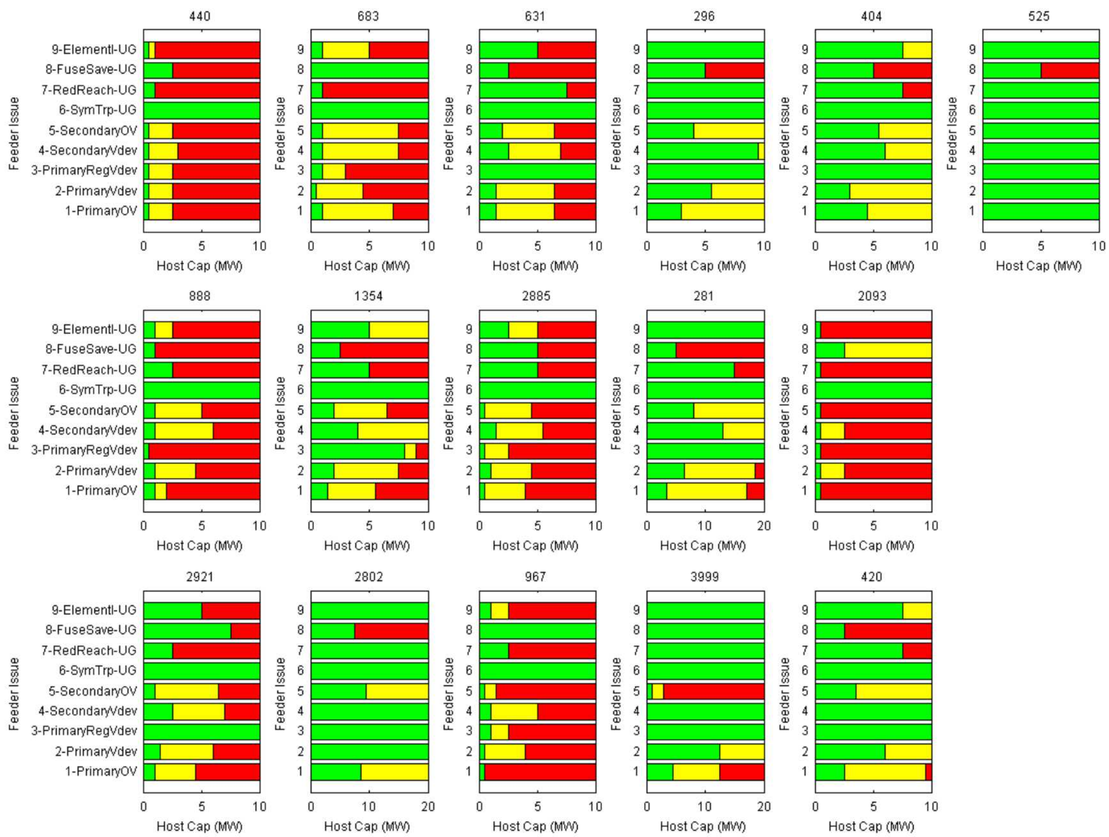



**Figure 3-11**
**Issue Specific Large-Scale PV Hosting Capacity**

Figure 3-12 identifies the overall range in hosting capacity for each feeder. The overall range is based on the minimum of minimums and minimum of maximums. Feeders above 15 kV are analyzed up to 20 MW penetration.

When the large-scale PV is interconnected to the distribution feeder with a grounded wye-delta transformer, there are considerably higher zero-sequence ground fault currents, thus significantly low hosting capacity due to potential protection issues. The PV interconnected with a transformer that blocks or limits zero-sequence currents has less protection-based issues. The overall hosting capacity for non-ground source is more commonly due to voltage-related issues and had a dependency on the PV location. The following figures only pertain to the non-ground source interconnect transformer.

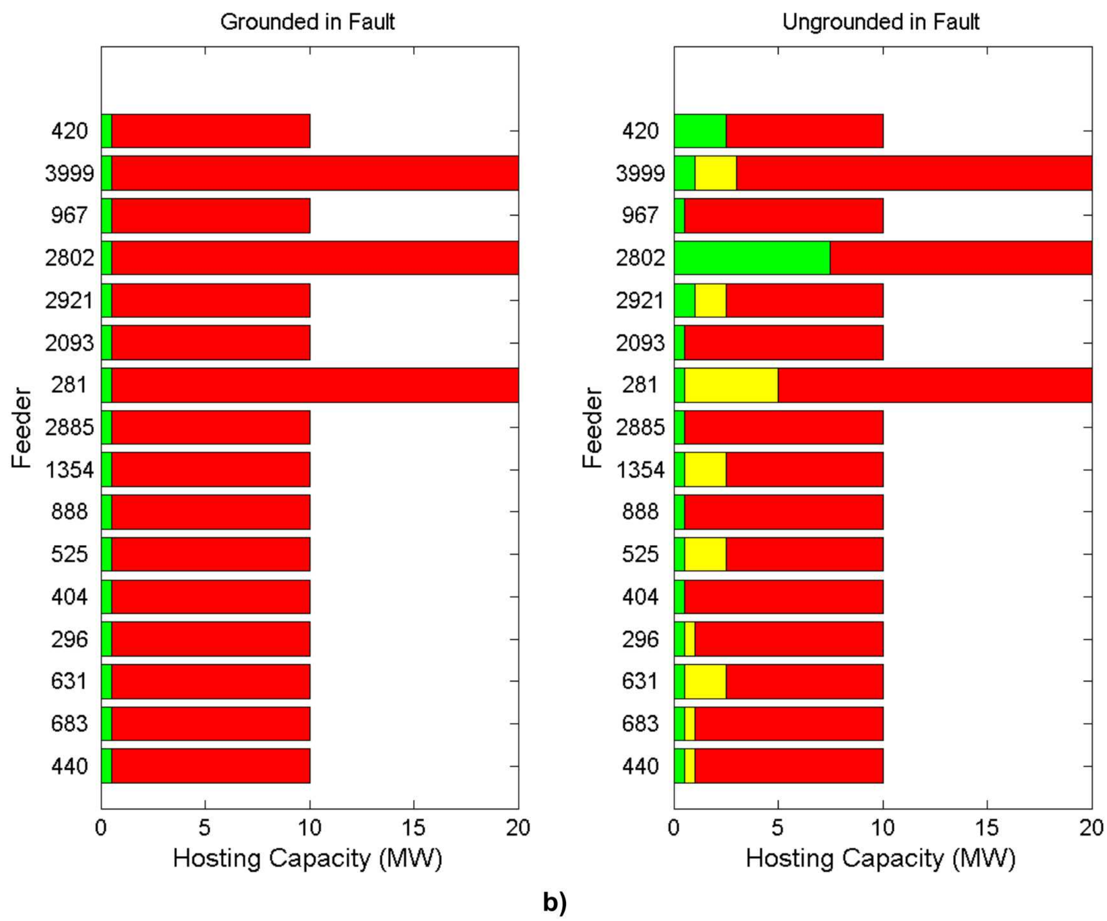



**Figure 3-12**
**Large-Scale PV Hosting Capacity a) Ground Source Interconnect Transformer b) Non Ground Source Interconnect Transformer**

### *Hosting Capacity with Respect to Feeder Characteristics*

The voltage class dependency of hosting capacity is shown in Figure 3-13. Most feeders analyzed are approximately 12 kV, but for the 4 kV and the 34.5 kV feeder, the hosting capacity can be seen lower/higher, respectively. The dependency on voltage class is greater for primary node voltage and penetration issues. Secondary node issues are less dependent on the primary voltage class. Sympathetic Tripping does not have any violations, thus the subplot is empty.

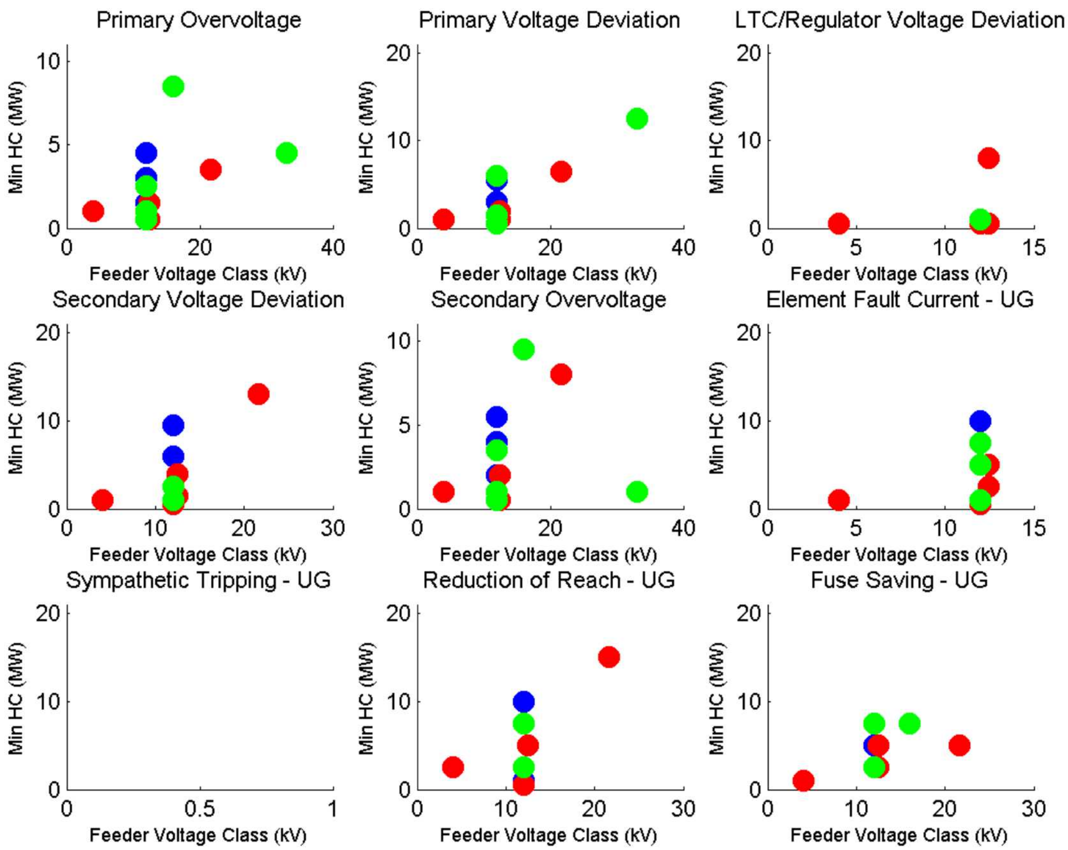



**Figure 3-13**
**Minimum Hosting Capacity with Respect to Feeder Voltage Class**

Within the 12 kV class feeders, there is considerable variation in the hosting capacity of a feeder. This variation shows that there are many other influencing factors that come into play. One additional factor that is significant is the resistance to the aggregate PV. The hosting capacity with respect to the aggregate PV location (resistance) is shown in Figure 3-14. There are stronger correlations in the large-scale PV analysis than in the small-scale PV analysis because the PV is more localized than distributed across the feeder at customer locations. The Element Fault Current shows there is more correlation with location of PV, while weak correlations remain for Reduction of Reach and Fuse Saving. Another significant factor reducing LTC/Regulator Voltage Deviation hosting capacity is the use of line drop compensation.

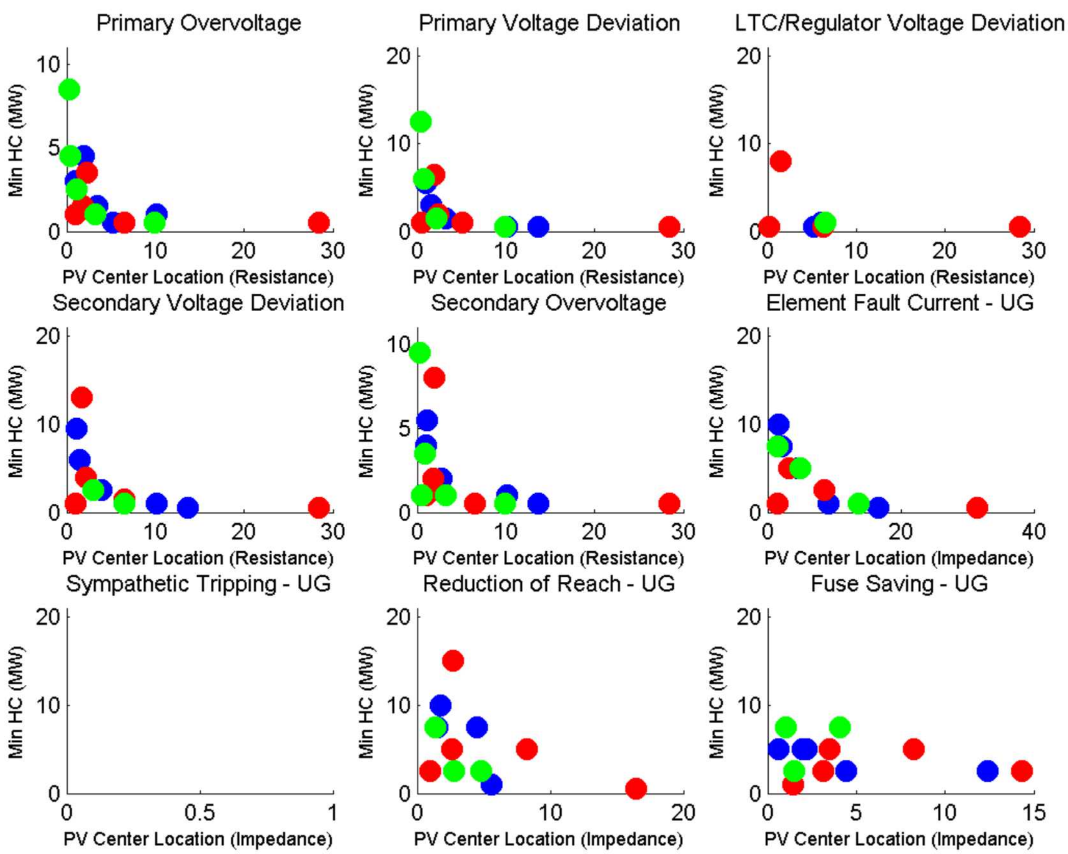



**Figure 3-14**
**Minimum Hosting Capacity with Respect to PV Location**

The percent of load screens illustrated in Figure 3-15 and Figure 3-16 over- and under-estimate each feeder's ability to accommodate PV. The screens can overestimate the hosting capacity for one issue and underestimate the hosting capacity for another (see hosting capacity for feeder with 20 MW peak load).

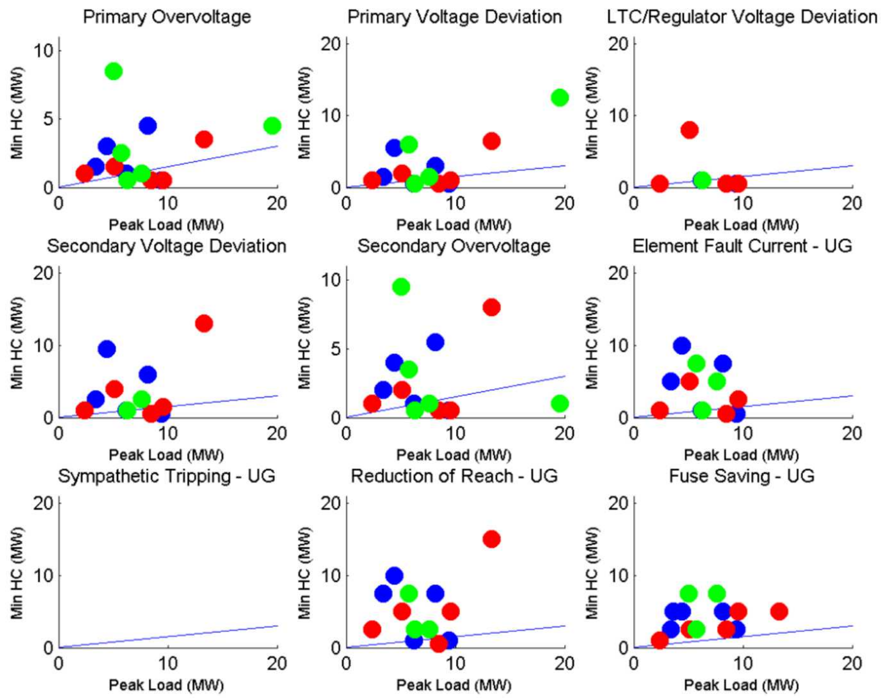



**Figure 3-15**
**Minimum Hosting Capacity with Respect to 15% Peak Load**

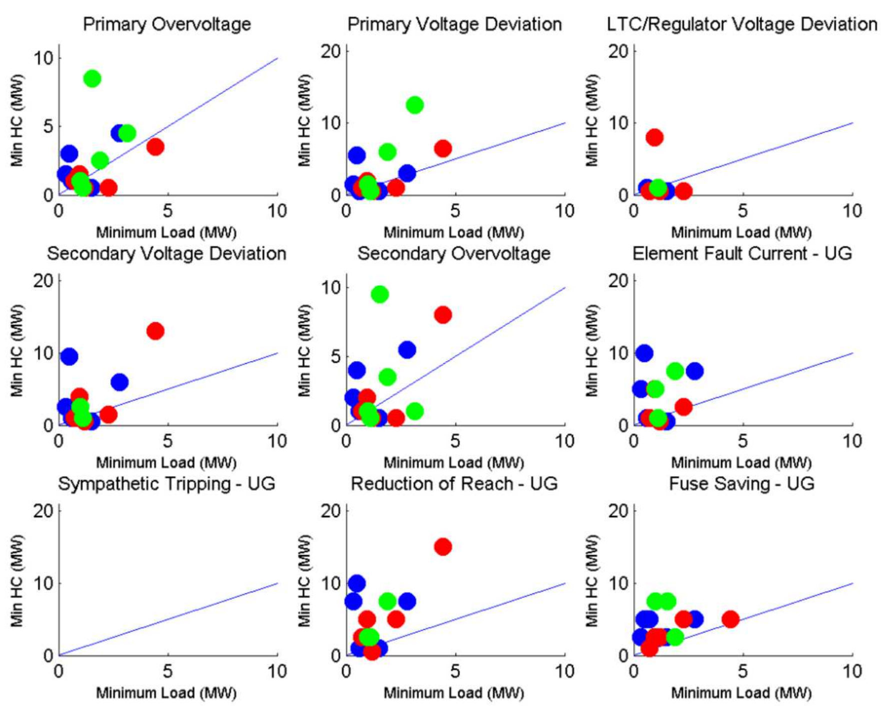



**Figure 3-16**
**Minimum Hosting Capacity with Respect to 100% Minimum Load**

### *Voltage Deviation Hosting Capacity with Respect to PV Location*

The voltage deviation hosting capacity correlation to PV location is more evident in the large-scale analysis as shown in Figure 3-17 because the PV is more centralized, closer/further from the substation, and pushed to higher penetrations.

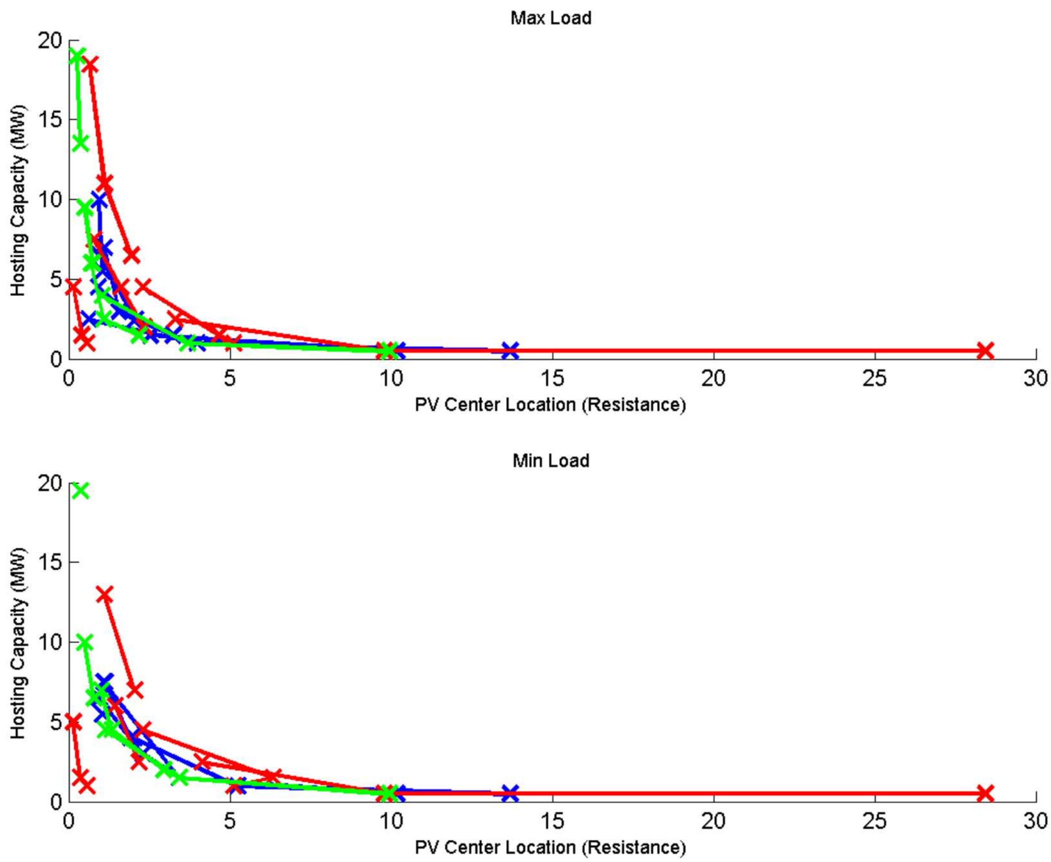



**Figure 3-17**
**Minimum/Median/Maximum Primary Voltage Deviation Hosting Capacity with Respect to PV Location**

### *Violation Location with Respect to PV Location*

The centralized location of the PV in the large-scale analysis also provides closer correlations with respect to violation location as shown in Figure 3-18. Voltage related issues typically occur near the PV location with the exception of LTC/Regulator Voltage Deviations which are typically closer to the substation. Some high penetration overvoltage issues occur near the substation and are independent of the PV location of the feeder. Secondary violations occur due to voltage change occurring on the primary and are typically close to the PV. Element Fault Current issues are typically near the PV, Reach issues are typically downstream, and Fuse issues are typically upstream.

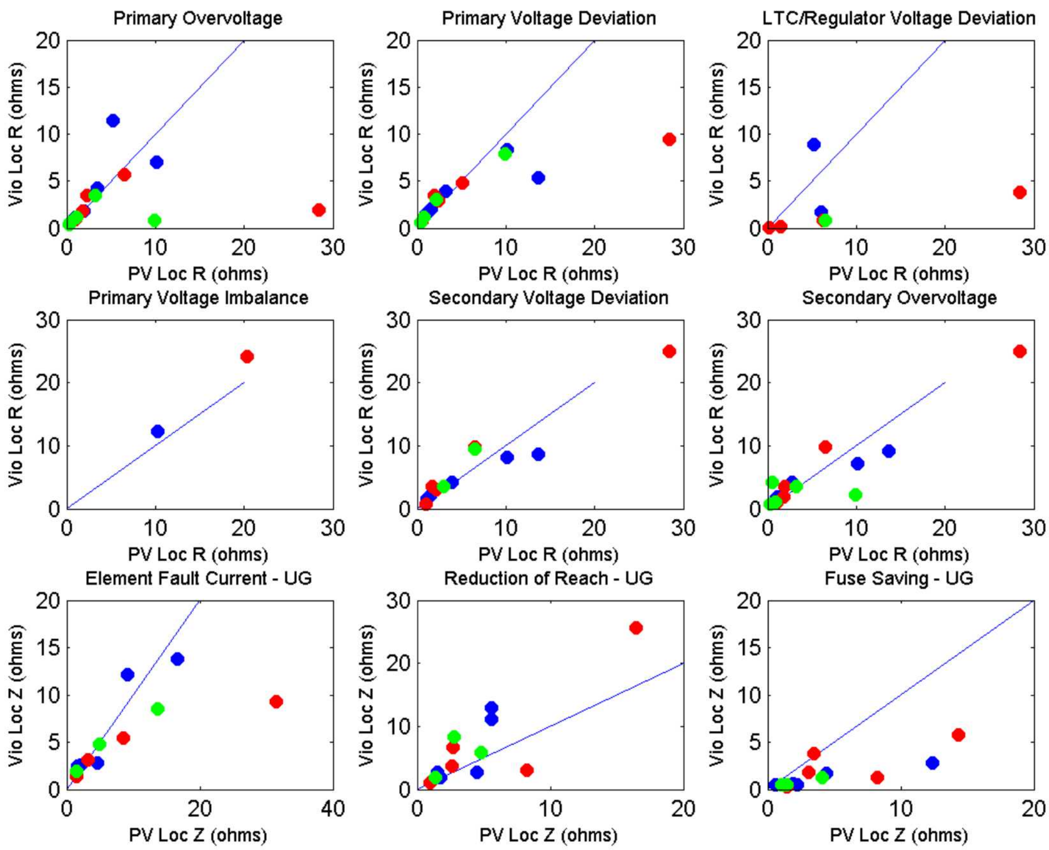



**Figure 3-18**
**Violation Location with Respect to PV Location**

### *Loading Level Impact on Hosting Capacity*

Similar to small-scale PV results, increase in loading generally decreases voltage deviation hosting capacity, while increasing overvoltage hosting capacity as shown in Figure 3-19. Overvoltage hosting capacity does tend to decrease with higher load when line drop compensation is utilized.

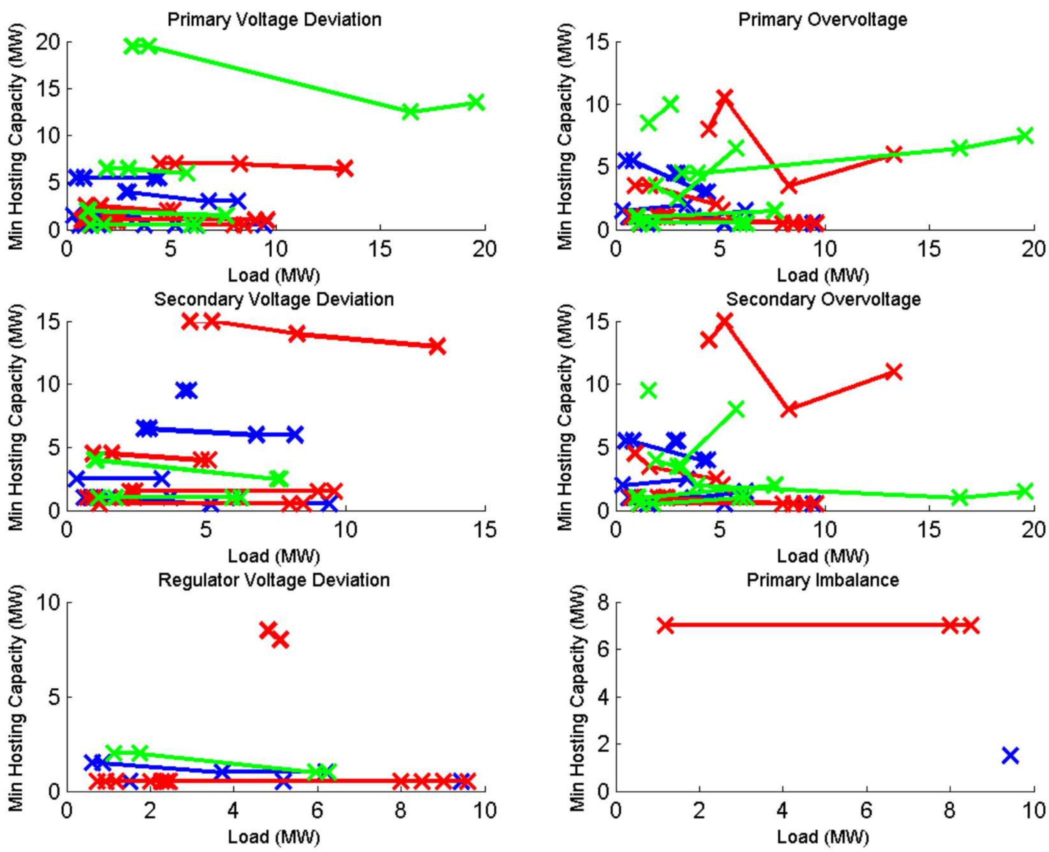



**Figure 3-19**
**Load Level Impact on Voltage-Based Hosting Capacity**

### *Harmonics*

High penetration of PV has a chance to increase harmonic distortion on the feeder. The maximum penetration (10 or 20 MW, depending on voltage class) is compared to the base case without PV to identify the change in harmonics. Figure 3-20 shows that significant increases in harmonics typically occur at minimum load (least damping) and in situations of high resonance. Again, these low load and high resonance conditions may be less likely to occur since capacitors are typically offline during low load.

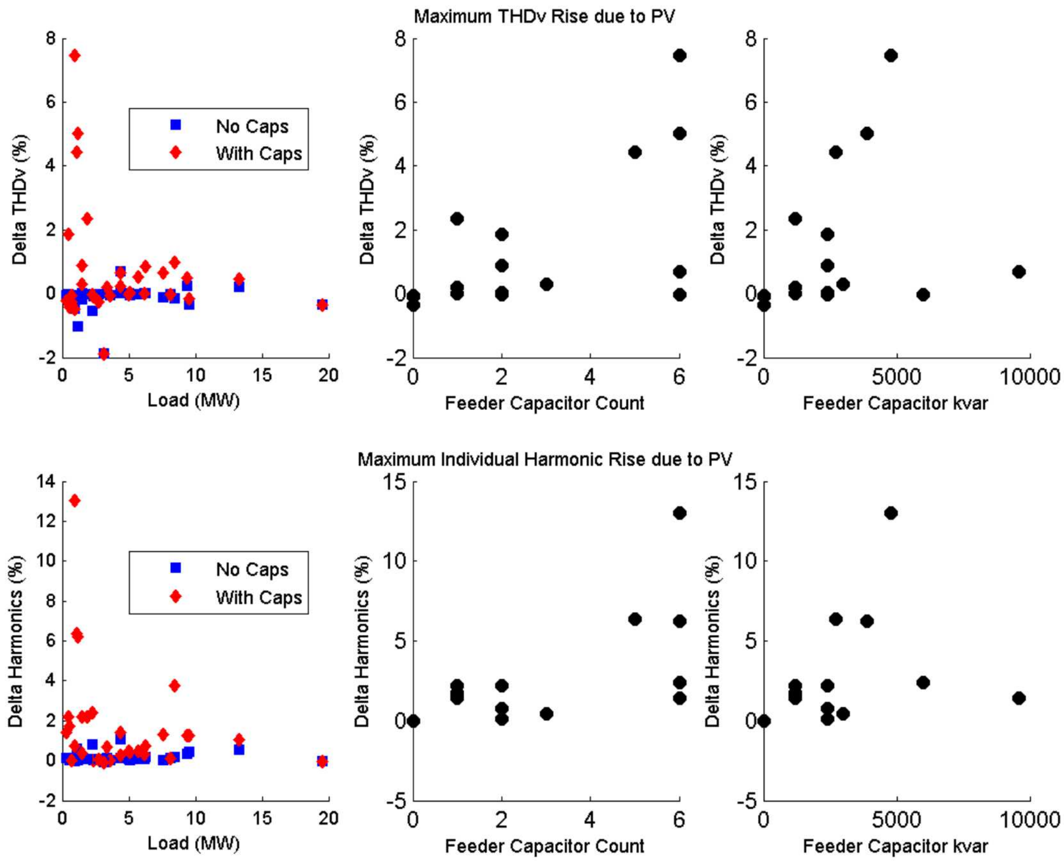



**Figure 3-20**
**Harmonics Impacted by Load/Capacitor Count/Reactive Compensation**

# 4

# CONCLUSION & INTRODUCTION MODIFIED SCREEN

The detailed feeder analysis has shown that the specific characteristics of the feeder under study have a significant influence on the impact from photovoltaics. The feeders analyzed for each utility cover a range in characteristics chosen to span the diverse set of feeders contained within each utility. Whether impact occurs can be generalized based on the characteristics of the feeders chosen; however, the magnitude of impact cannot be determined based solely on those characteristics. How those characteristics interact dynamically within the model ultimately dictate the amount of PV that can be hosted (accommodated). The different issues that possibly occur are also dependent on the feeder and how PV interacts with all elements.

The main factors influencing feeder impact from PV include:

- Feeder voltage class
- Feeder resistance
- PV system electrical location

The feeder impact from aggregate PV based on 15% of peak or 100 % of minimum daytime load is shown to typically be conservative compared to what the feeder can truly accommodate. Additionally, there are instances where the percent of load screen fails to identify an adverse penetration of PV.

The results determined through the detailed feeder analysis play a direct role in the improvement to the existing California P.U.C. Rule 21. Additional feeder characteristics will be used to update the fast track screening process to identify when interconnection requests should be examined more closely in supplemental review. Updates to Rule 21 supplemental review will also identify when higher levels of PV could be accommodated without initiating the detailed review process. Most of these updates to the supplemental review originate directly from the learnings of the detailed study. The updates will provide the utility additional guidance on the information/data and equations needed to make a better determination of the impact from aggregate levels of PV on a feeder.

# A
# DETAILED FEEDER RESULTS

## Feeder 440

The studied 12 kV feeder, is one of three served off the substation transformer. The measured SCADA total feeder demand is 9.4 MW. There are 110 primary feeder miles that extend a maximum length of 10 miles from the substation. There are approximately 1954 residential customers and 404 commercial customers on the feeder. The load center is near the substation. There is a substation load tap changer and six sets of three single-phase line regulators on the feeder. Each set of line regulators is gang operated and in a delta configuration. All regulators are modeled in a co-generation mode to maintain the 123V setpoint and 4V band at the low side tap (voltages referred to a 120V nominal base). The majority of single-phase service transformers are also connected line-line on the primary. There are three feeder capacitors, each 1200 kvar. A feeder voltage profile plot at peak load is shown in Figure A-1a). while a schematic illustrating system impedance is shown in Figure A-1b).

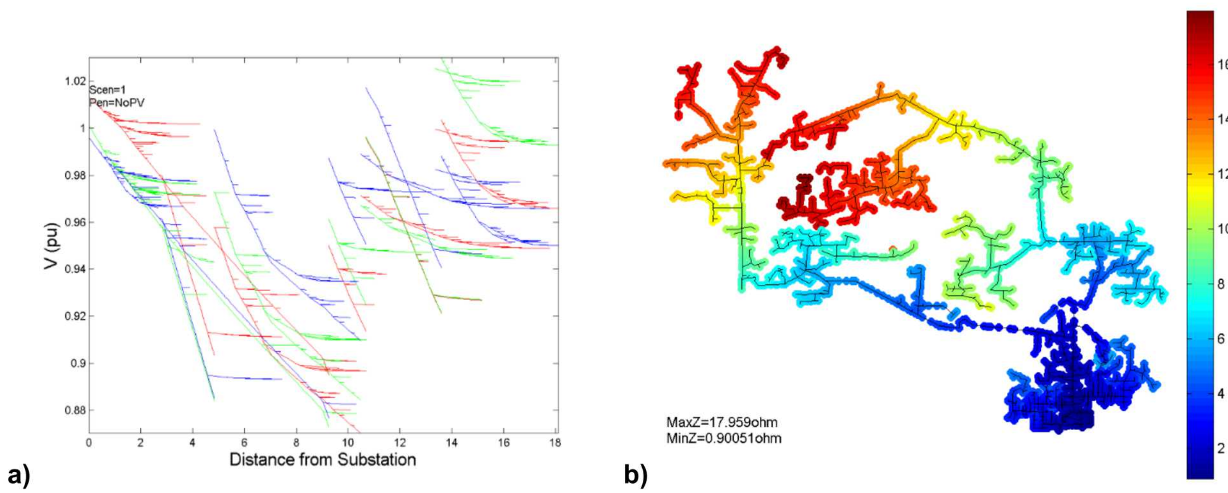
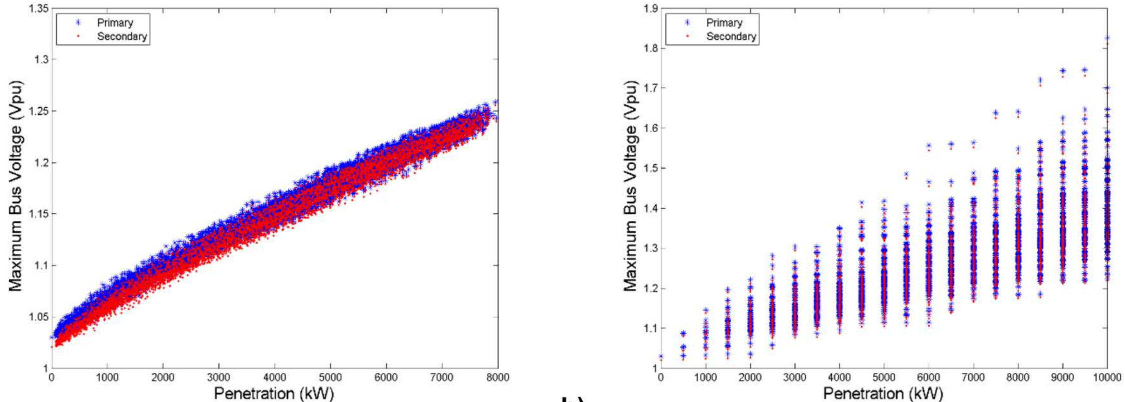


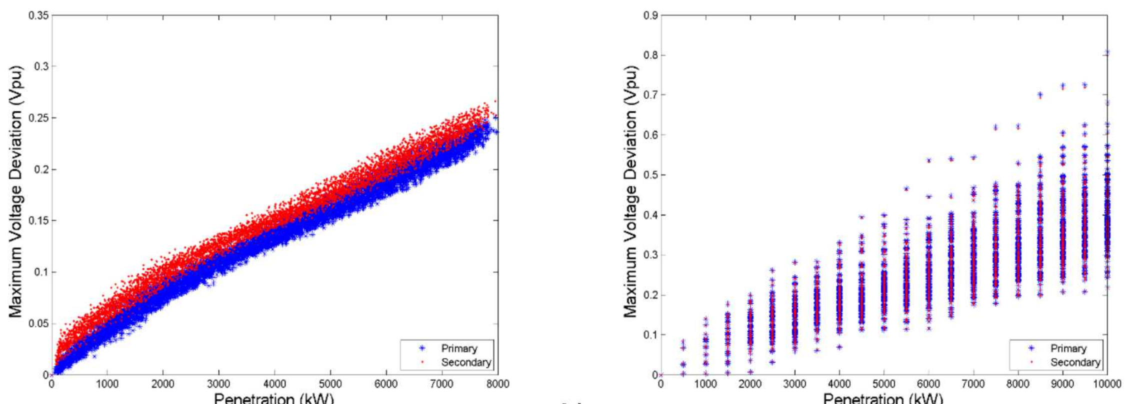

**Figure A-1**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

## *Voltage*



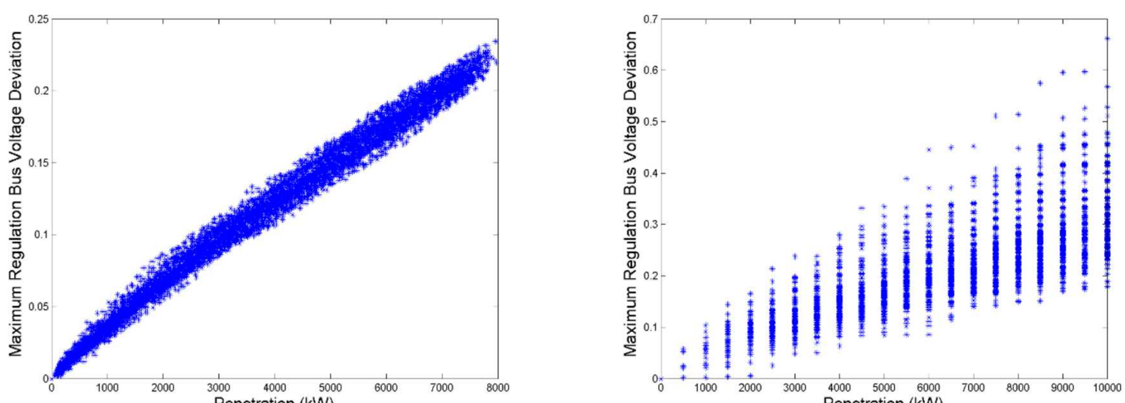

a) b)

**Figure A-2**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

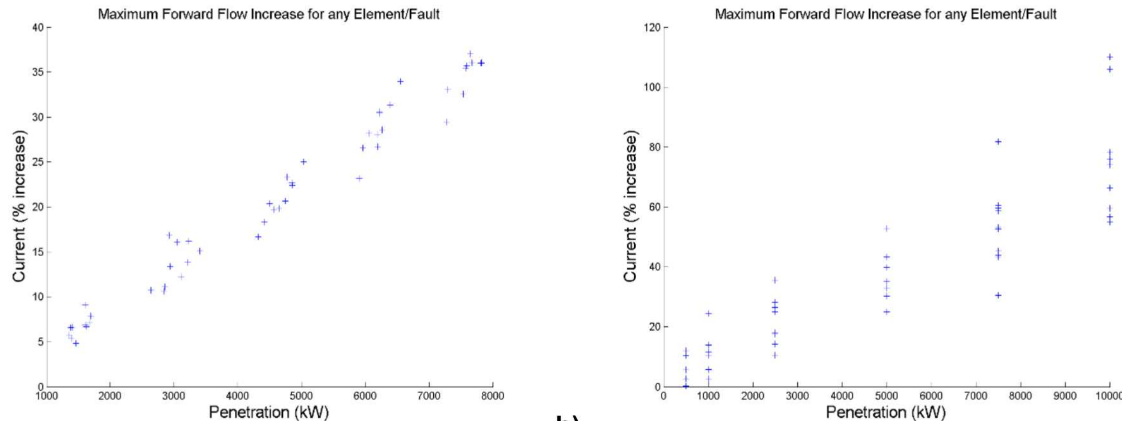
**Figure A-3**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

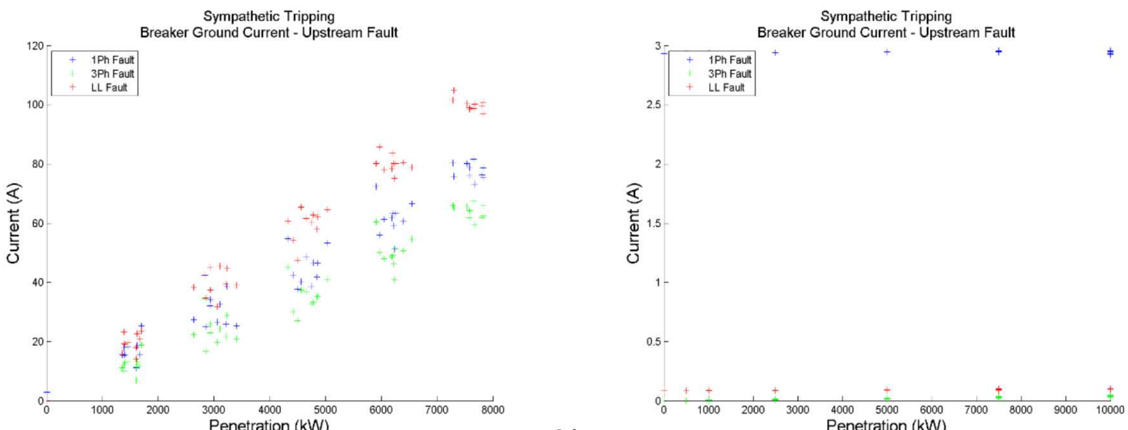
**Figure A-4**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*



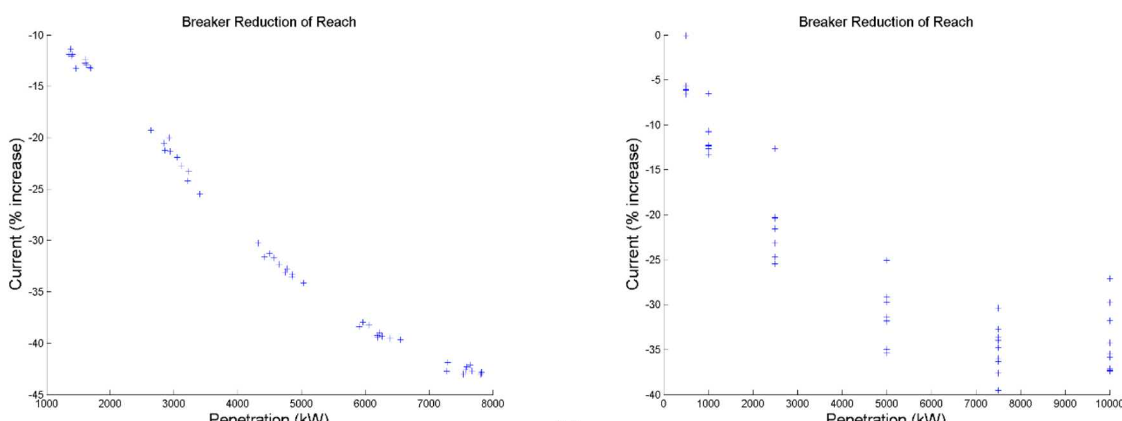

**a)** **b)**

**Figure A-5**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**



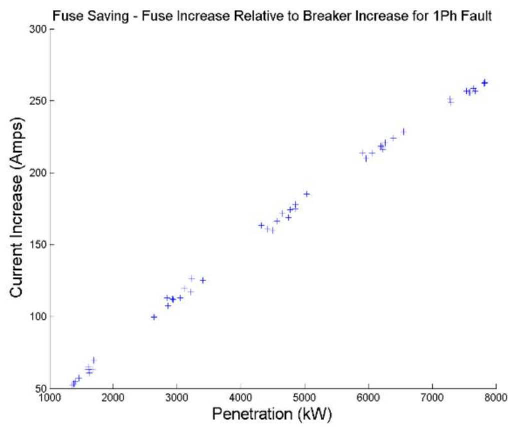

**a)** **b)**

**Figure A-6**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**

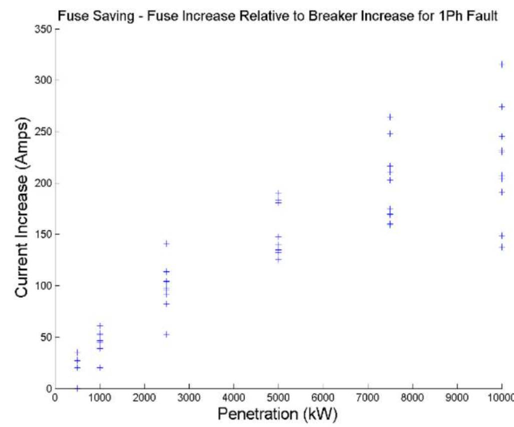



**a)** **b)**

**Figure A-7**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**




**a)**




**b)**

**Figure A-8**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

### Feeder 683

The studied 12 kV feeder peak load is 6.2 MW. There are 72 primary feeder miles that extend a maximum length of 11 miles from the substation. There are approximately 1107 residential customers and 132 commercial customers on the feeder. The substation three-phase LTC regulates voltage on the feeder. The LTC is modeled in a co-generation mode to maintain the 120.5 V setpoint and 3 V band at the low side tap. There is one feeder capacitor with 1200 kvar total compensation. The bank is voltage controlled with 119/123V on/off settings. There is one feeder regulator with 121 V setpoint and 4 V band. The voltage on the feeder is lower than typical because this feeder is controlled for conservation voltage reduction. A feeder voltage profile plot at peak load is shown in Figure A-9a, while a schematic illustrating system impedance is shown in Figure A-9b.

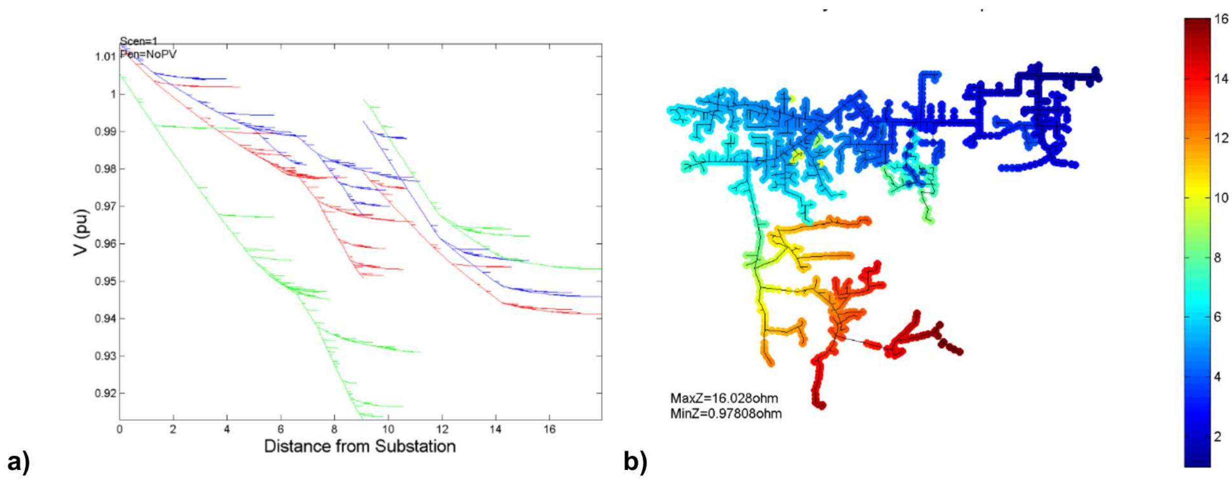



**Figure A-9**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

#### *Voltage*

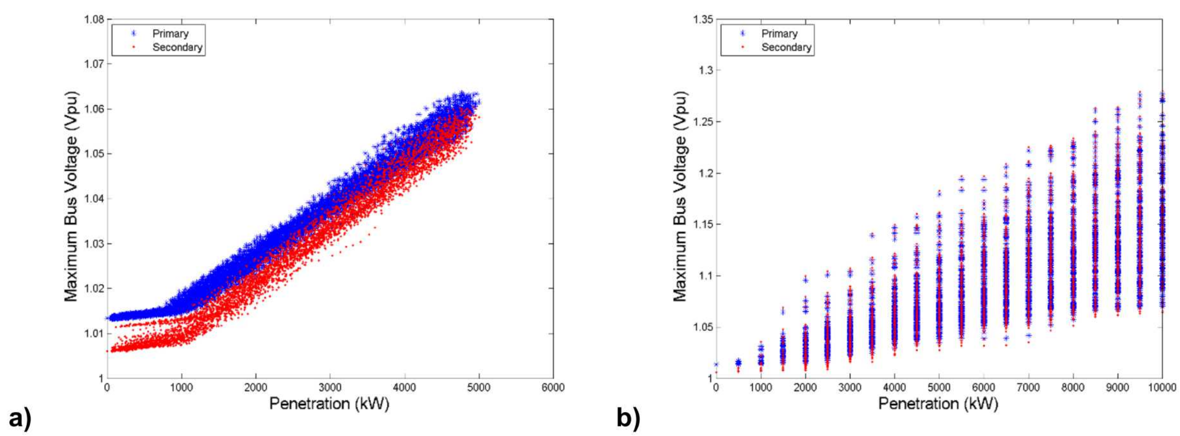
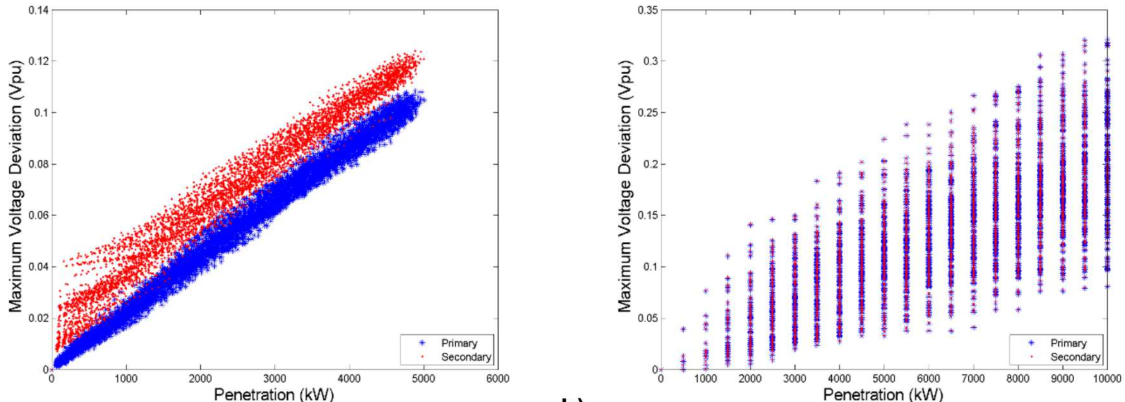
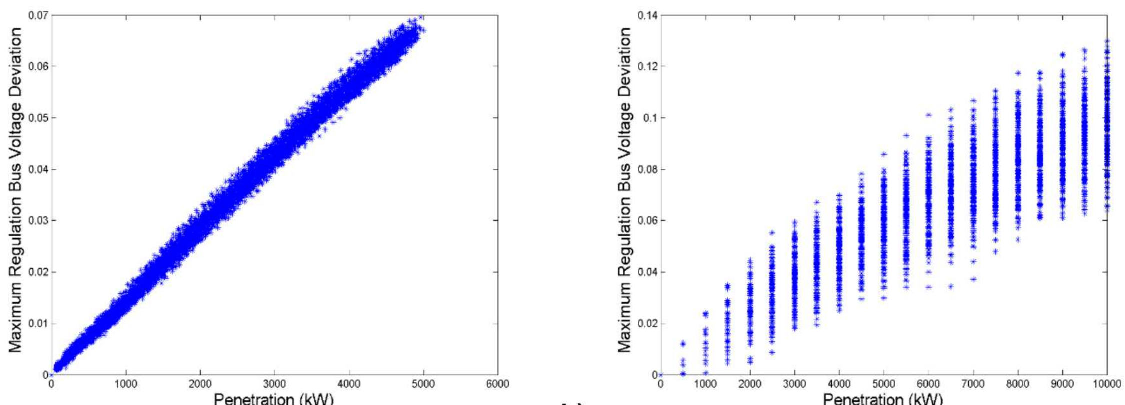



**Figure A-10**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

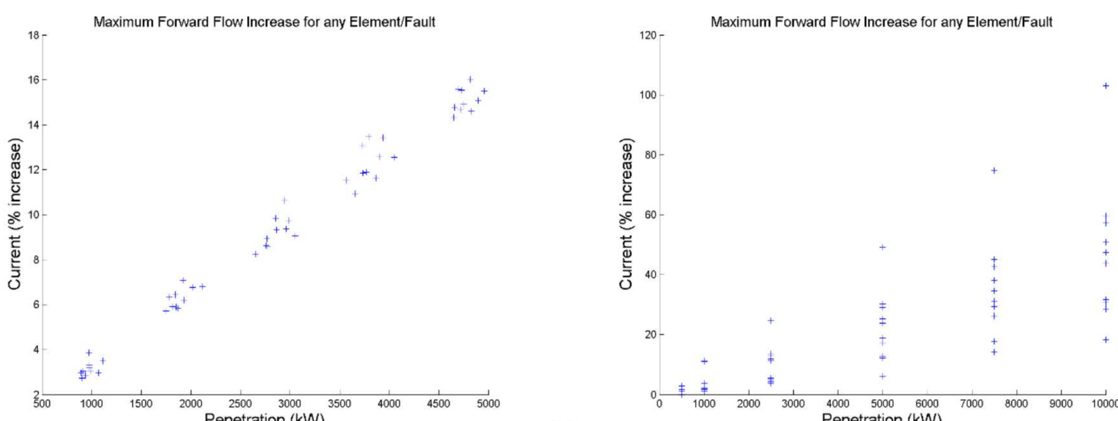
**Figure A-11**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

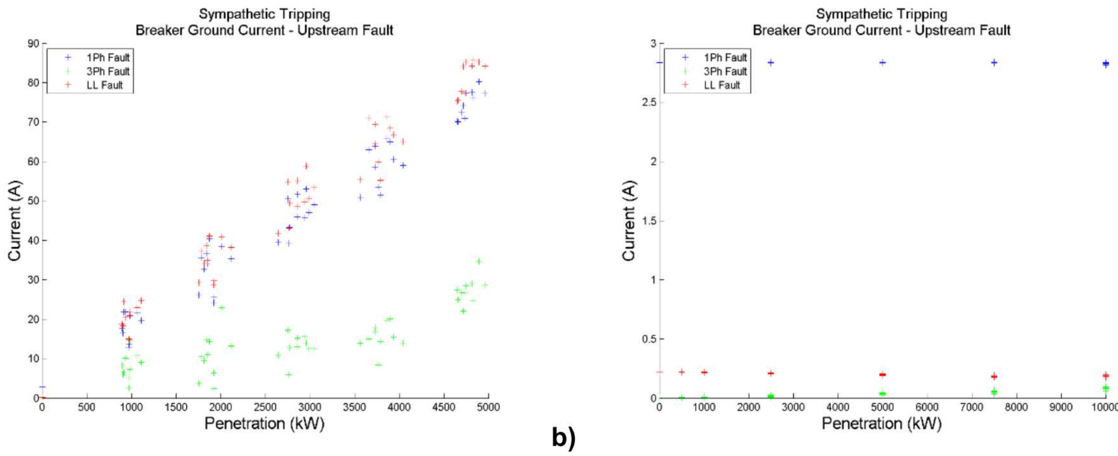
**Figure A-12**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*



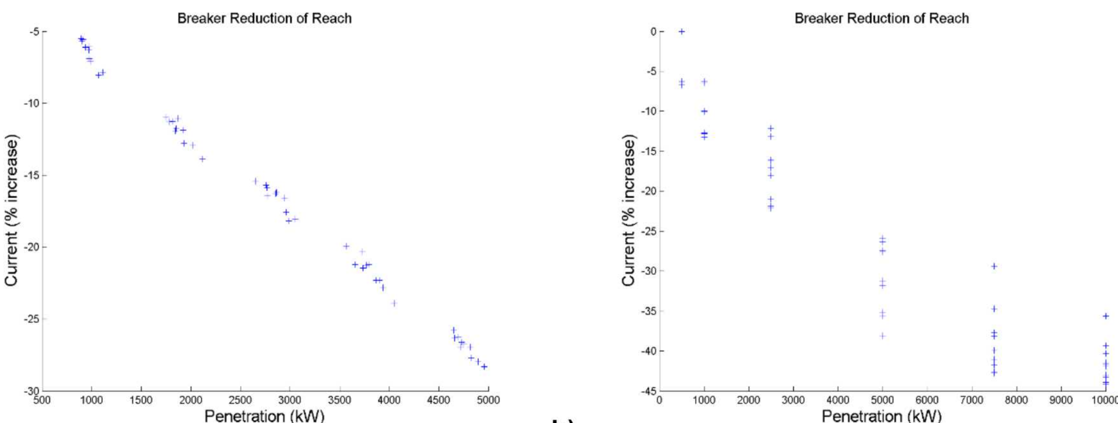

a) b)

**Figure A-13**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**



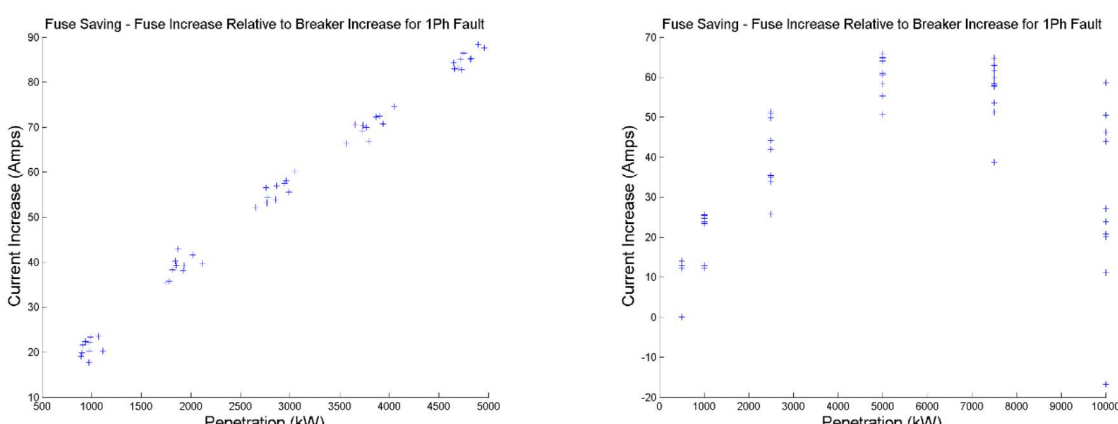

a) b)

**Figure A-14**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-15**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-16**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 631

The studied 12 kV feeder peak load is 3.4 MW with 23.9 MW at the substation. There are 32 primary feeder miles that extend a maximum length of 7.2 miles from the substation. There are approximately 363 residential customers and 152 commercial customers on the feeder. The substation three-phase LTC regulates voltage on the feeder. The LTC is modeled in a co-generation mode to maintain the 123 V setpoint and 4 V band at the low side tap. There is one feeder capacitor with 1200 kvar total compensation. The bank is voltage controlled with 119/123V on/off settings. A feeder voltage profile plot at peak load is shown in Figure A-17a, while a schematic illustrating system impedance is shown in Figure A-17b.

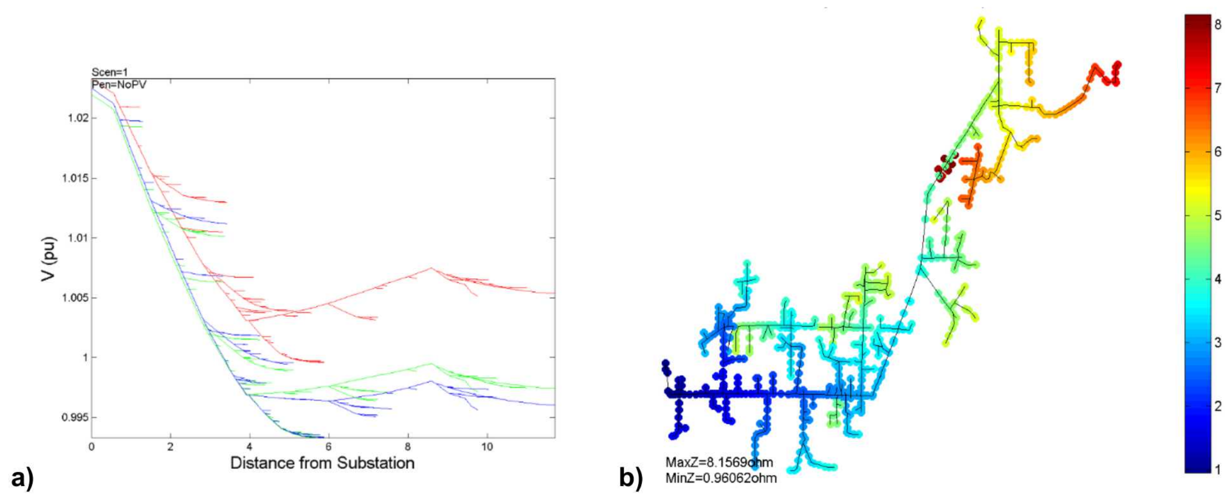



**Figure A-17**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

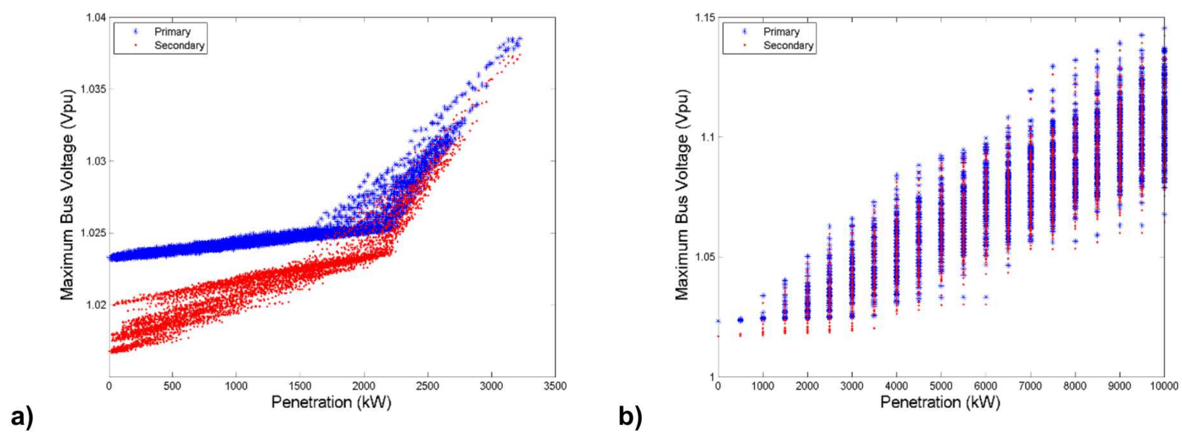
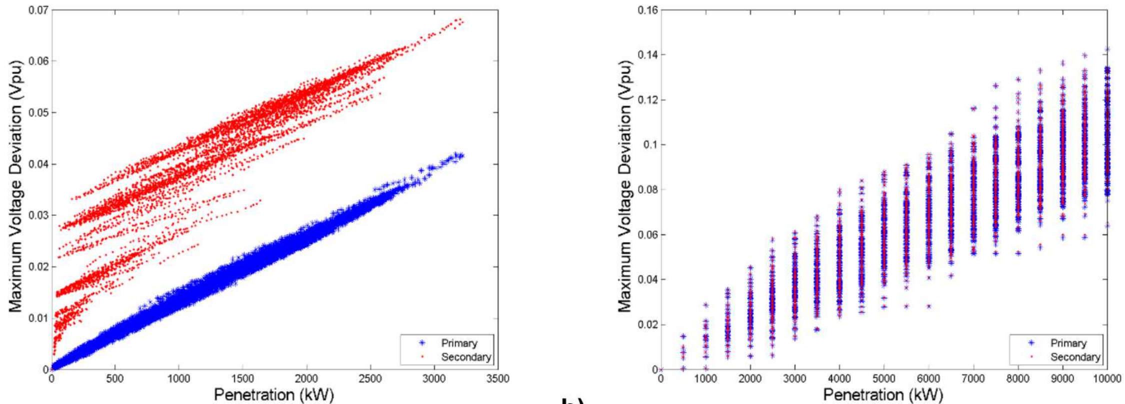
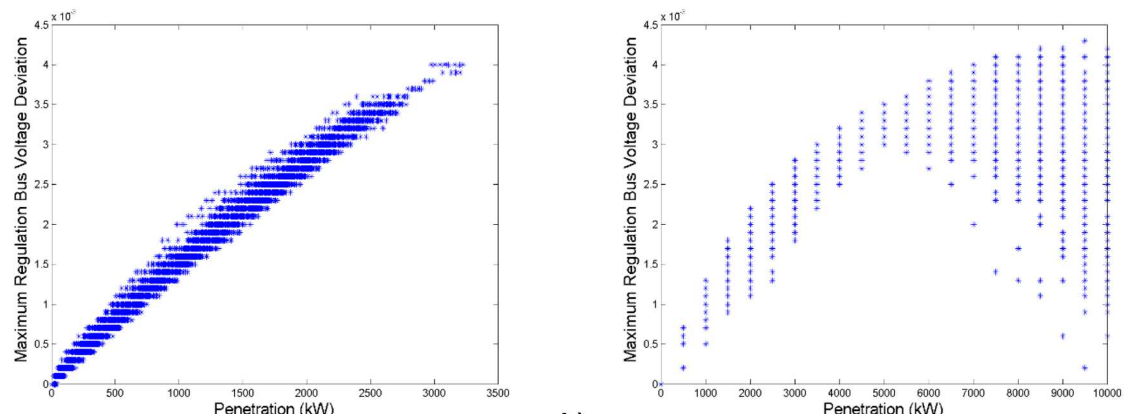



**Figure A-18**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

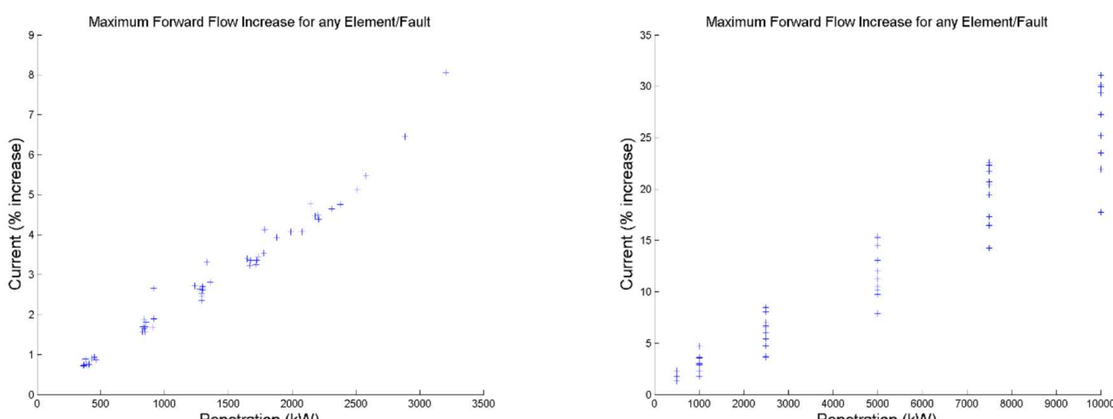
**Figure A-19**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

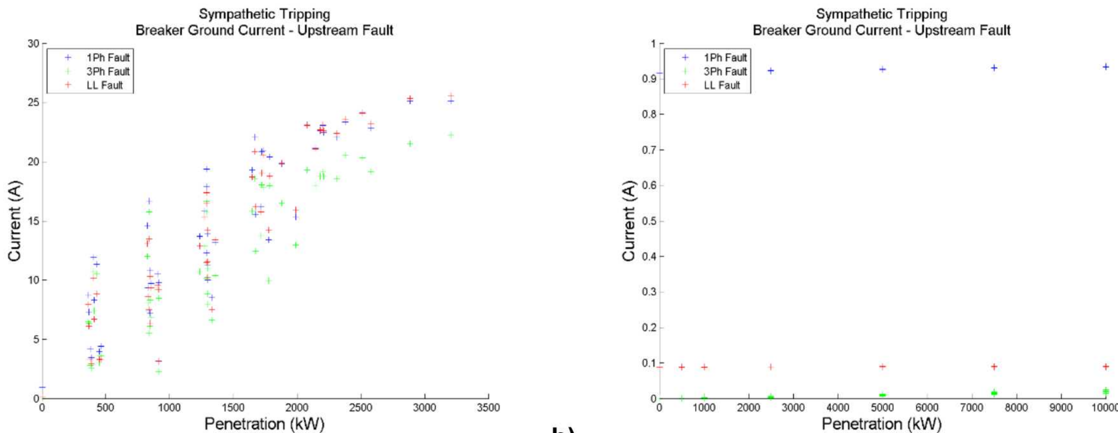
**Figure A-20**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*



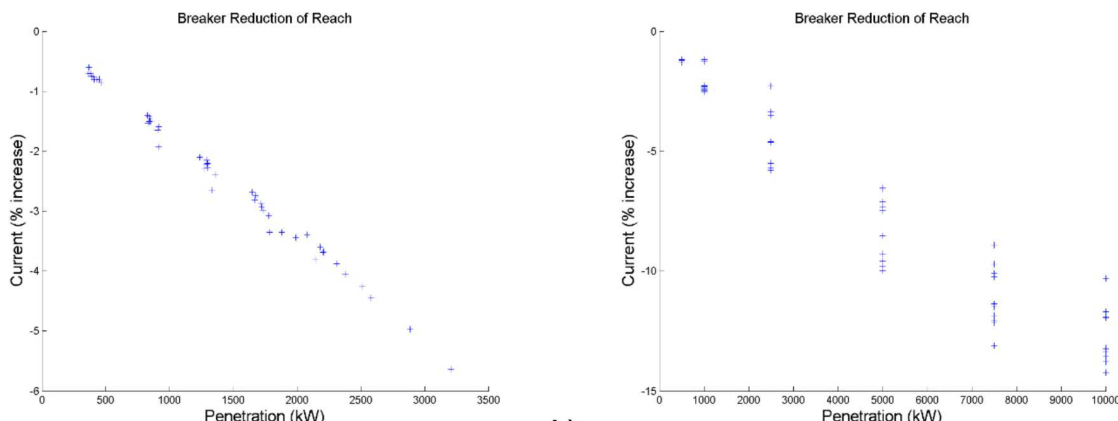

a) b)

**Figure A-21**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**



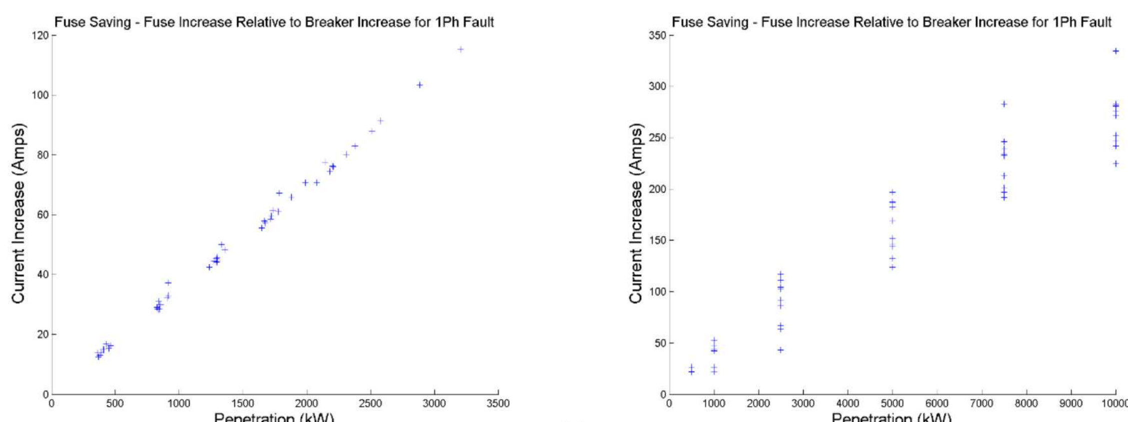

a) b)

**Figure A-22**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-23**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-24**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 296

The studied 12 kV feeder peak load is 4.4 MW with 37.6 MW at the substation. There are 22 primary feeder miles that extend a maximum length of 2.7 miles from the substation. There are approximately 1278 residential customers and 195 commercial customers on the feeder. The substation three-phase LTC regulates voltage on the feeder. The LTC is modeled in a co-generation mode to maintain the 123 V setpoint and 4 V band at the low side tap. There are two feeder capacitors with 2400 kvar total compensation. The two banks are each 1200 kvar and voltage controlled with 119/125V on/off settings. There is one single-phase step-down transformer that reduces the primary voltage to 4.16 kV. A feeder voltage profile plot at peak load is shown in Figure A-25a, while a schematic illustrating system impedance is shown in Figure A-25b.

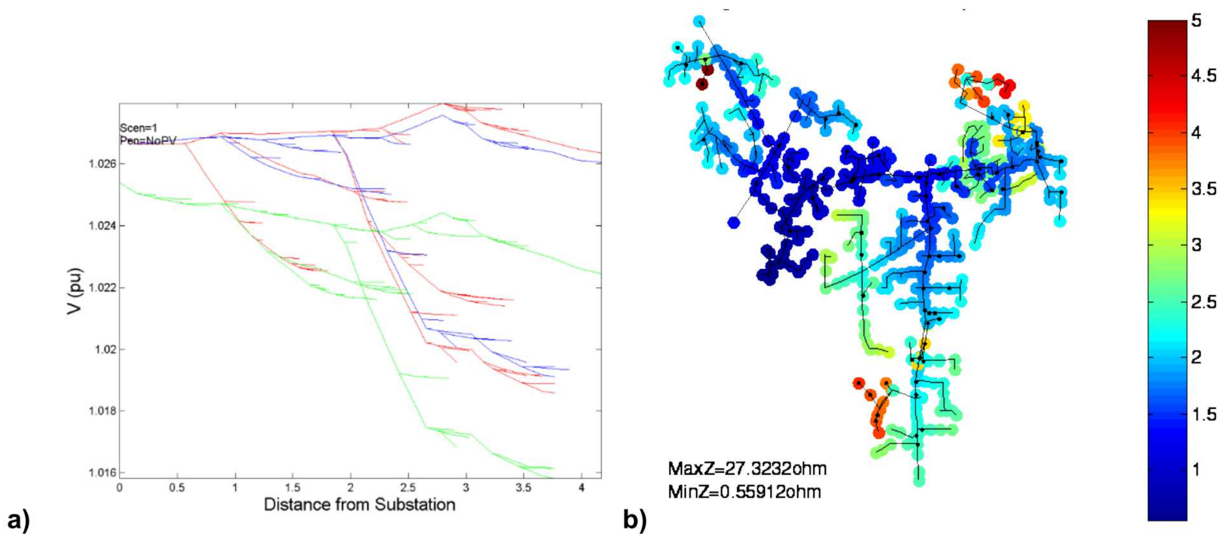



**Figure A-25**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

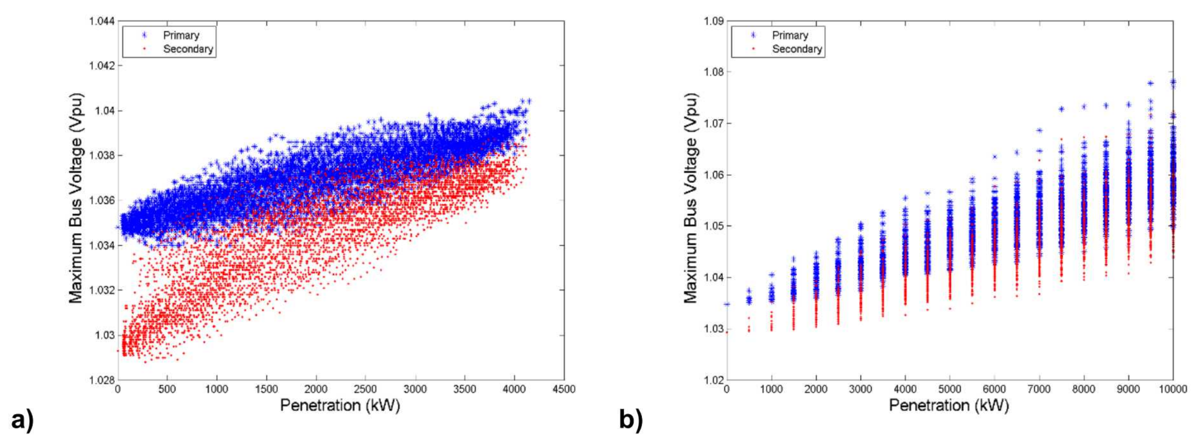
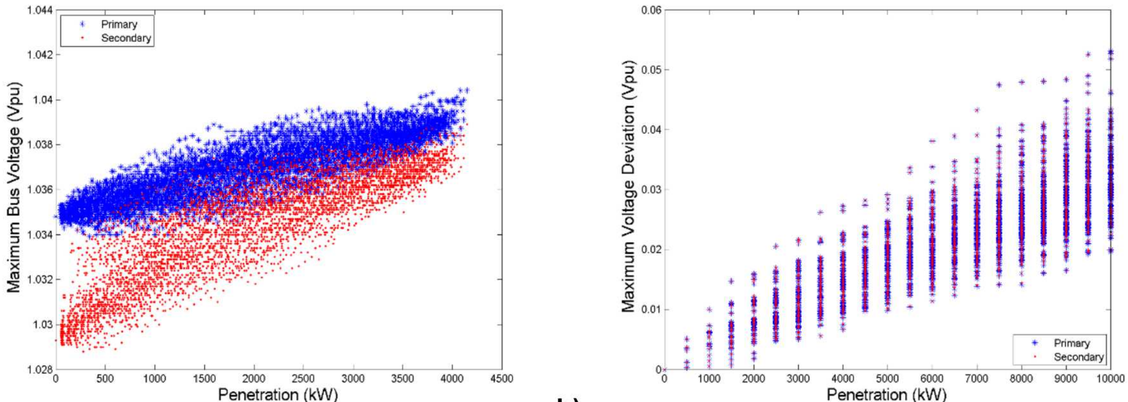
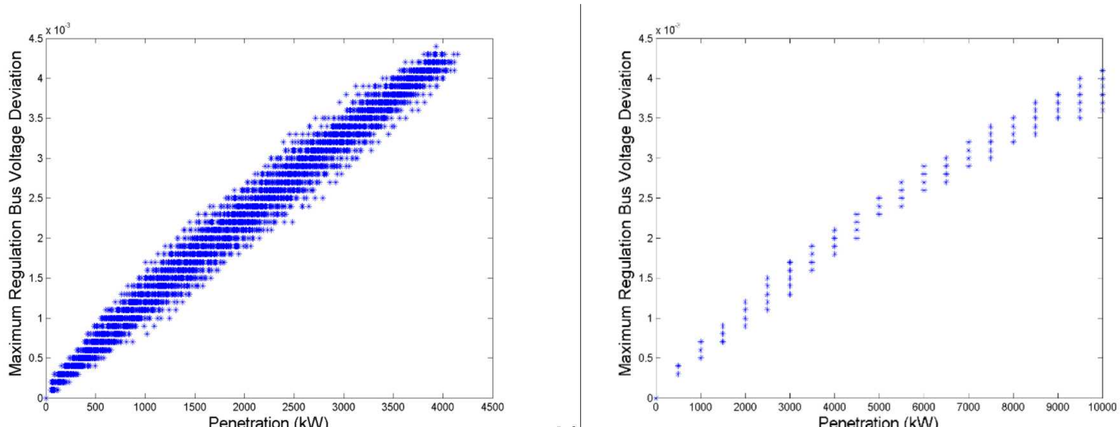



**Figure A-26**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

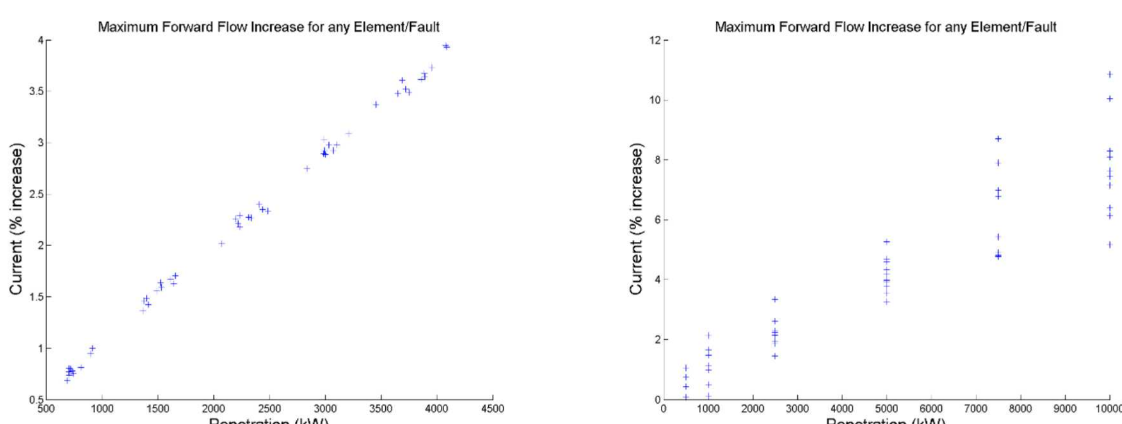
**Figure A-27**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-28**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*




a) b)

**Figure A-29**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**

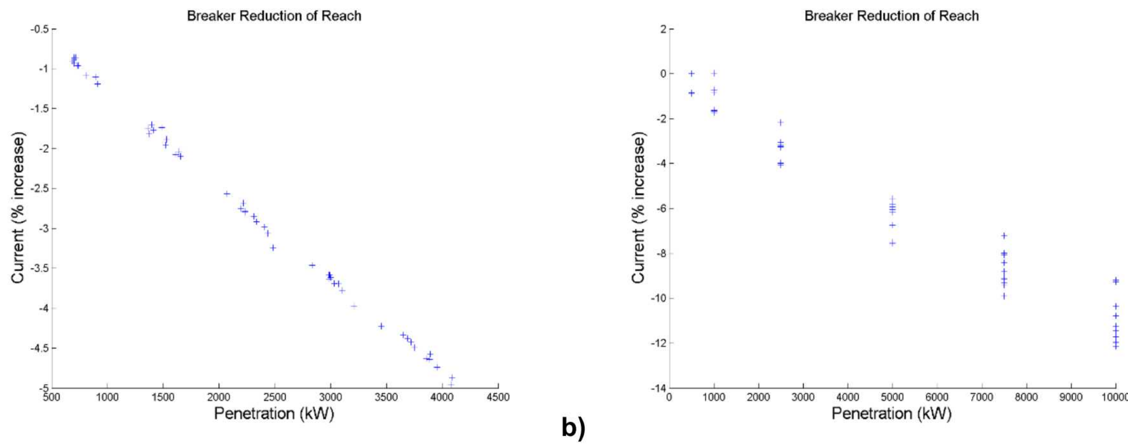



**Figure A-30**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**

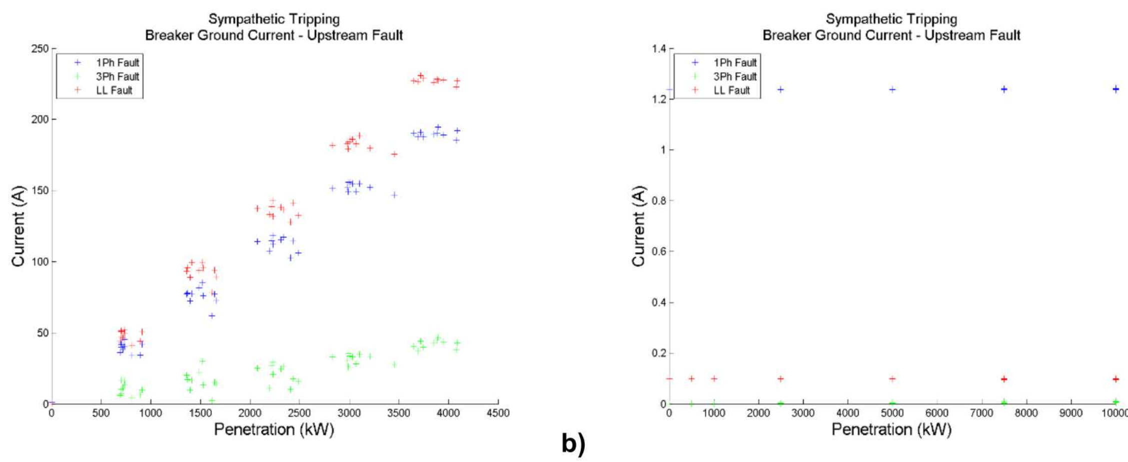



**Figure A-31**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**

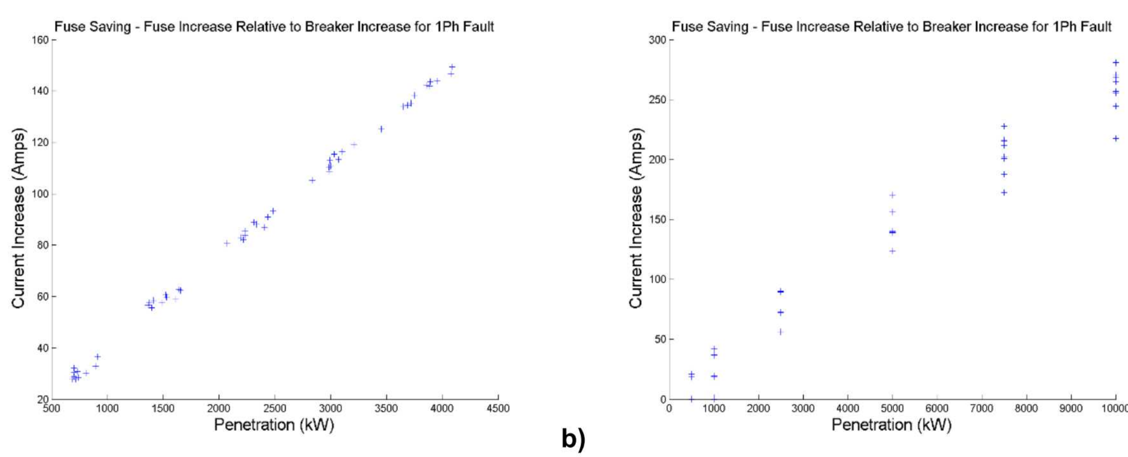



**Figure A-32**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 404

The studied 12 kV feeder peak load is 8.2 MW with 22.7 MW at the substation. There are 24.6 primary feeder miles that extend a maximum length of 4.0 miles from the substation. There are approximately 3598 residential customers and 185 commercial customers on the feeder. The substation three-phase LTC regulates voltage on the feeder. The LTC is modeled in a co-generation mode to maintain the 120.5 V setpoint and 3 V band at the low side tap. This feeder is controlled for Conservation Voltage Reduction (CVR). There are two feeder capacitors with 2400 kvar total compensation. The two banks are each 1200 kvar and manually fixed in service. There are two single-phase step-down transformers that reduce the primary voltage to 2.4 $kV_{LL}$. A feeder voltage profile plot at peak load is shown in Figure A-33a, while a schematic illustrating system impedance is shown in Figure A-33b.

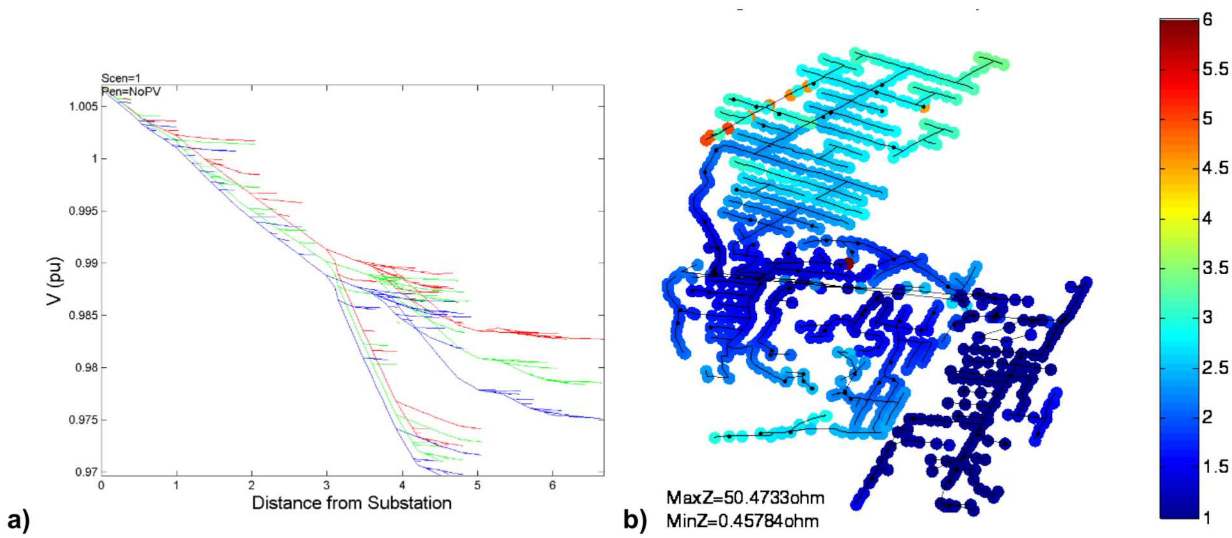



**Figure A-33**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

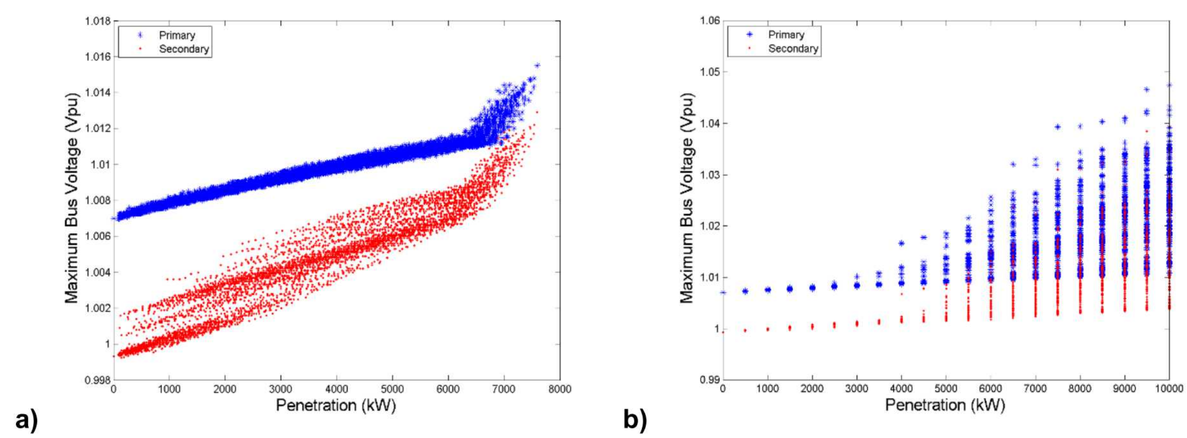
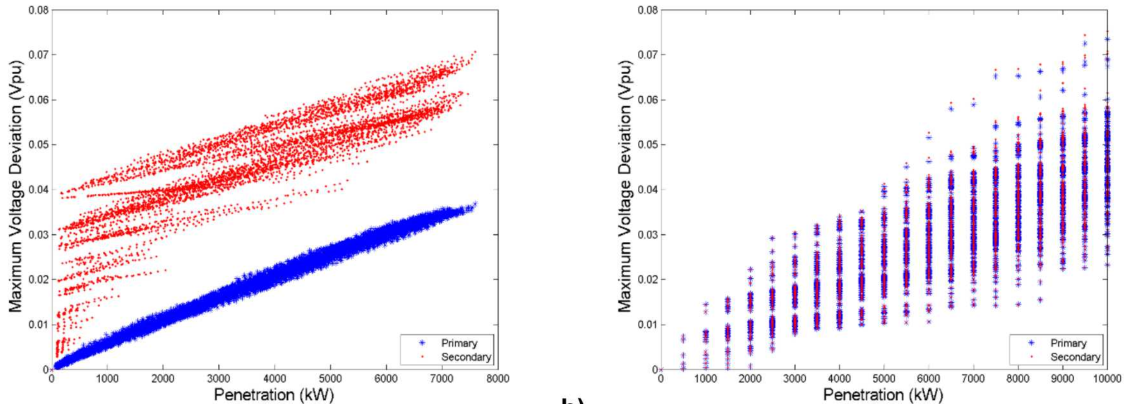
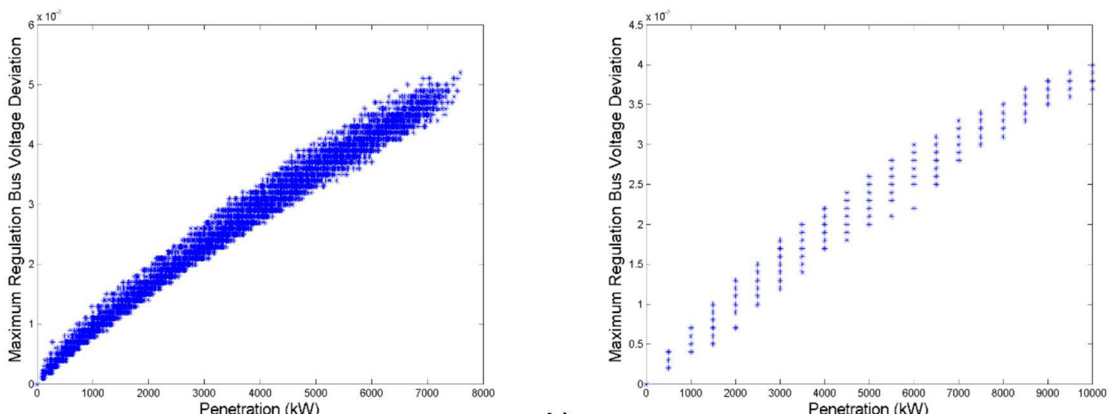



**Figure A-34**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

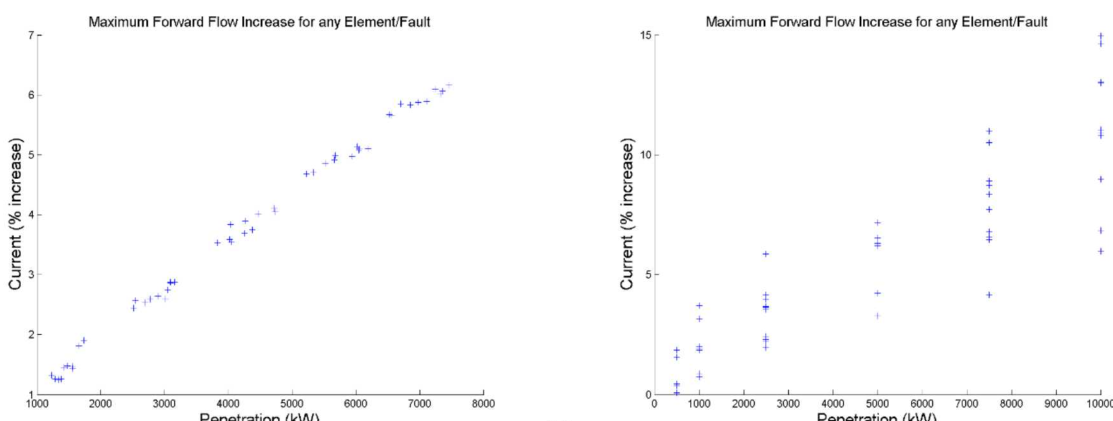
**Figure A-35**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

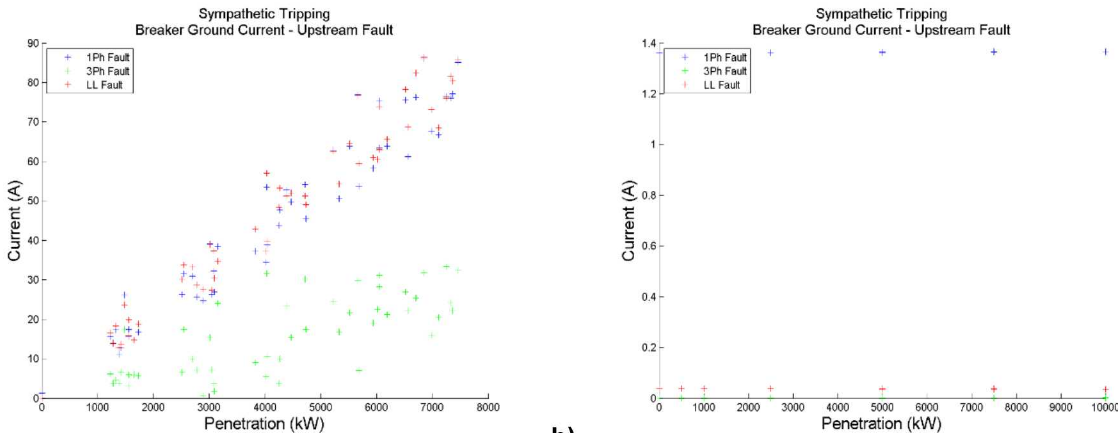
**Figure A-36**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*



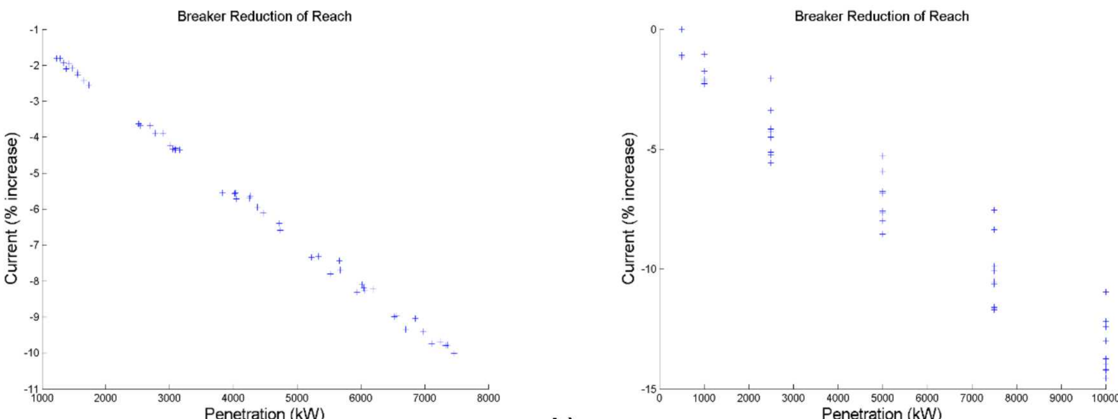

a) b)

**Figure A-37**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**



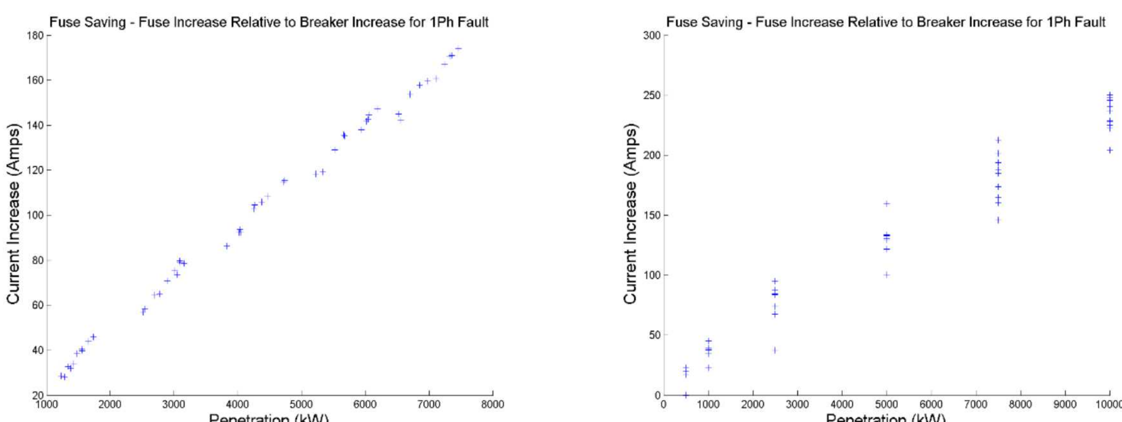

a) b)

**Figure A-38**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-39**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-40**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 525

The studied 12 kV feeder peak load is 3.7 MW with 23 MW at the substation. There are 4.9 primary feeder miles that extend a maximum length of 1.1 miles from the substation. There are 0 residential customers and 261 commercial customers on the feeder. The substation three-phase LTC regulates voltage on the feeder. The LTC is modeled in a co-generation mode to maintain the 123 V setpoint and 4 V band at the low side tap. There are zero feeder capacitors. A feeder voltage profile plot at peak load is shown in Figure A-41a, while a schematic illustrating system impedance is shown in Figure A-41b.

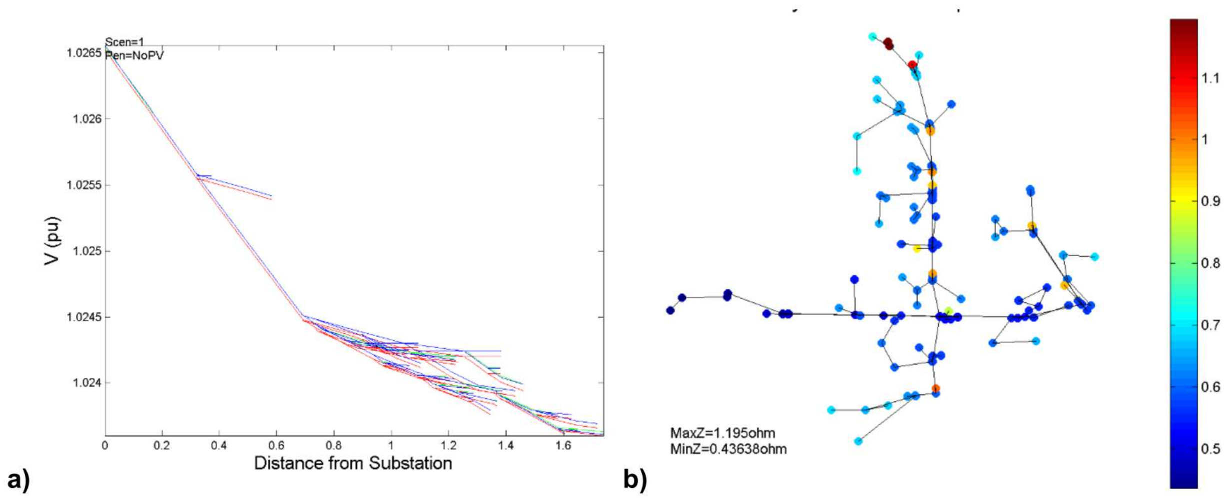



**Figure A-41**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

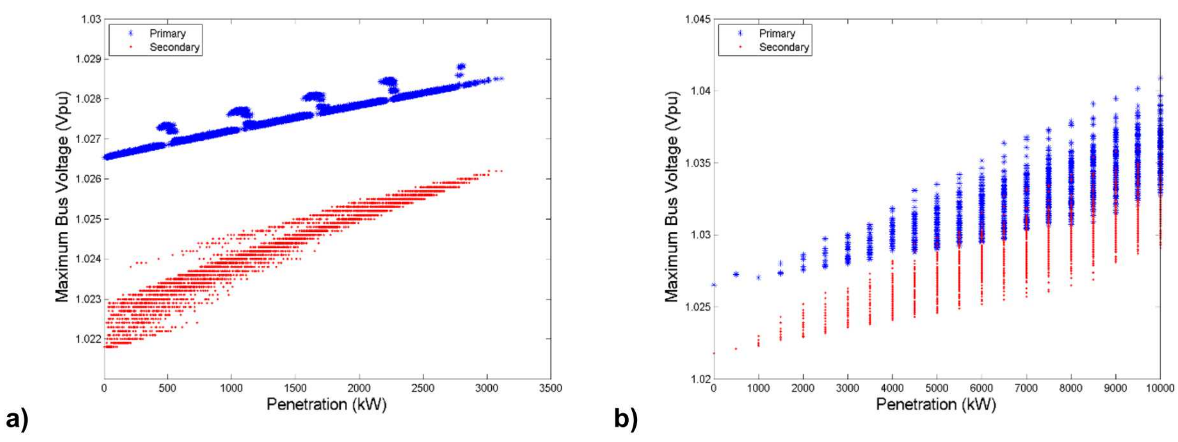



**Figure A-42**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**

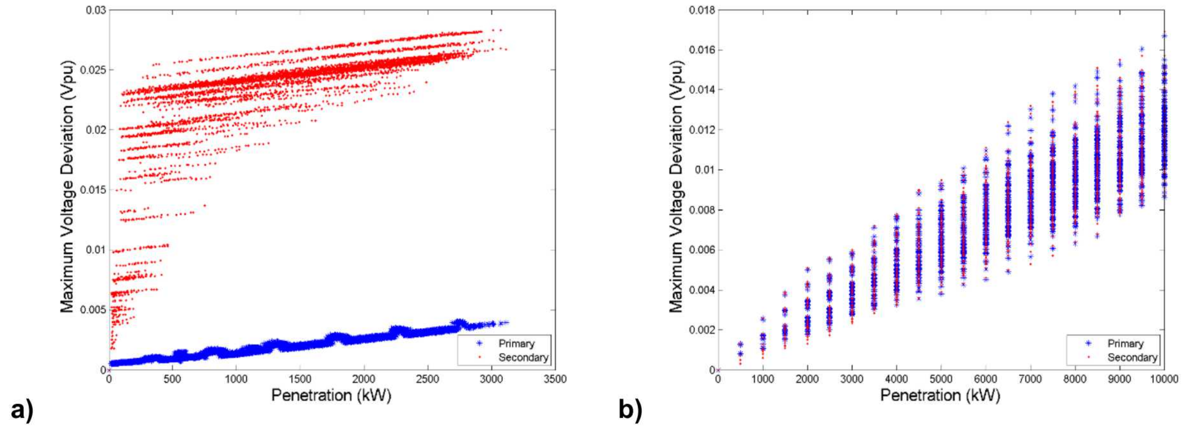



**Figure A-43**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

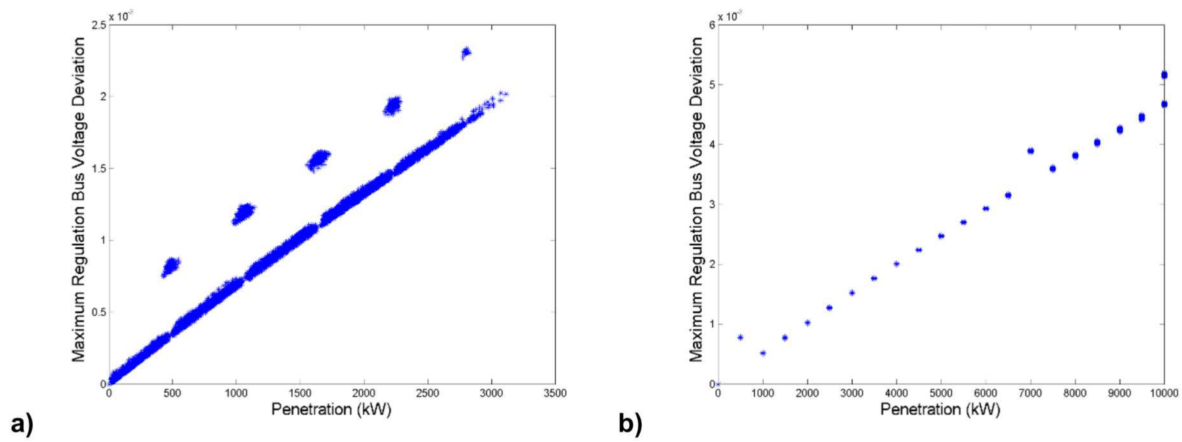



**Figure A-44**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*

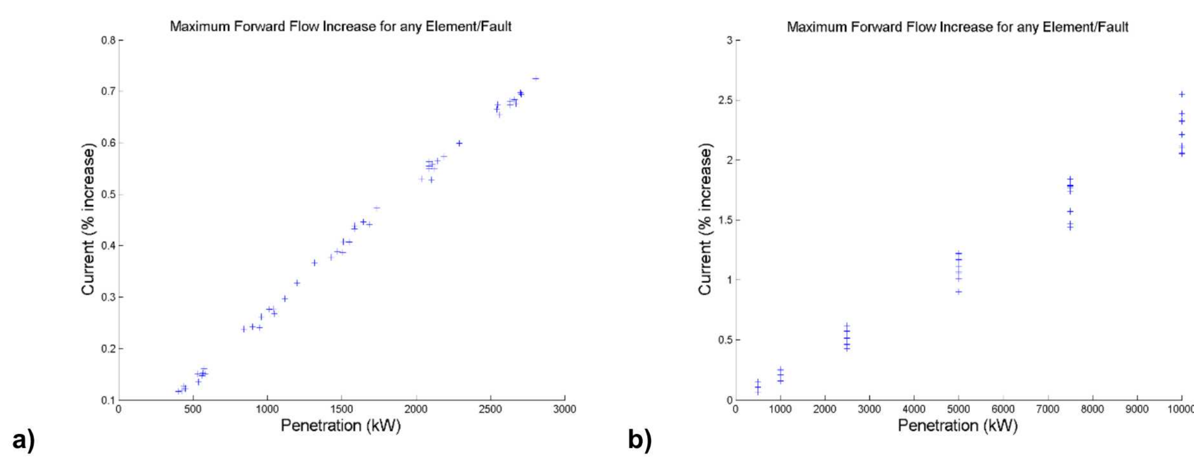



**Figure A-45**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**

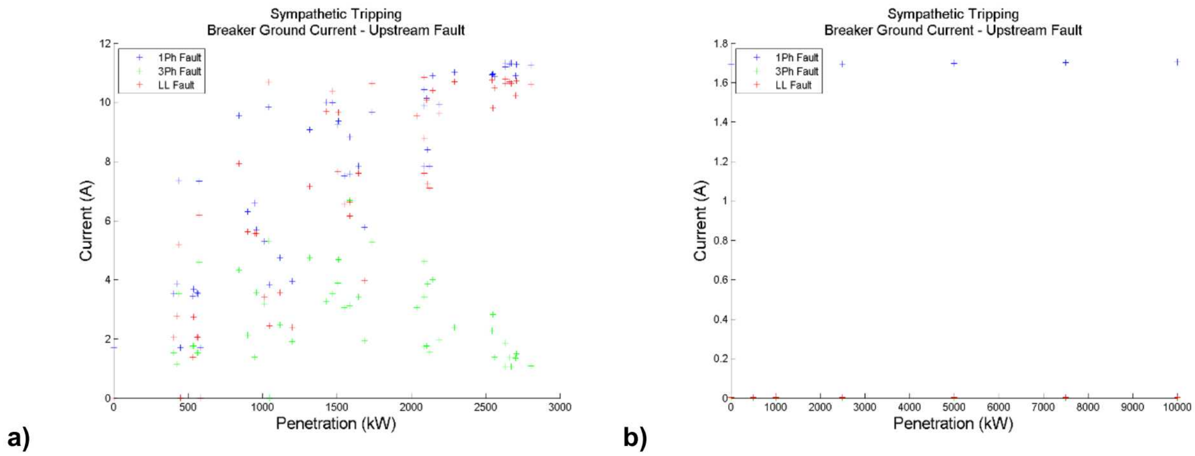



**Figure A-46**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**

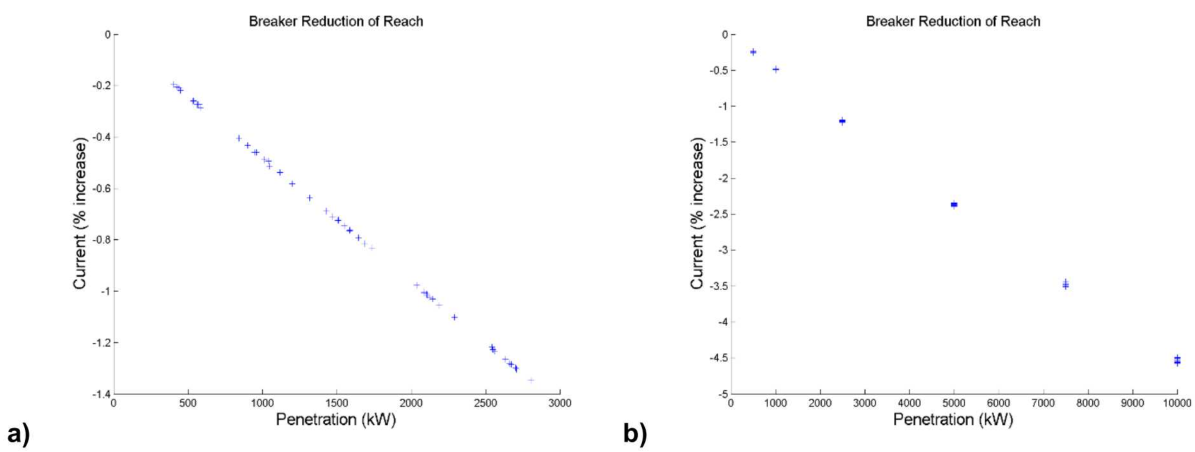



**Figure A-47**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**

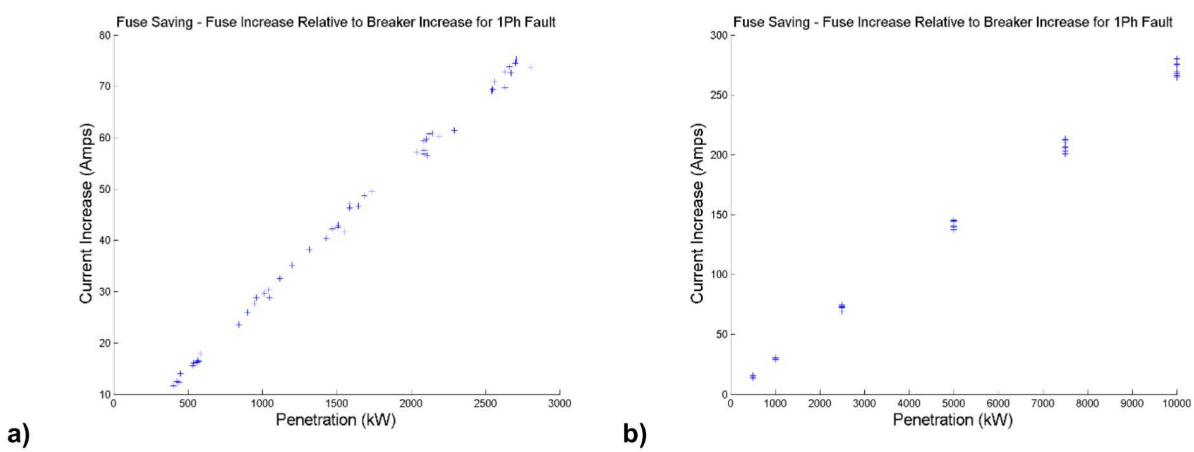
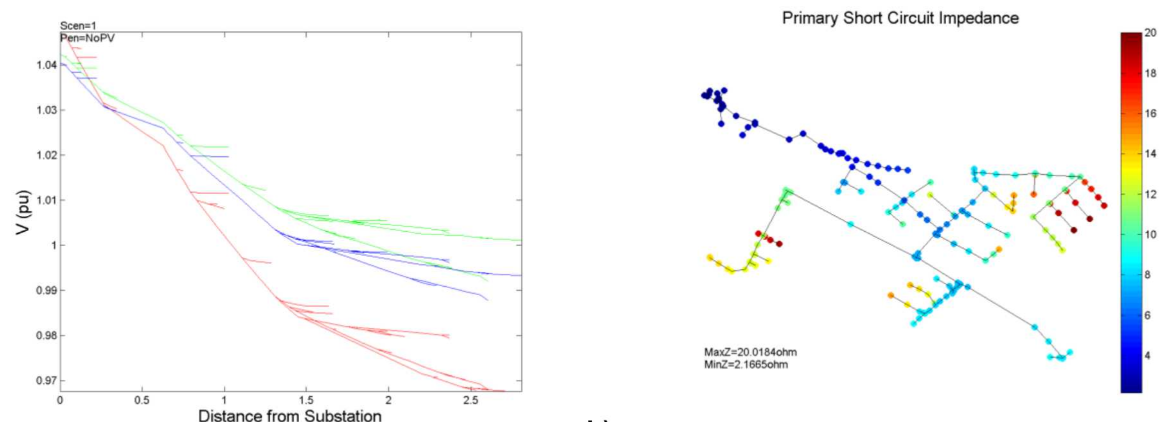



**Figure A-48**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 888

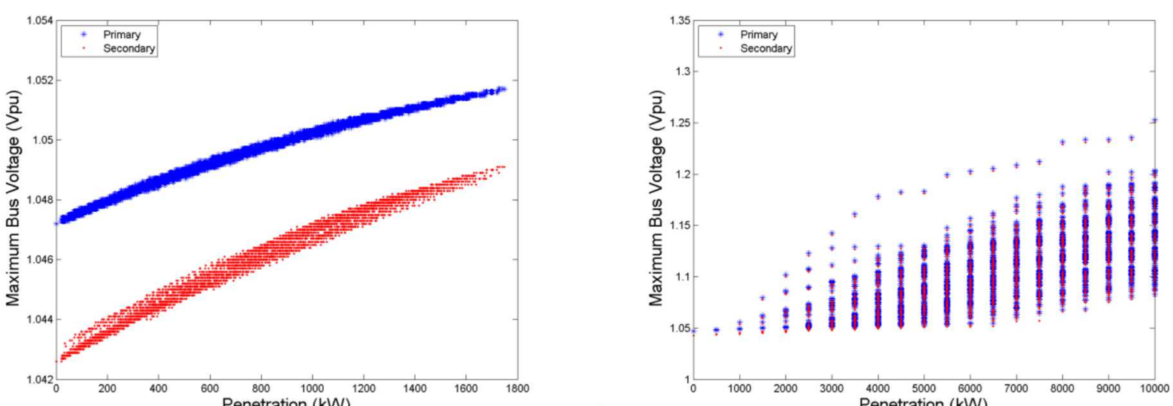
The studied 4 kV feeder peak load is 2.2 MW with 11.8 MW at the substation. There are 5.5 primary feeder miles that extend a maximum length of 1.7 miles from the substation. There are approximately 1236 residential customers and 2 commercial customers on the feeder. Three 1-phase regulators regulate voltage on the feeder with line drop compensation. A feeder voltage profile plot at peak load is shown in Figure A-49a, while a schematic illustrating system impedance is shown in Figure A-49b.




a) b)

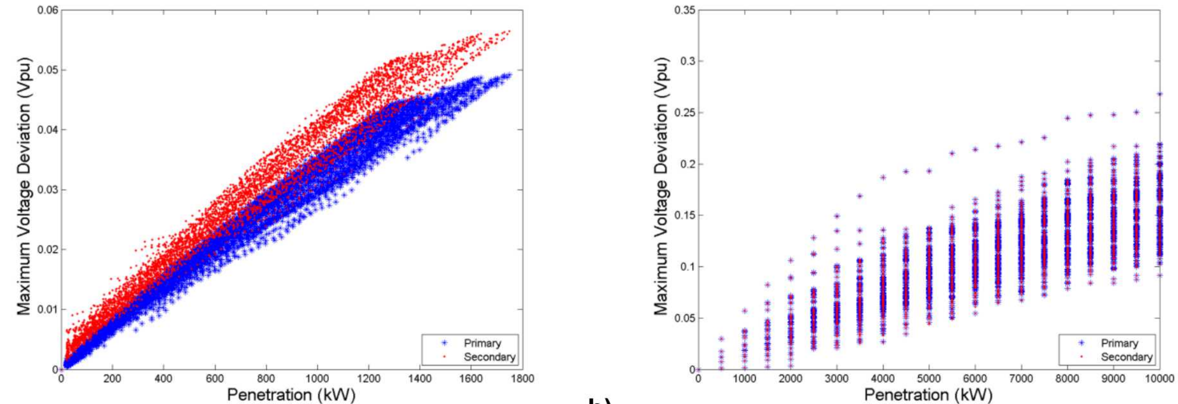
**Figure A-49**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*



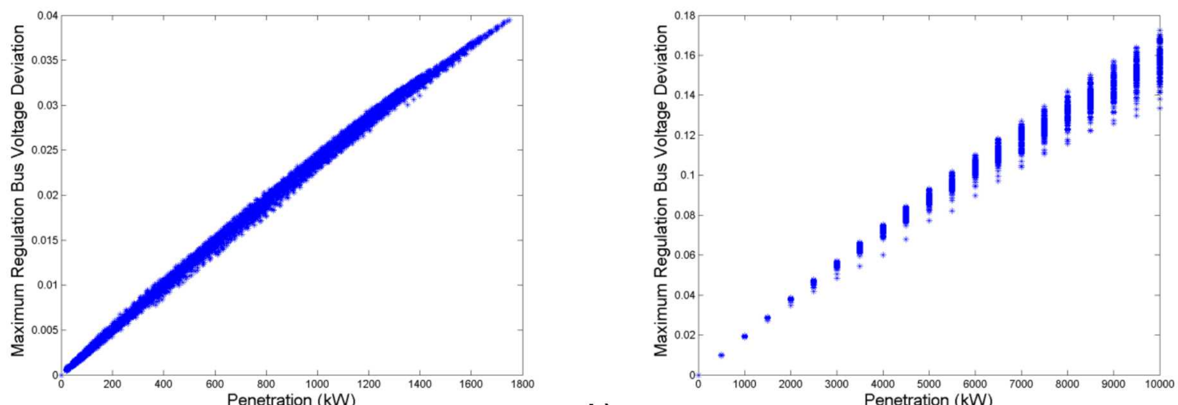

a) b)

**Figure A-50**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

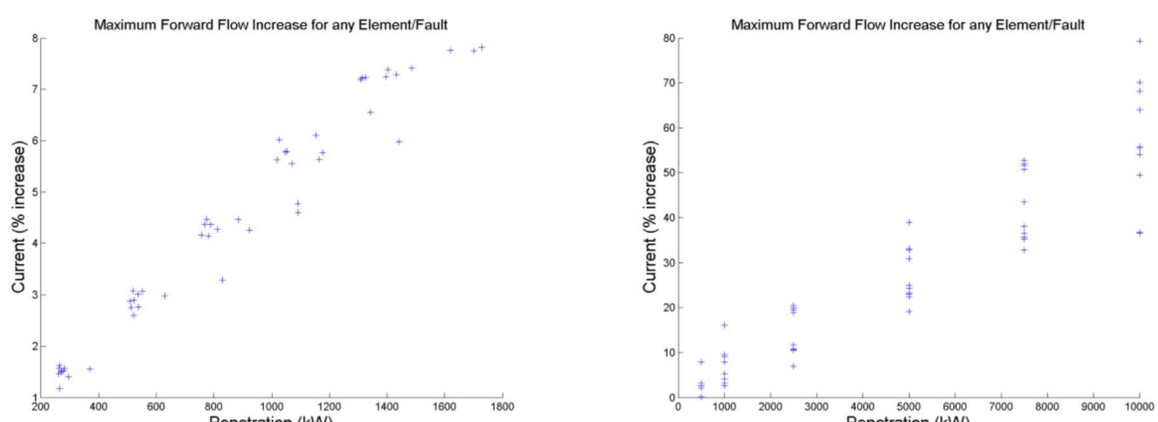
**Figure A-51**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

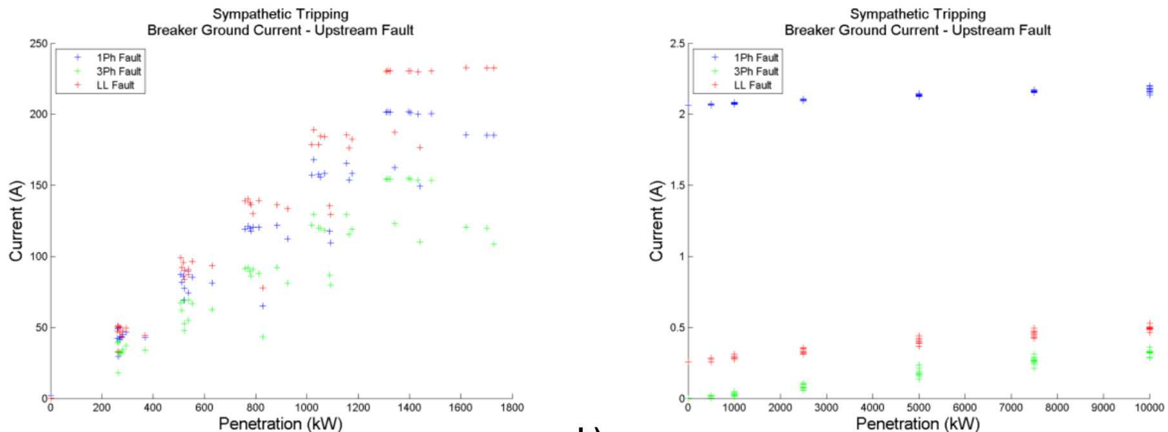
**Figure A-52**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*



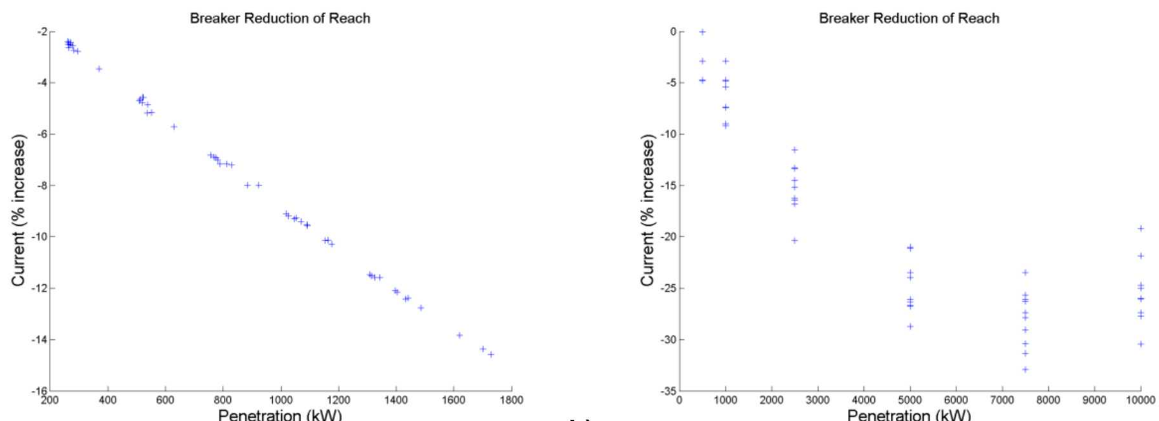

a) b)

**Figure A-53**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**



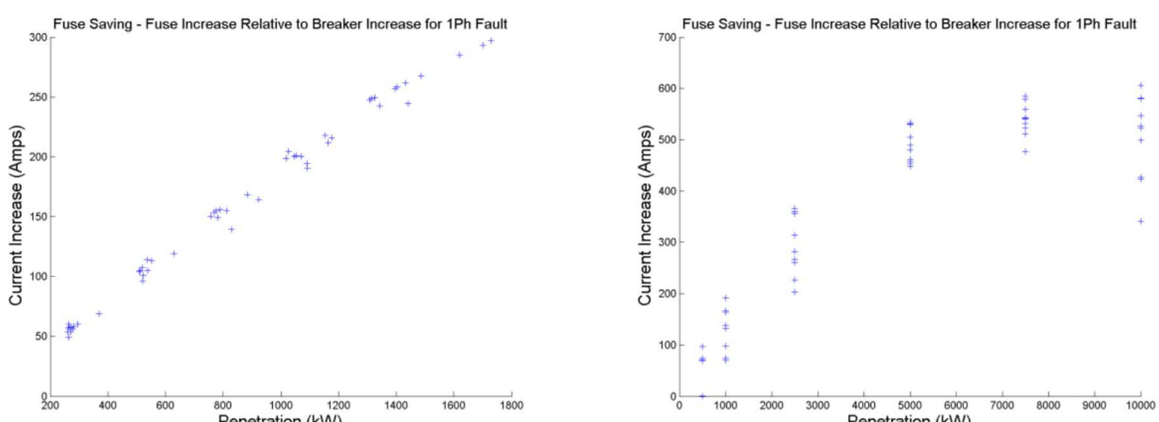

a) b)

**Figure A-54**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-55**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-56**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 1354

The studied 12 kV feeder peak load is 5.2 MW with 14.2 MW at the substation. There are 5.8 primary feeder miles that extend a maximum length of 1.7 miles from the substation. There are approximately 1826 residential customers and 4 commercial customers on the feeder. The substation three-phase LTC regulates voltage on the feeder with line drop compensation. The LTC is modeled in a co-generation mode to maintain the 119.51 V setpoint and 2.08 V band at the low side tap. There are two feeder capacitors with 2400 kvar total compensation. The two banks are each 1200 kvar and time-controlled. A feeder voltage profile plot at peak load is shown in Figure A-57a, while a schematic illustrating system impedance is shown in Figure A-57b.

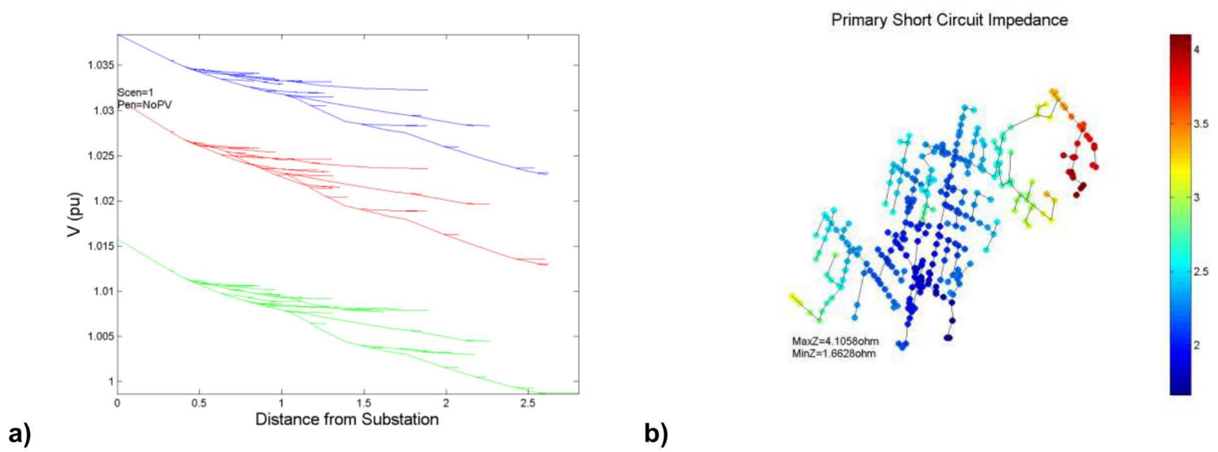



**Figure A-57**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

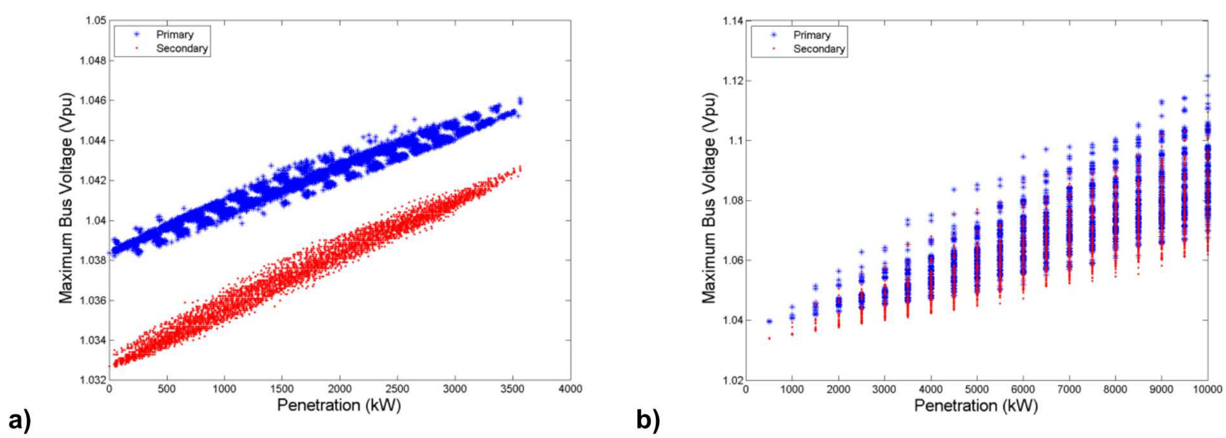
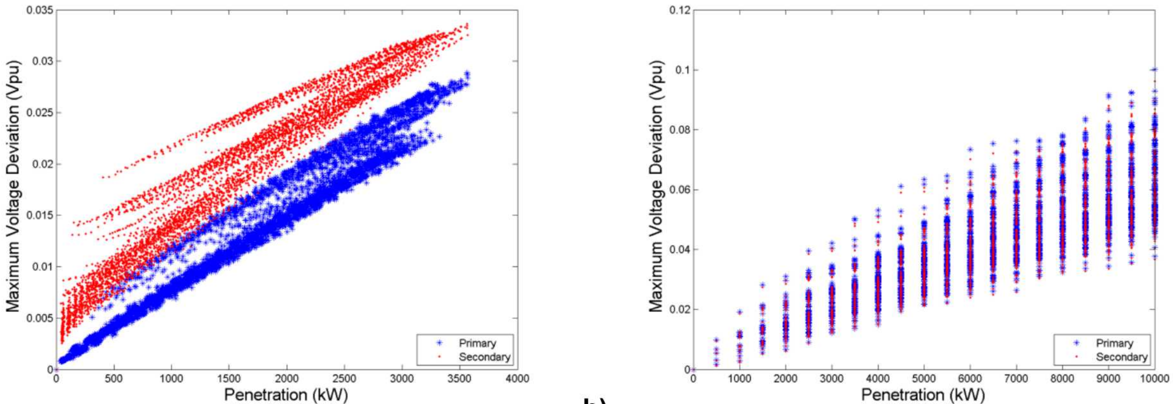
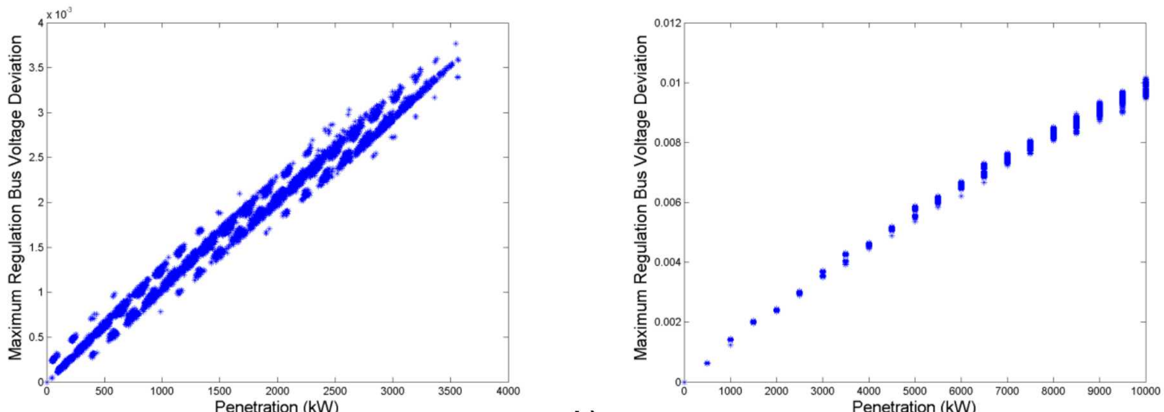



**Figure A-58**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

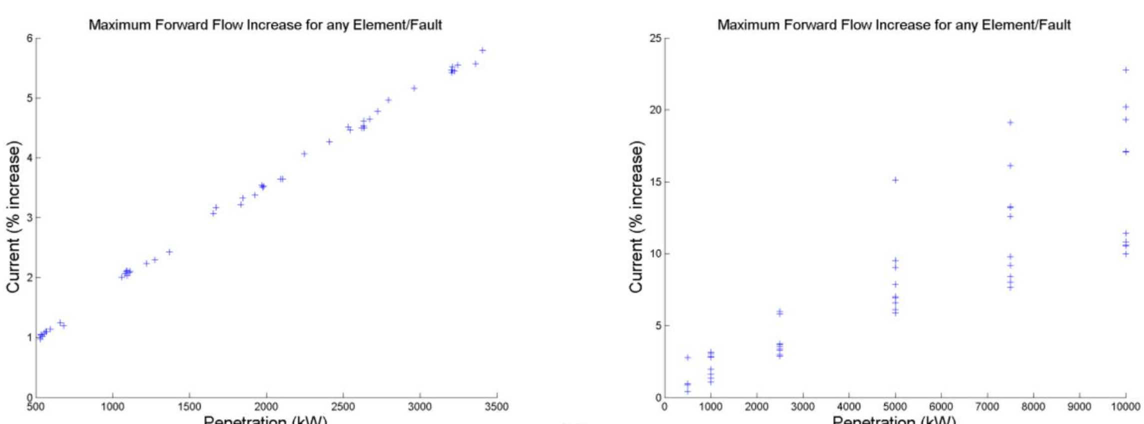
**Figure A-59**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

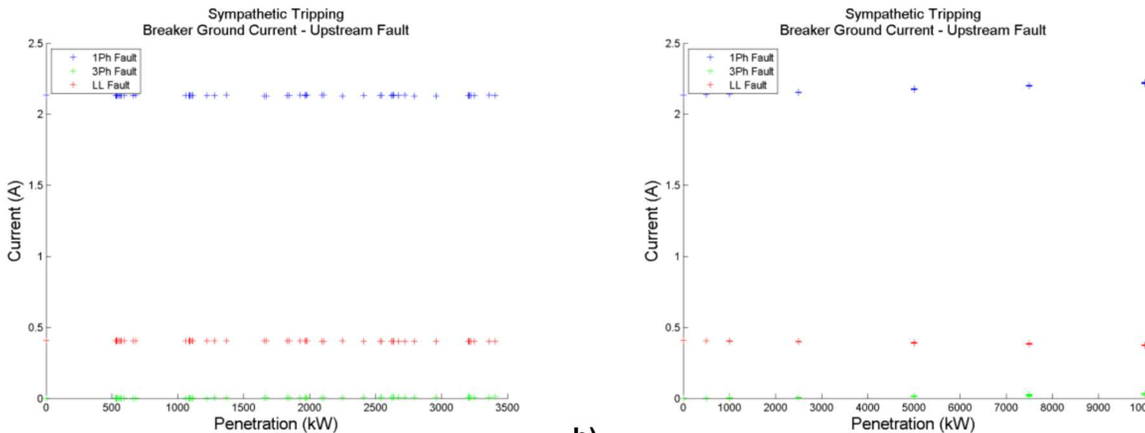
**Figure A-60**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*



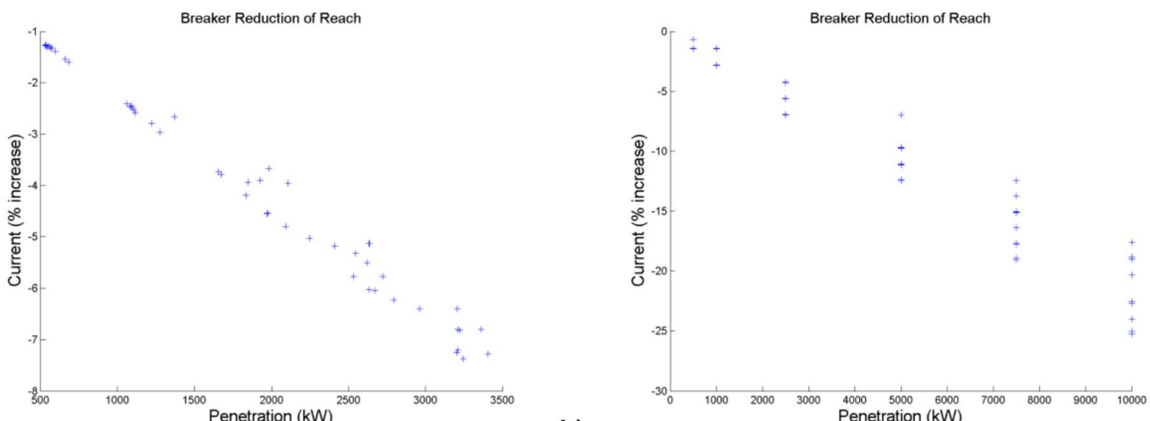

a) b)

**Figure A-61**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**



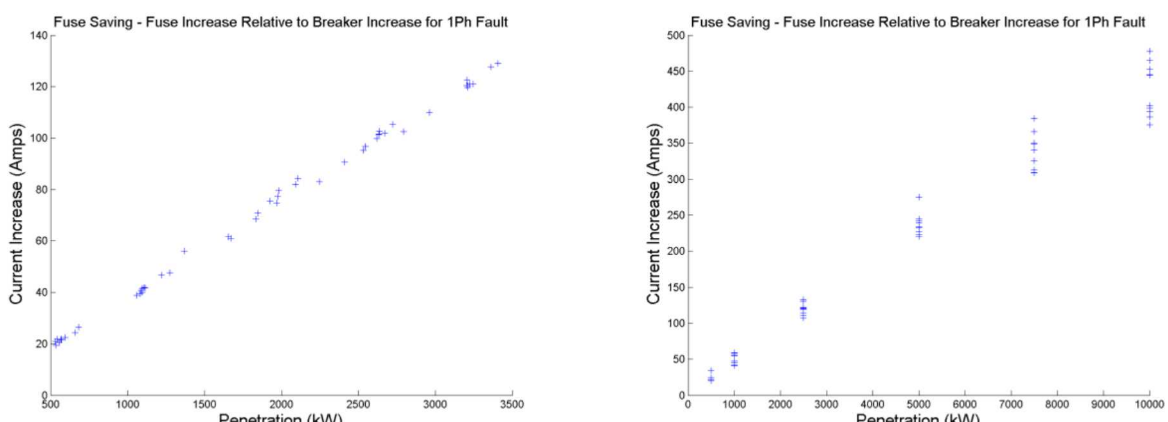
a) b)

**Figure A-62**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**



a) b)

**Figure A-63**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**

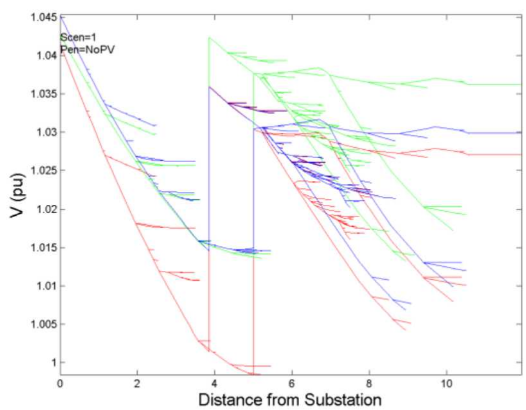


a) b)

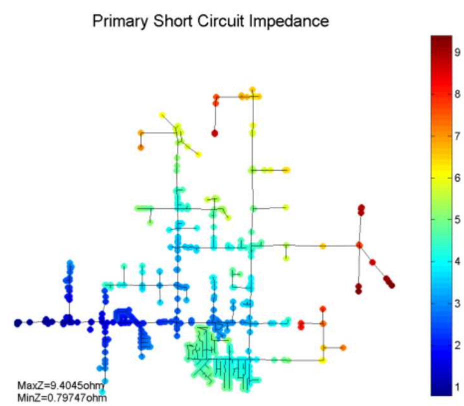
**Figure A-64**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 2885

The studied 12 kV feeder peak load is 9.25 MW with 20.9 MW at the substation. There are 50.4 primary feeder miles that extend a maximum length of 8.03 miles from the substation. There are approximately 1210 residential customers and 10 commercial customers on the feeder. The substation three-phase LTC regulates voltage on the feeder with line drop compensation. The LTC is modeled in a co-generation mode to maintain the 121.07 V setpoint and 1.56 V band at the low side tap. This feeder contains two open-delta voltage regulators with line drop compensation. There are six feeder capacitors (one fixed) with 6000 kvar total compensation. Two of the capacitors are time-controlled, 3 are temperature-controlled, and 1 is voltage-controlled. Four capacitor banks are each 900 kvar and and two capacitor banks are each 1200 kvar. A feeder voltage profile plot at peak load is shown in Figure A-65a, while a schematic illustrating system impedance is shown in Figure A-65b.



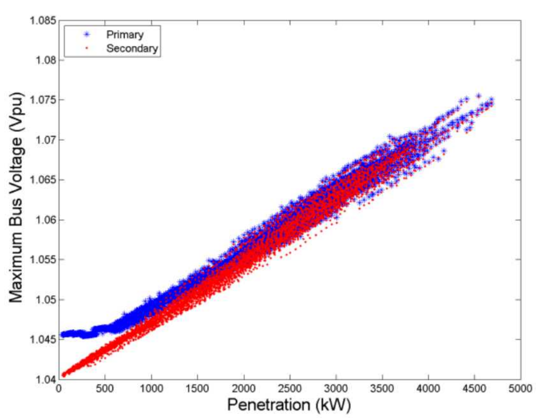

**a)**



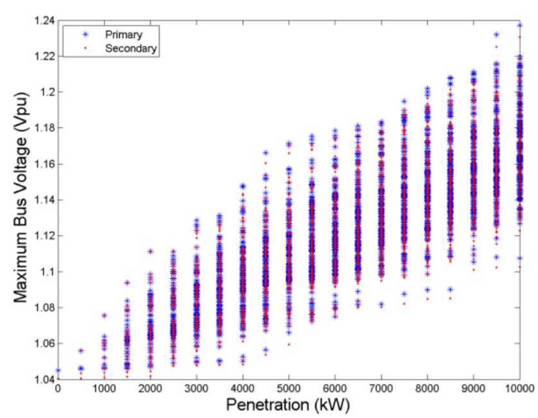

**b)**

**Figure A-65**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

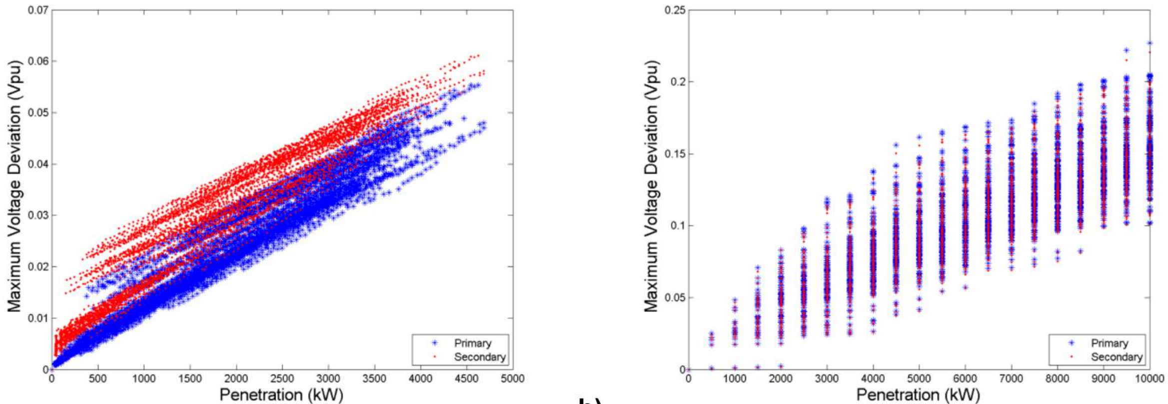



**a)**



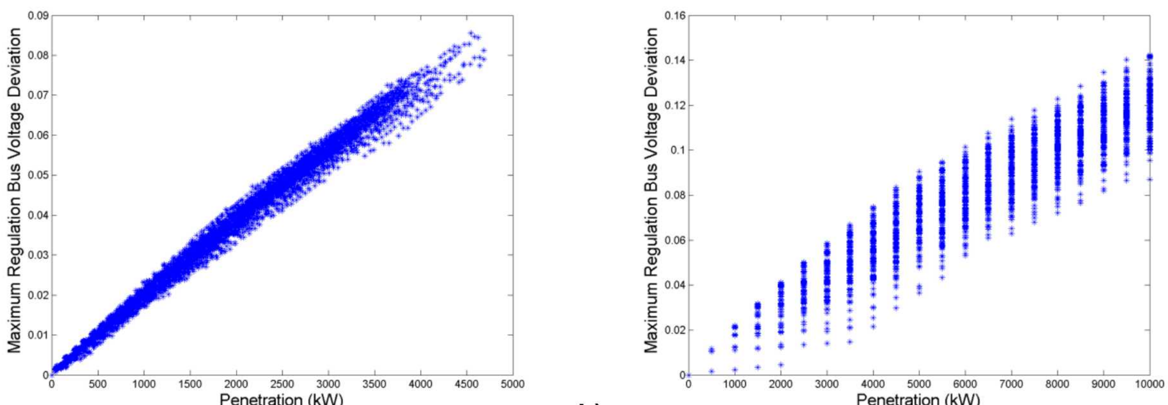

**b)**

**Figure A-66**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

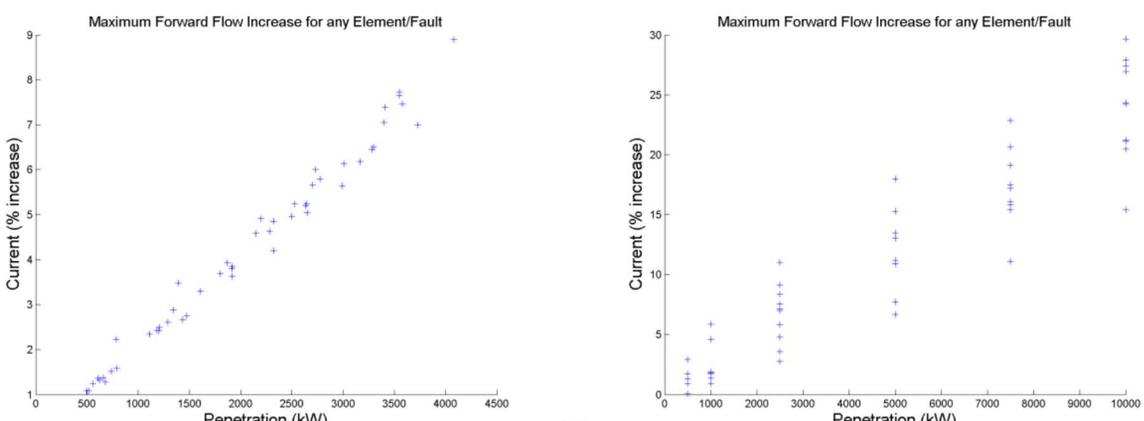
**Figure A-67**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

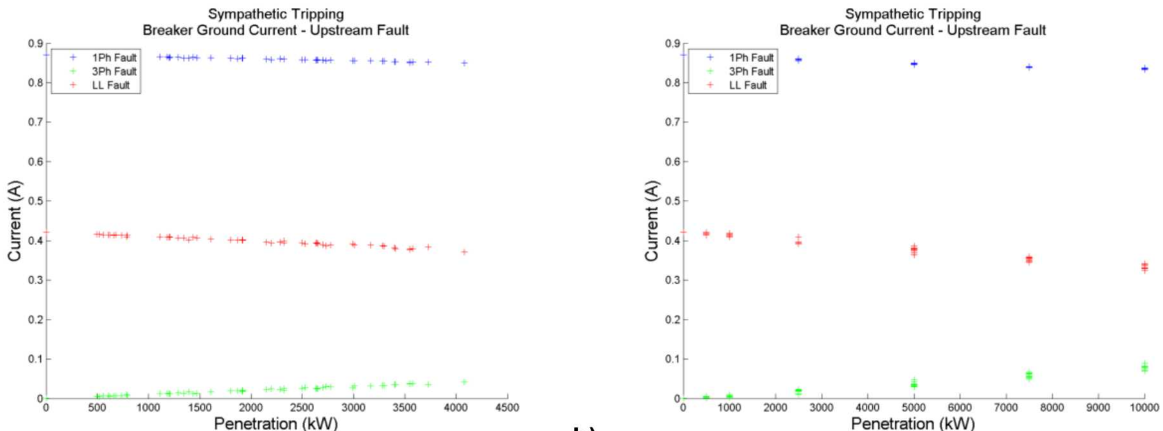
**Figure A-68**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*



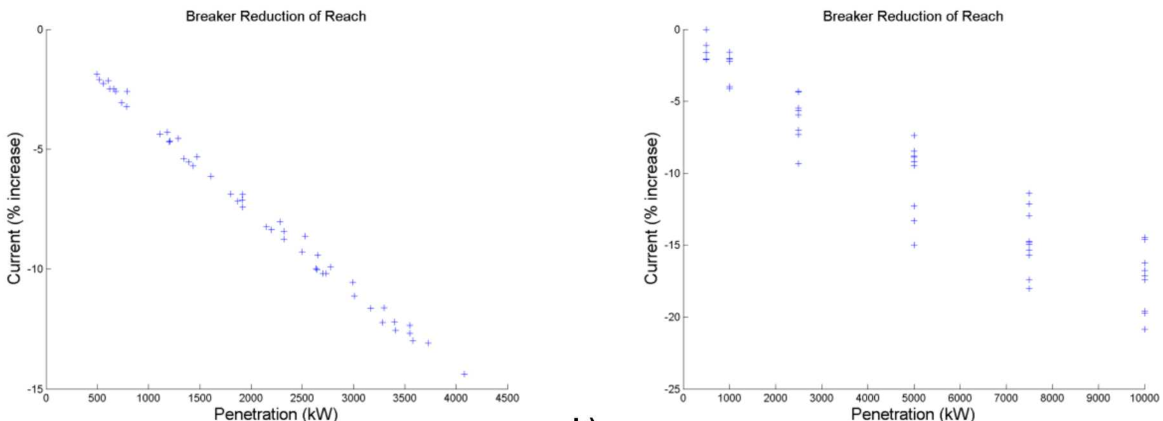

a) b)

**Figure A-69**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**



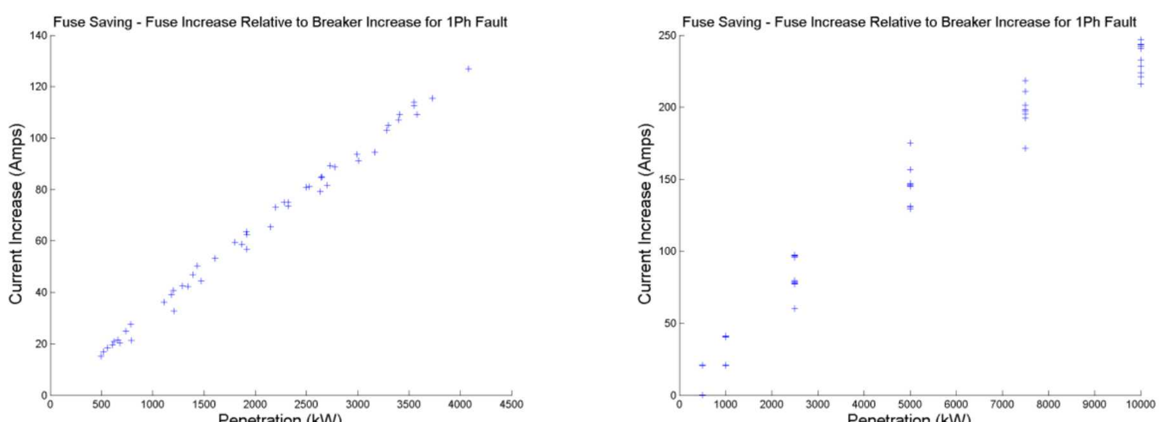

a) b)

**Figure A-70**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-71**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-72**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 281

The studied 21 kV feeder peak load is 16.7 MW with 58.3 MW at the substation. There are 26.9 primary feeder miles that extend a maximum length of 6.76 miles from the substation. There are approximately 3155 residential customers and 14 commercial customers on the feeder. The substation three-phase LTC regulates voltage on the feeder with line drop compensation. The LTC is modeled in a co-generation mode to maintain the 121.53 V setpoint and 1.5V band at the low side tap. There are four feeder capacitors with 9600 kvar total compensation. Four capacitors are time-controlled and two are voltage-controlled. Four capacitor banks are each 1800 kvar and two capacitor banks are each 1200 kvar. A feeder voltage profile plot at peak load is shown in Figure A-73a, while a schematic illustrating system impedance is shown in Figure A-73b.

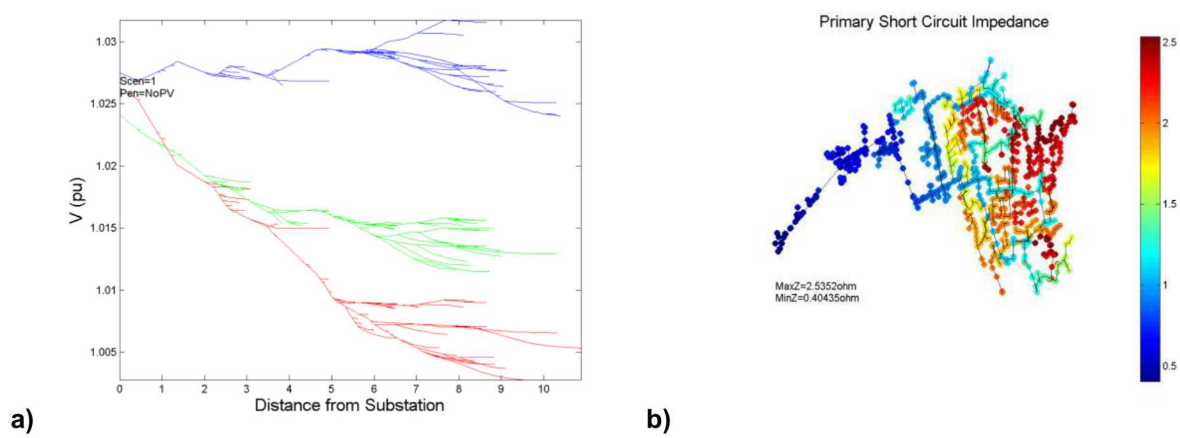



**Figure A-73**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

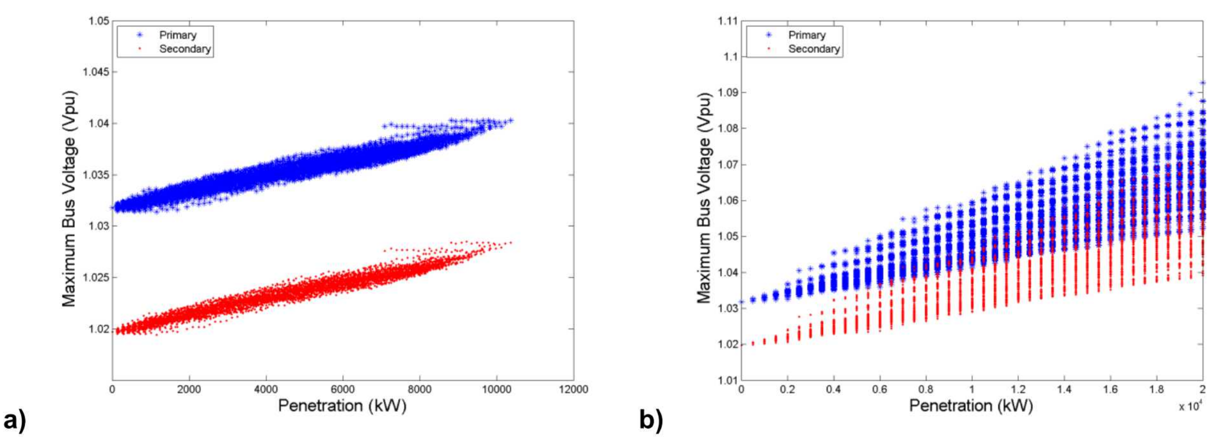
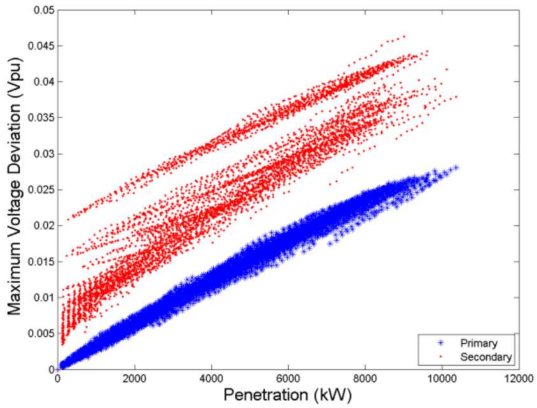
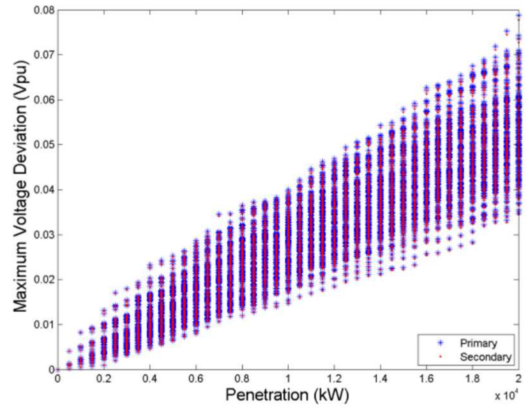



**Figure A-74**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**

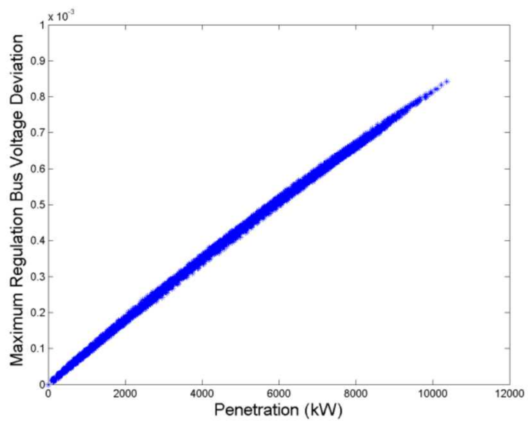


a)

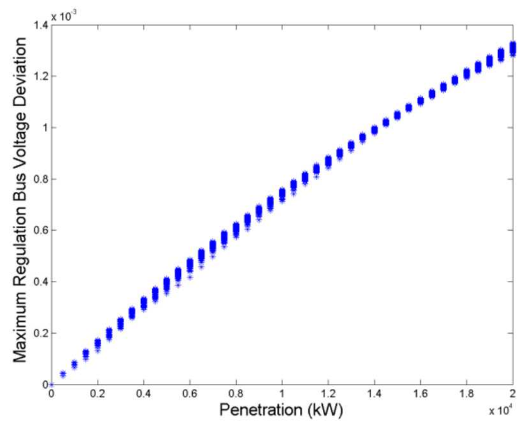


b)

**Figure A-75**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**



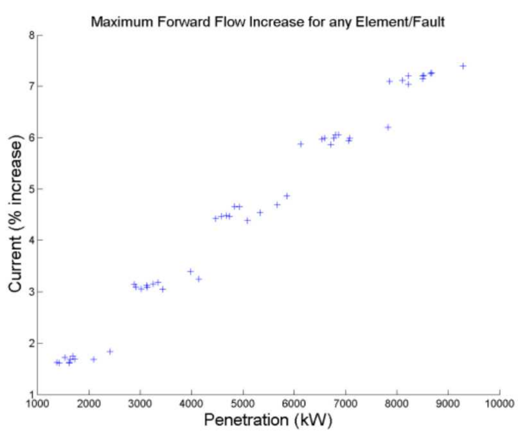
a)



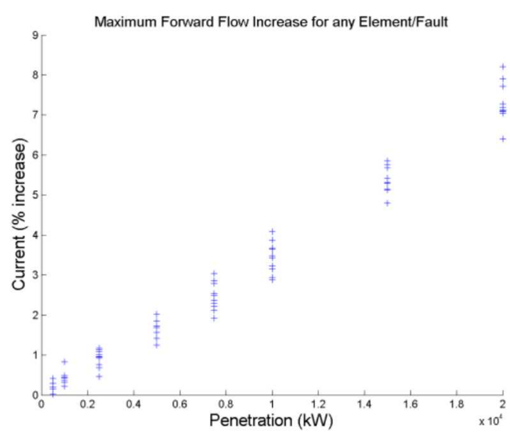
b)

**Figure A-76**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*

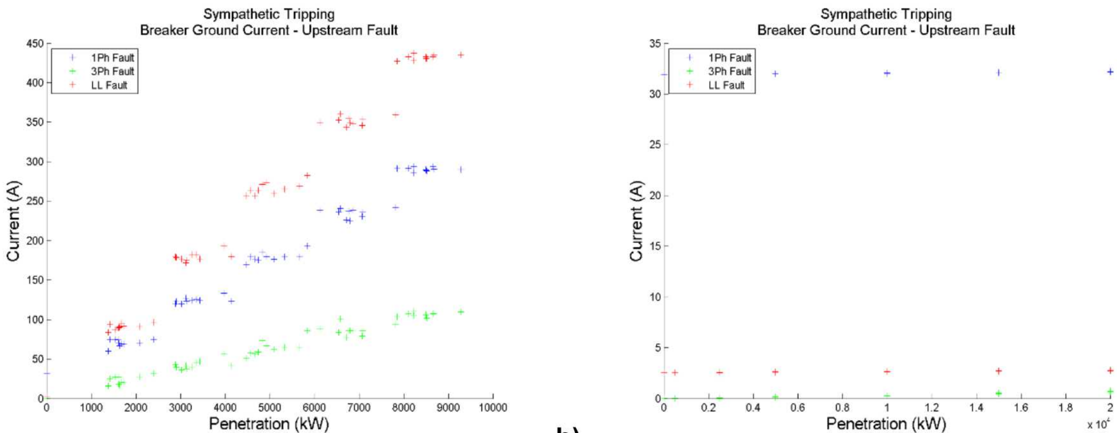


a)



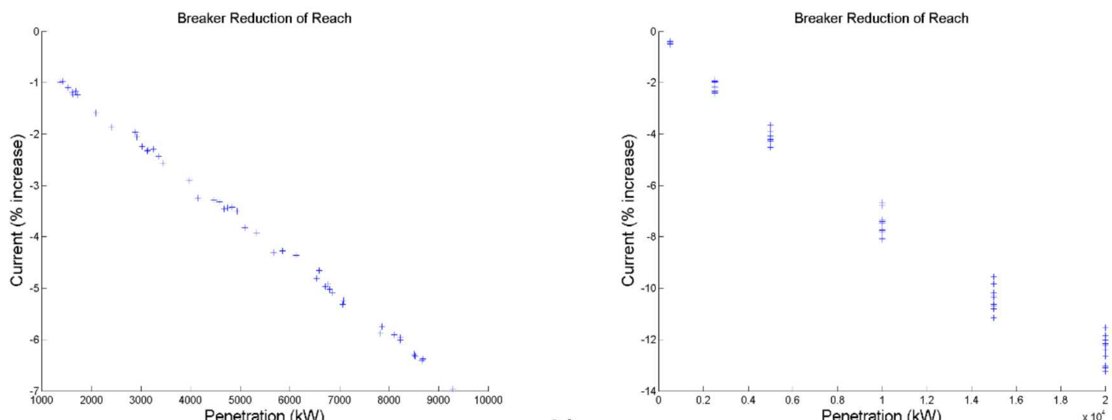
b)

**Figure A-77**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**



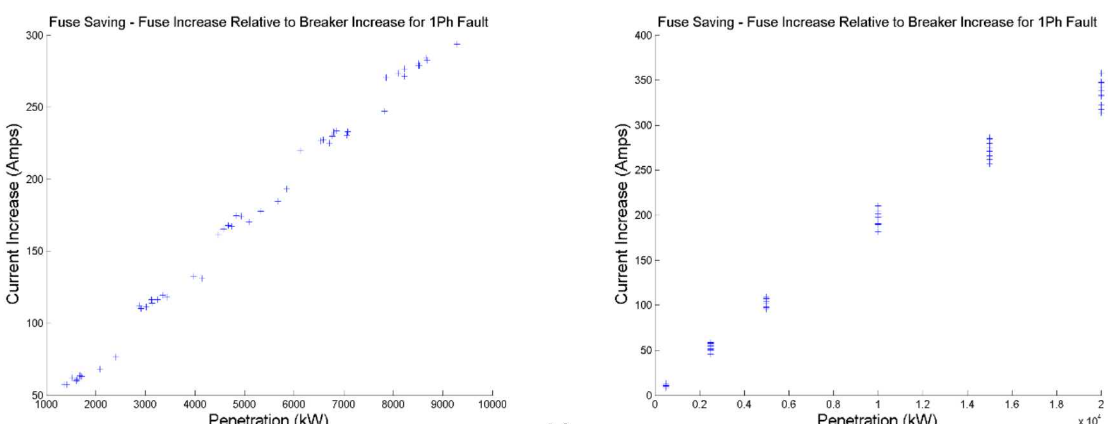

a) b)

**Figure A-78**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-79**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-80**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 2093

The studied 12 kV feeder peak load is 8.5 MW and is the only feeder at the substation. There are 128.8 primary feeder miles that extend a maximum length of 19.0 miles from the substation. There are two main laterals branches starting near the substation. There are approximately 1012 residential customers and 37 commercial customers on the feeder. The substation three-phase LTC regulates voltage on the feeder with line drop compensation. The LTC is modeled in a co-generation mode to maintain the 121.59 V setpoint and 2.08 V band at the low side tap. This feeder also contains three voltage regulators with line drop compensation and a booster. Two voltage regulators are open-delta and one is a closed-delta regulator. There are seven time-controlled capacitors on the feeder but one has been disconnected. The remaining six feeder capacitors provide 3900 kvar total compensation. Five of the capacitor banks are 600 kvar and one capacitor bank is 900 kvar. A feeder voltage profile plot at peak load is shown in Figure A-81a, while a schematic illustrating system impedance is shown in Figure A-81b.

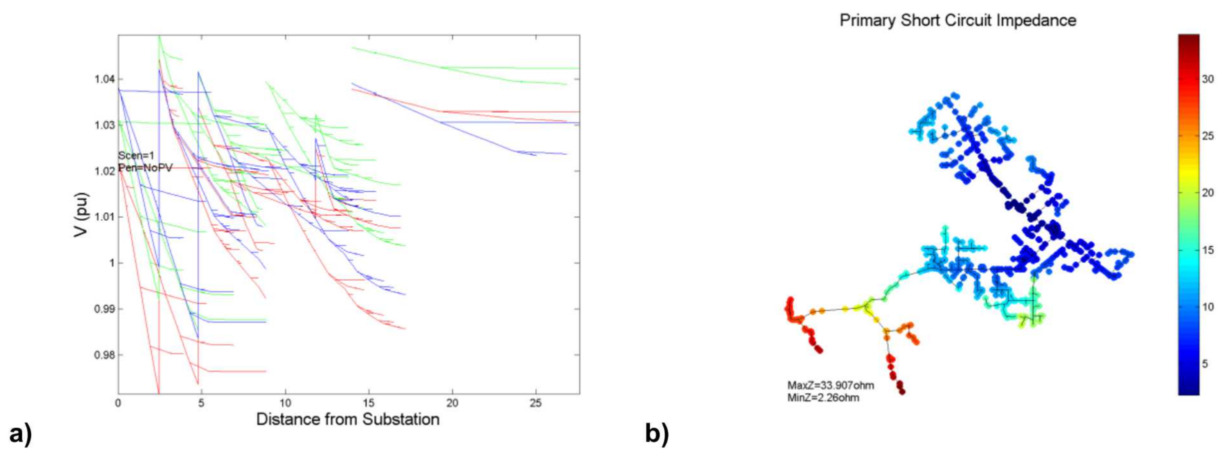



**Figure A-81**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

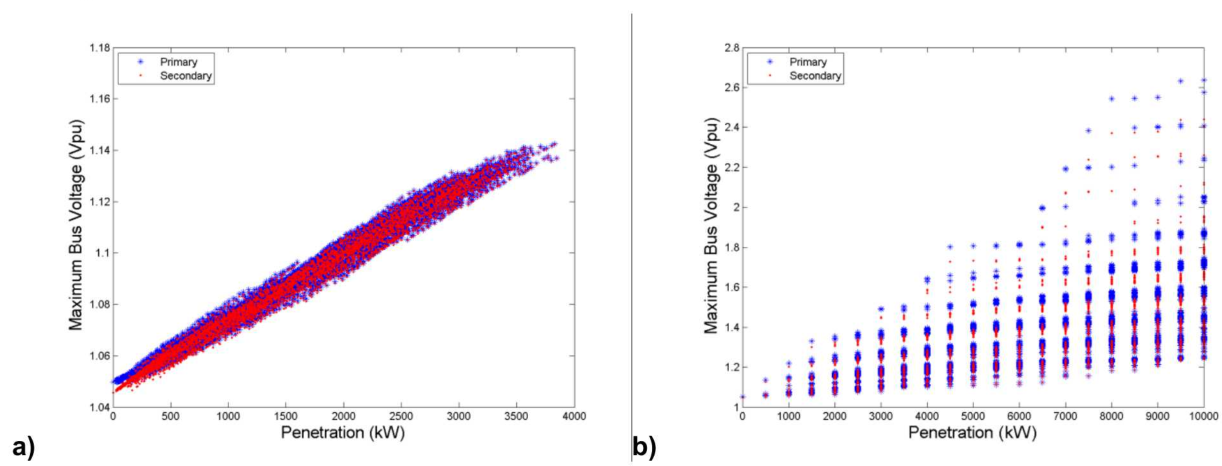
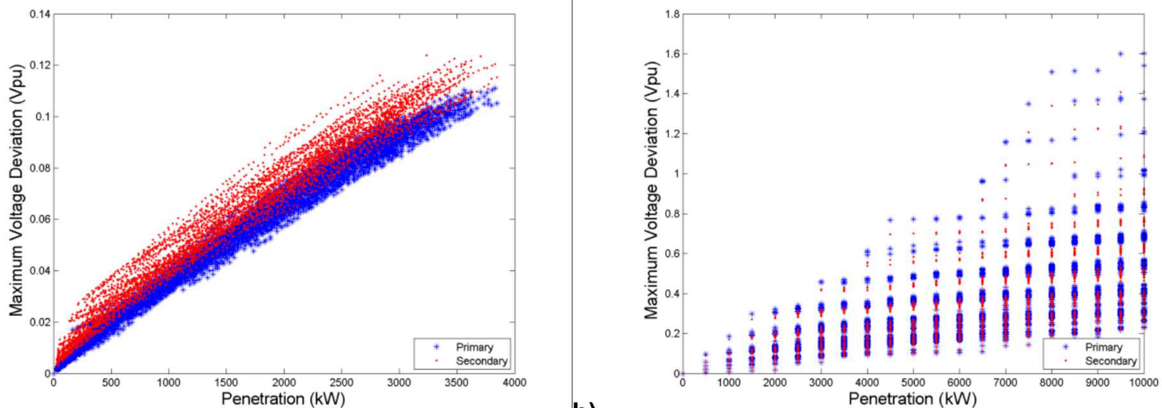
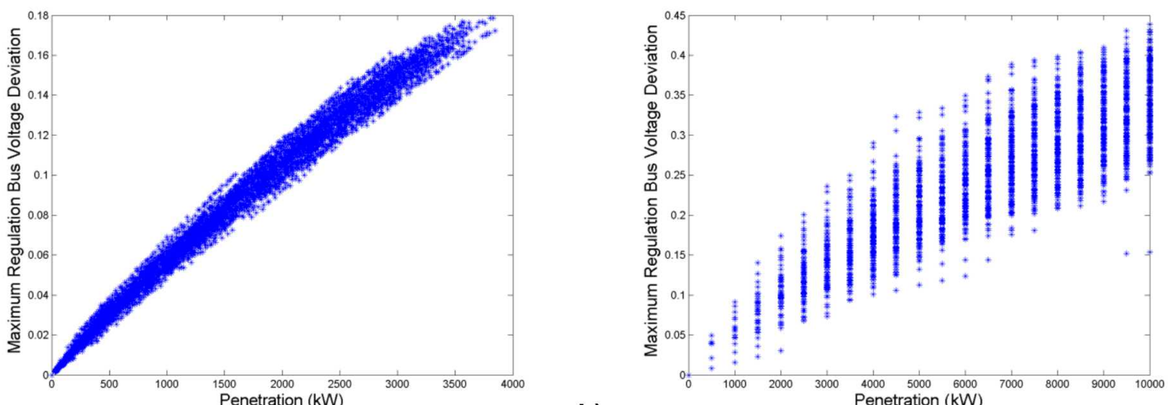



**Figure A-82**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

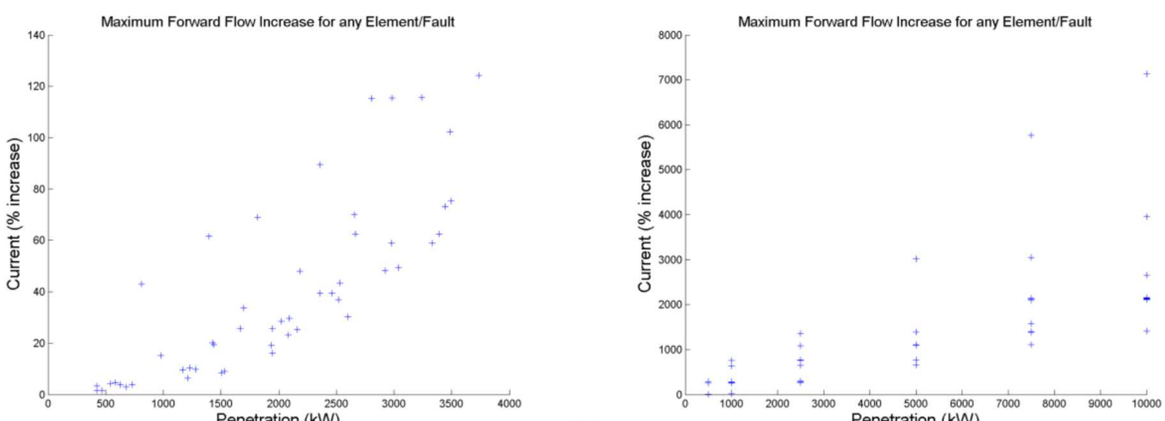
**Figure A-83**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-84**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*




a) b)

**Figure A-85**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**

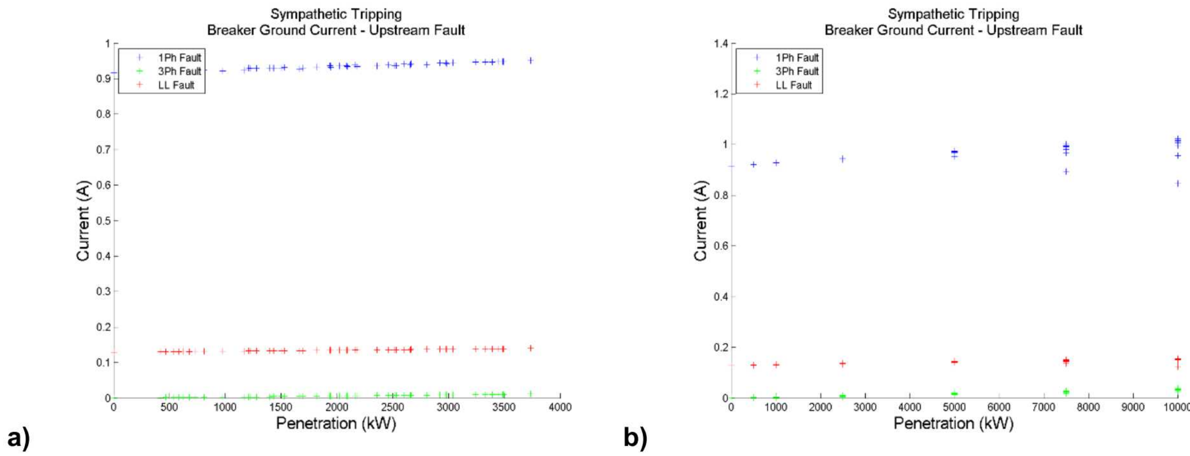



**Figure A-86**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**

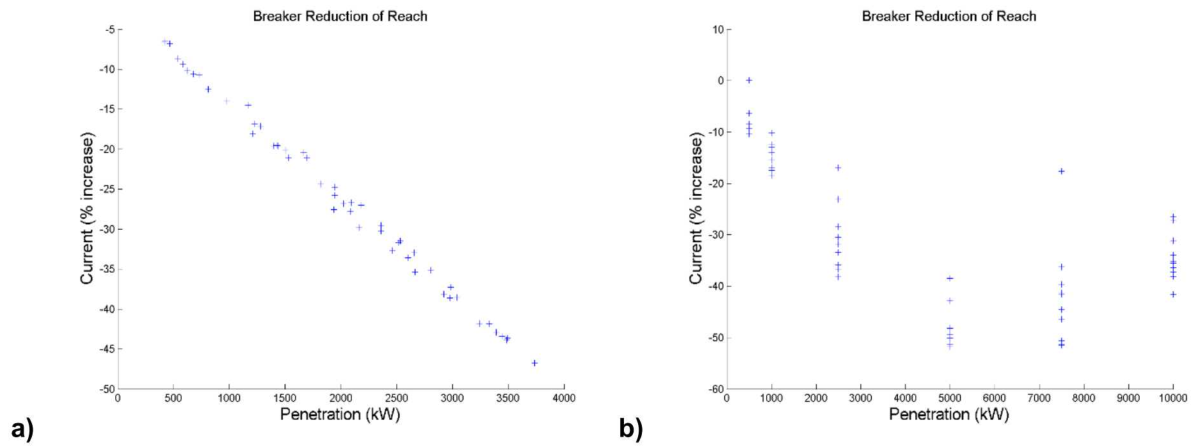



**Figure A-87**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**

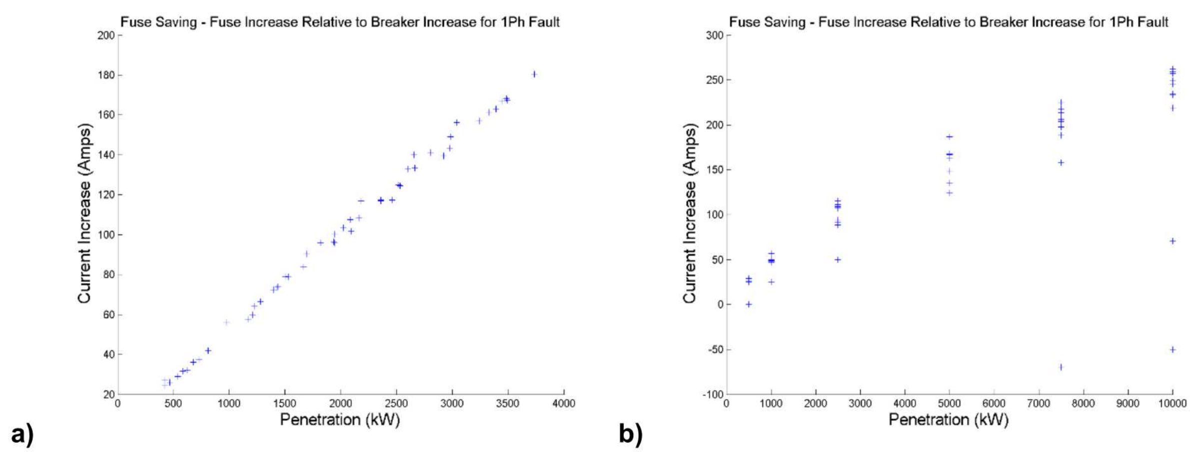



**Figure A-88**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 2921

The studied 12 kV feeder peak load is 7.65 MW. There are 37 primary feeder miles that extend a maximum length of 9.7 miles from the substation within a rural, agricultural area. There are approximately 152 residential customers and 259 commercial customers on the feeder. There are six feeder capacitors totaling 4800 kvar compensation all with voltage controlled settings. Four banks have voltage settings of 120/126V on/off, one bank is controlled at 121/125V on/off and one bank 118/125V on/off (all voltages referenced to 120V nominal base). There are no regulators or LTC on this feeder. A feeder voltage profile plot at peak load is shown in Figure A-89a. A schematic illustrating system impedance is shown in Figure A-89b.

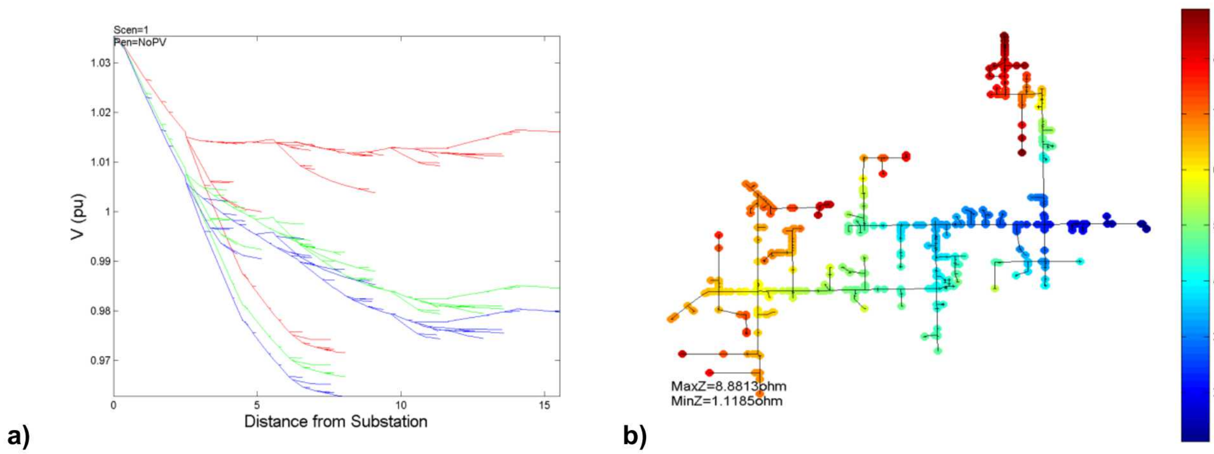



**Figure A-89**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

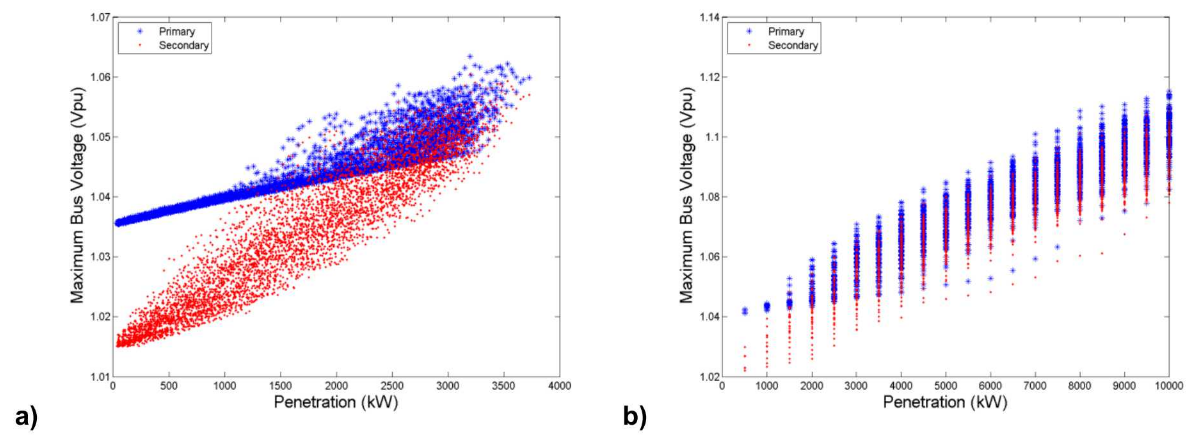
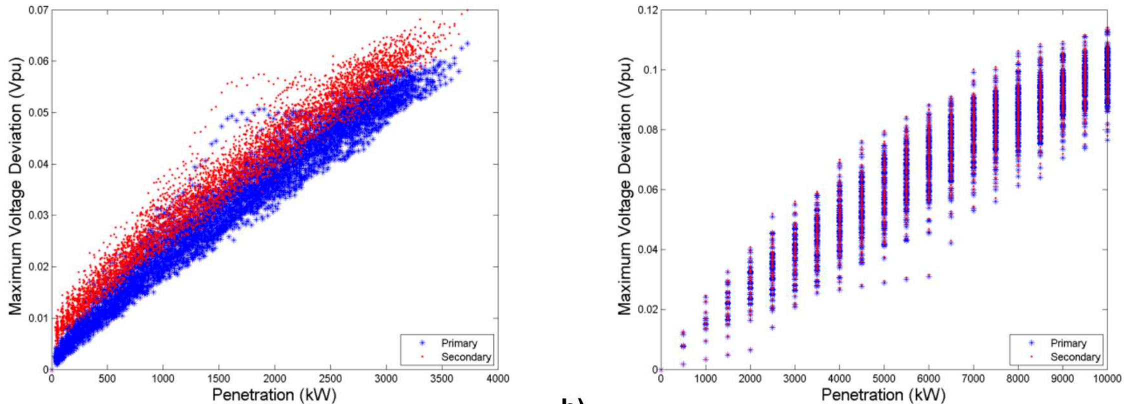


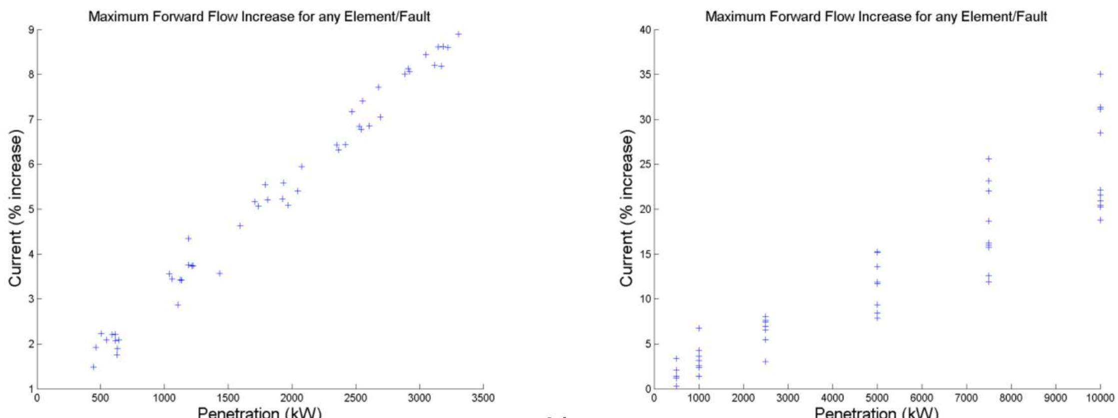

**Figure A-90**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

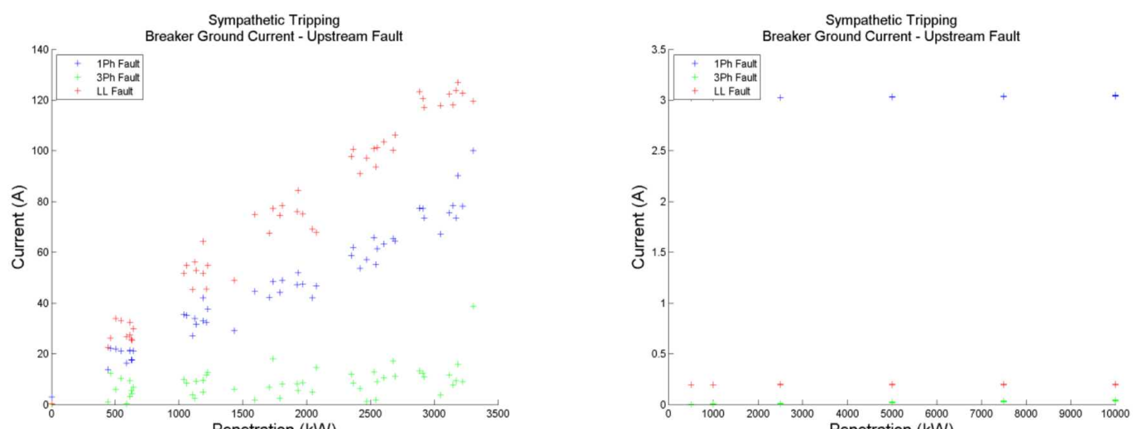
**Figure A-91**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*



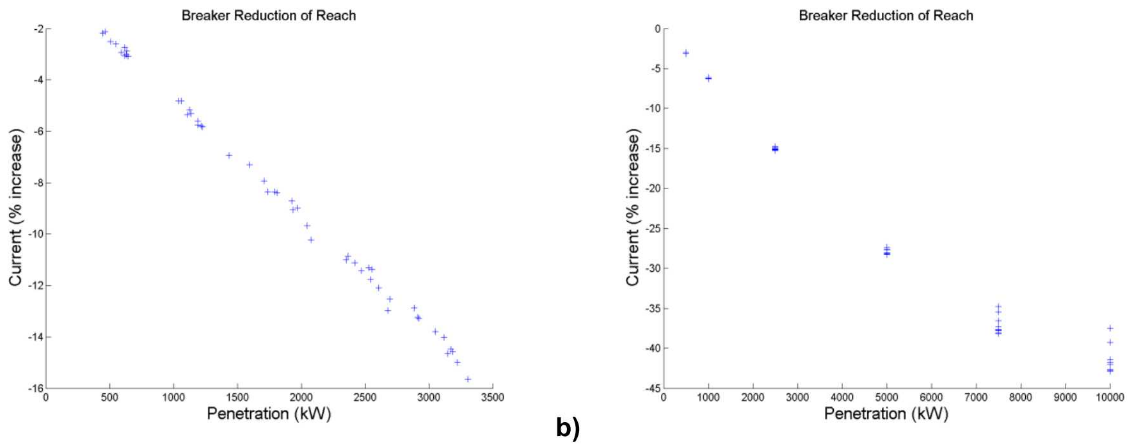

a) b)

**Figure A-92**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**



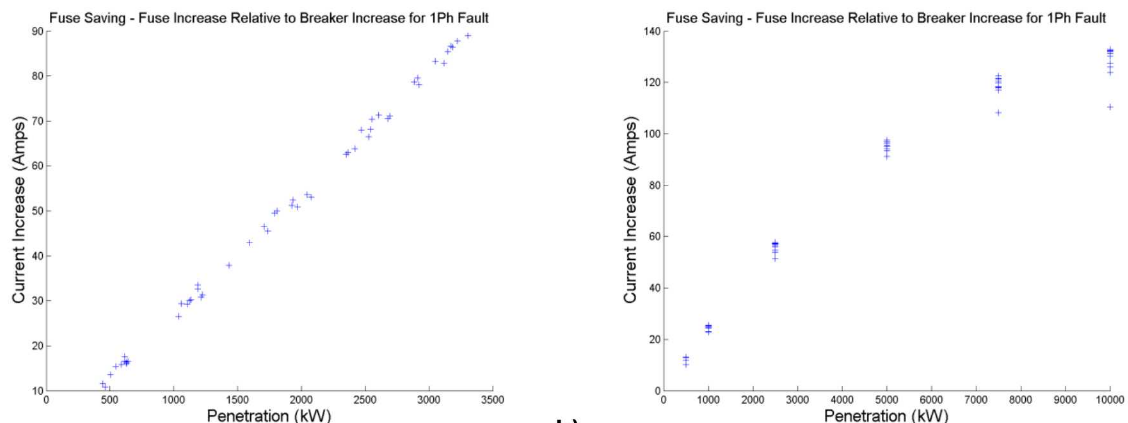

a) b)

**Figure A-93**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-94**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-95**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 2802

The studied 16 kV feeder peak load is 4.84 MW. There are 8.5 primary feeder miles that extend a maximum length of 2.7 miles from the substation within a high density suburban residential/commercial retail area. There are approximately 1305 residential customers, 43 industrial/commercial customers on the feeder. There are three feeder capacitors totaling 3000 kvar compensation all with voltage controlled settings. Two banks have voltage settings 120/123V on/off and one bank is controlled at 119/123V on/off (all voltages referenced to 120V nominal base). There are no regulators or LTC on this feeder. A feeder voltage profile plot at peak load is shown in Figure A-96a. A schematic illustrating system impedance is shown in Figure A-96b.

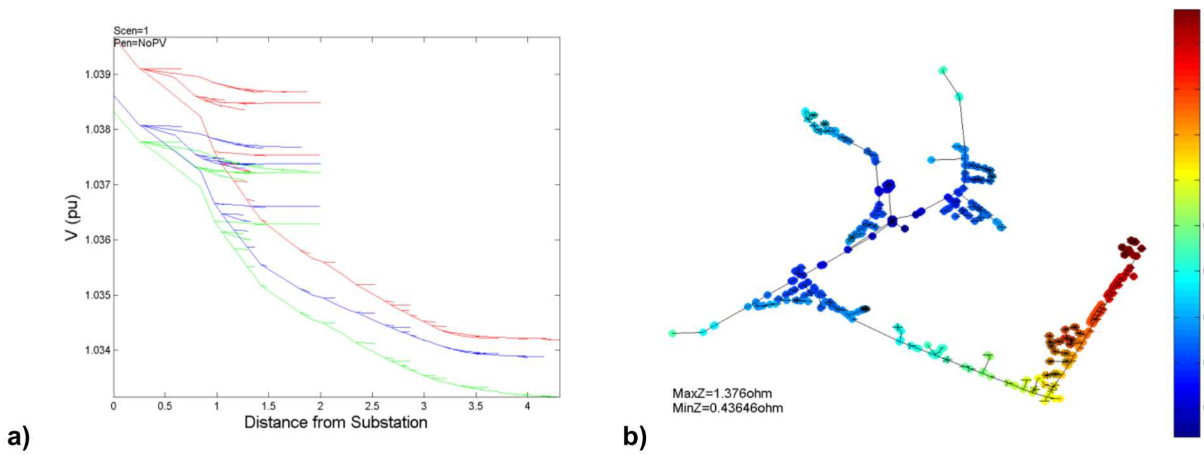



**Figure A-96**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

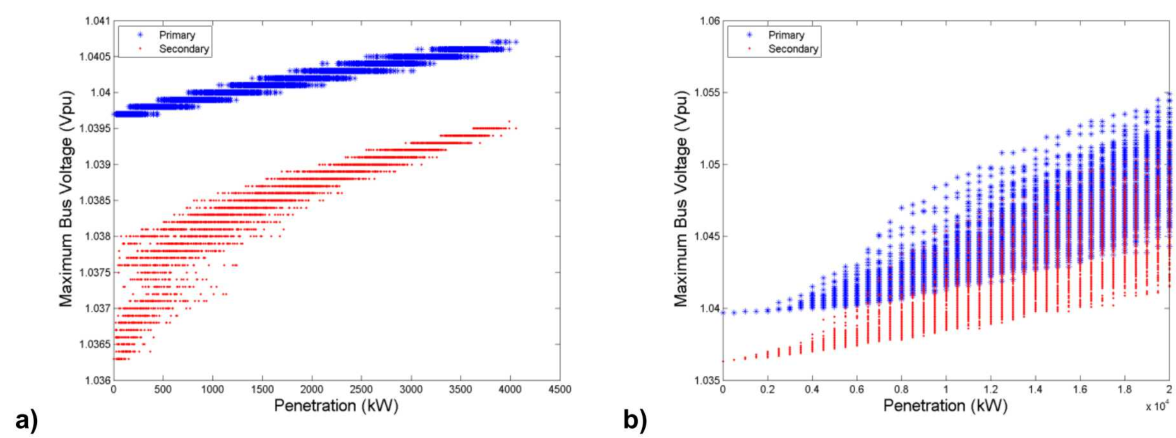



**Figure A-97**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**

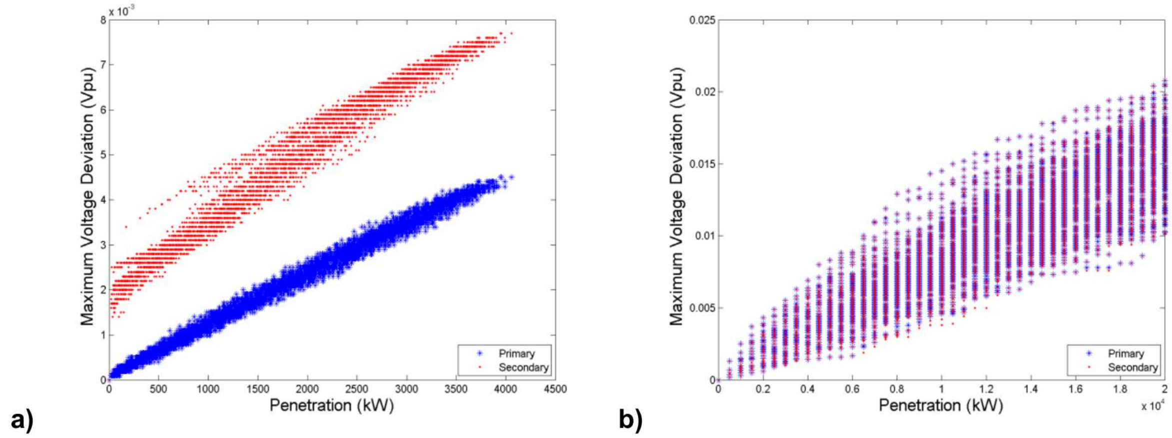



**Figure A-98**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*

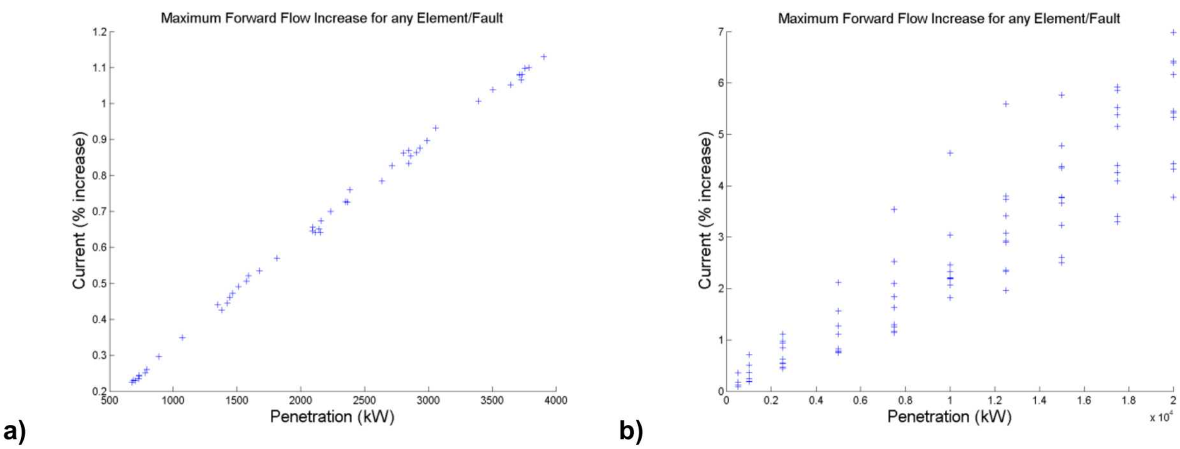



**Figure A-99**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**

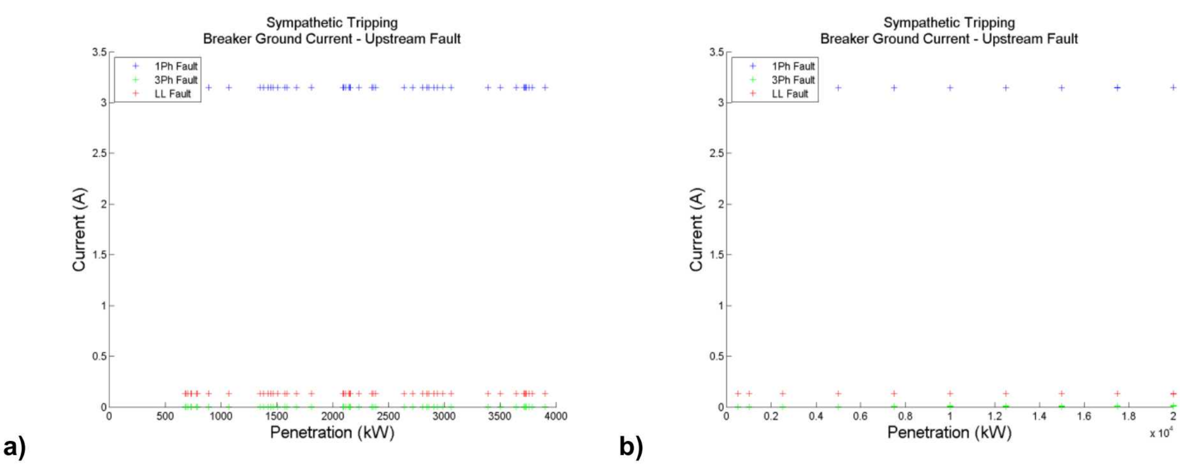



**Figure A-100**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**

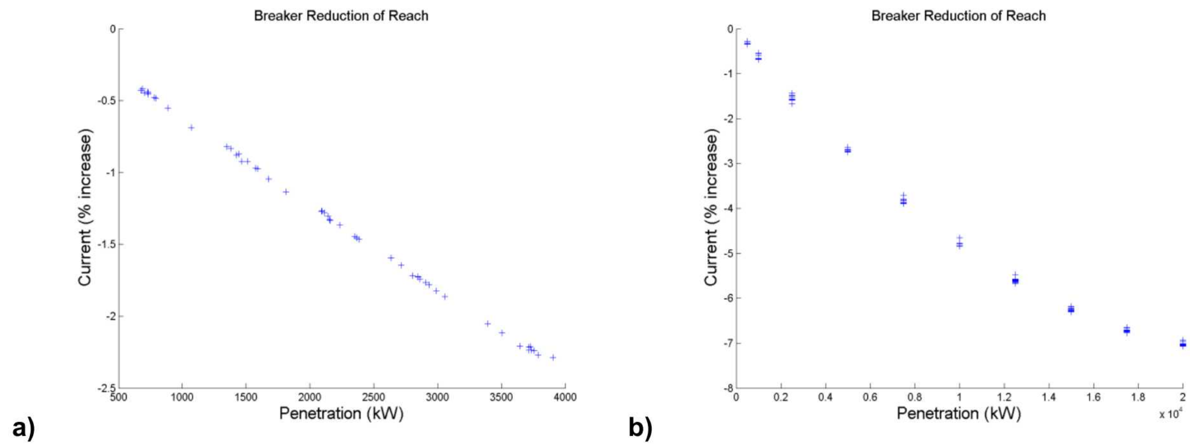



**Figure A-101**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**

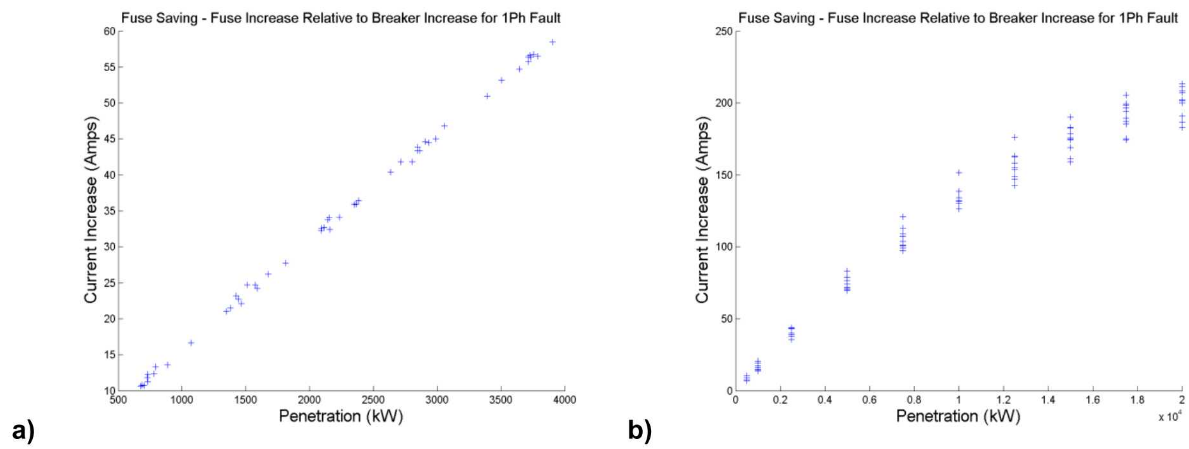
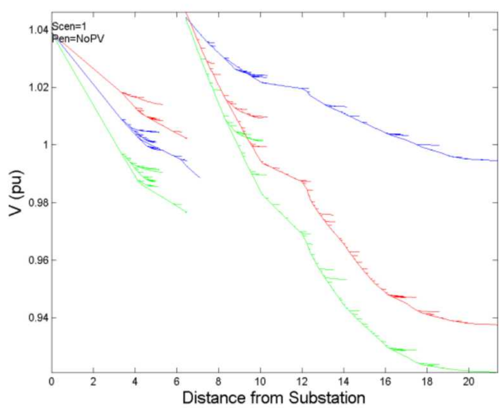


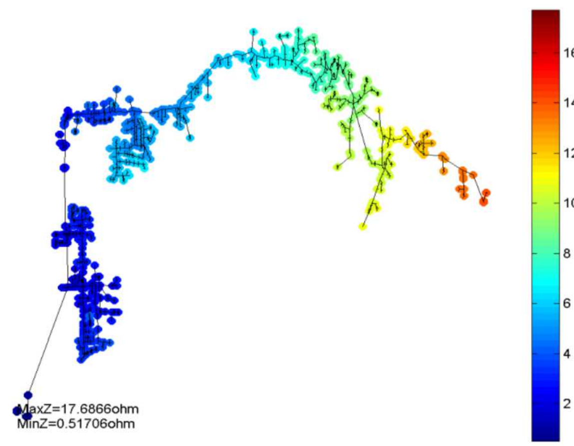

**Figure A-102**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 967

The studied 12 kV feeder peak load is 4.84 MW. There are 27.9 primary feeder miles that extend a maximum length of 13.4 miles from the substation within a high density suburban residential/commercial retail area. There are approximately 1537 residential customers and 40 commercial customers on the feeder. There are five feeder capacitors totaling 2700 kvar compensation. Four banks have voltage controlled settings and one is time-bias voltage control. Three banks have voltage settings 118/121.5V on/off, one bank is controlled at 118/123V on/off and the one time-bias voltage bank has a daytime schedule 121/125V on/off and nighttime 118/122 V on/off. There is not an LTC, but there is one mid-feeder line regulator approximately 4 miles from the feeder head controlled to 126V with a 2V band. All controller voltages are referenced to 120V nominal base. Note that during modeling the regulator target voltage has been dropped to 125.5V to avoid voltage violations in the no PV base case (i.e. a 126V target with 2V band can result in the no PV base case with regulated bus voltages higher than 1.05). A feeder voltage profile plot at peak load is shown in Figure A-103a. A schematic illustrating system impedance is shown in Figure A-103b.



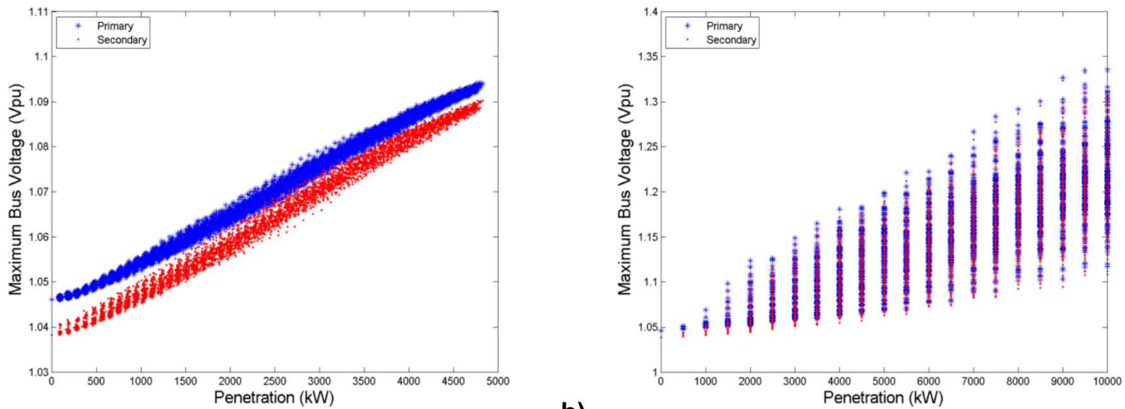

a)




b)

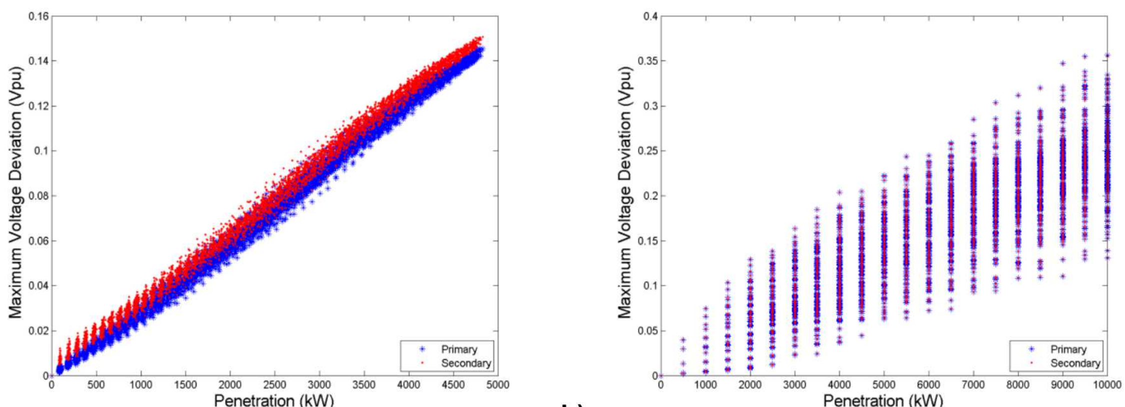
**Figure A-103**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

## *Voltage*



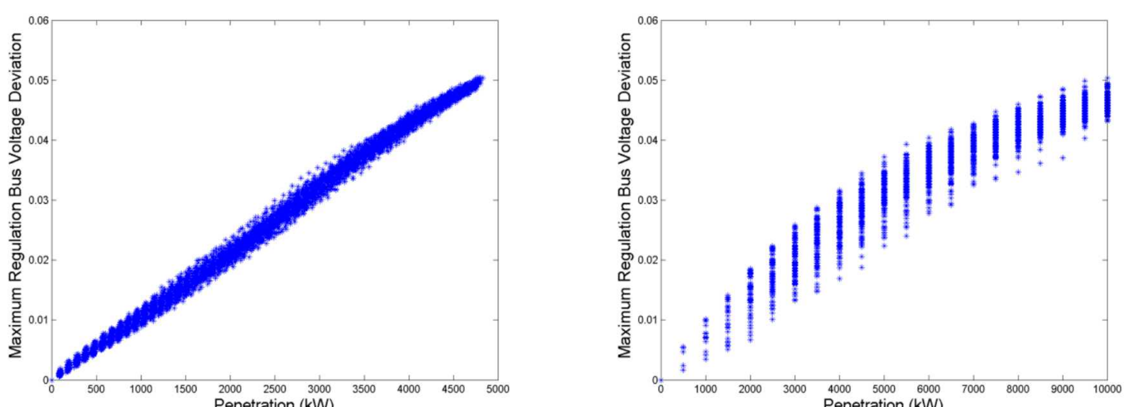

a) b)

**Figure A-104**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

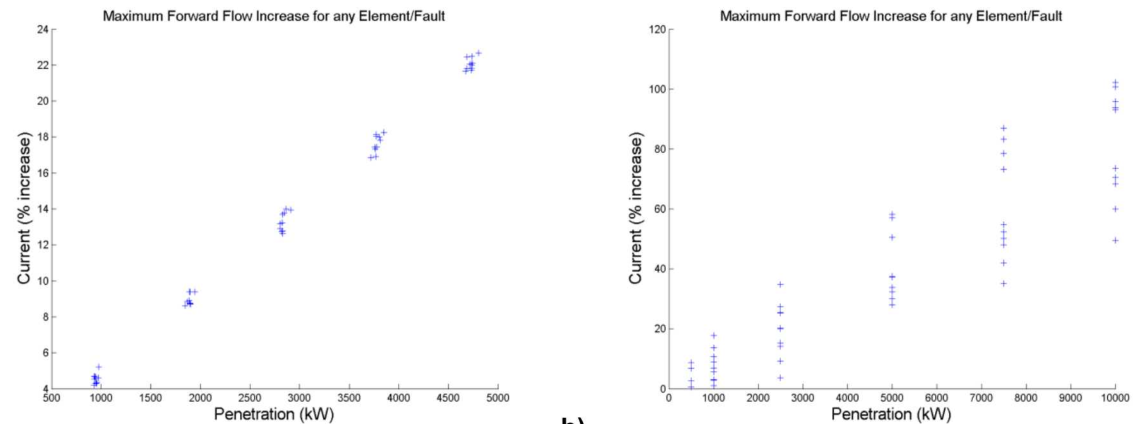
**Figure A-105**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

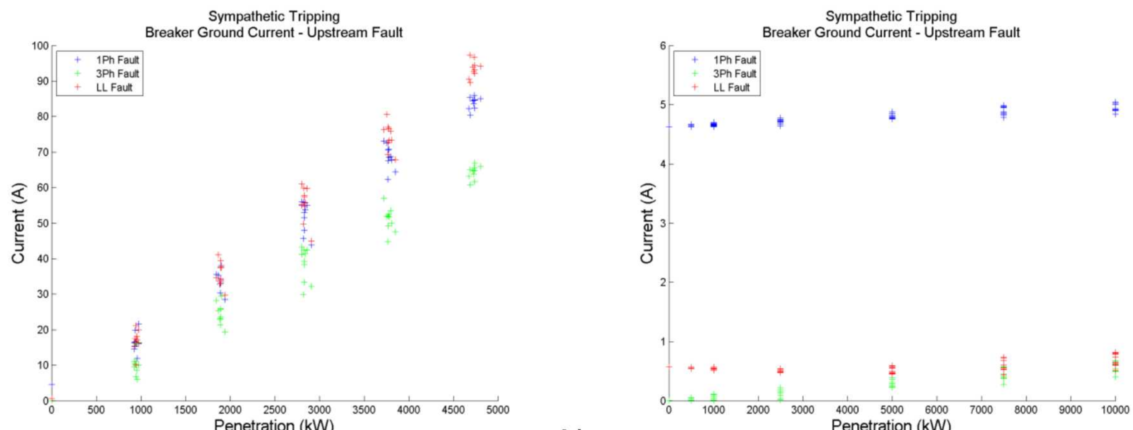
**Figure A-106**
**Regulator Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*



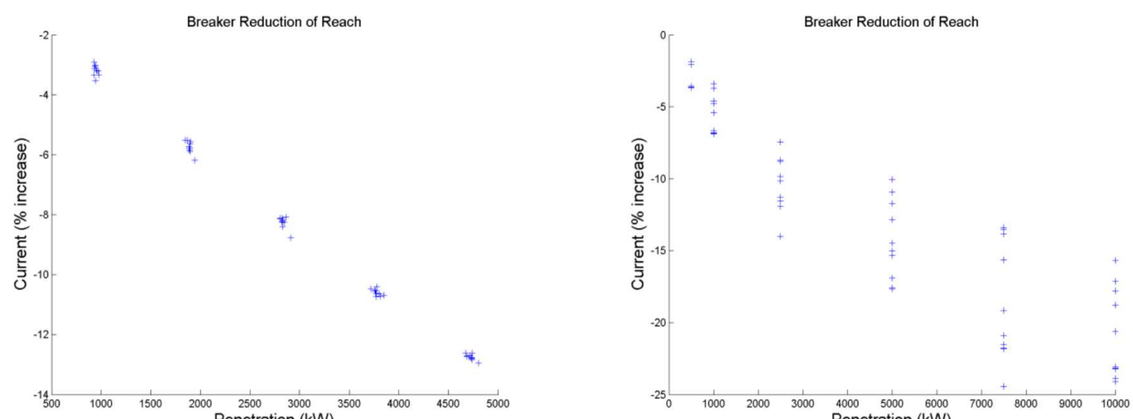

a) b)

**Figure A-107**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**



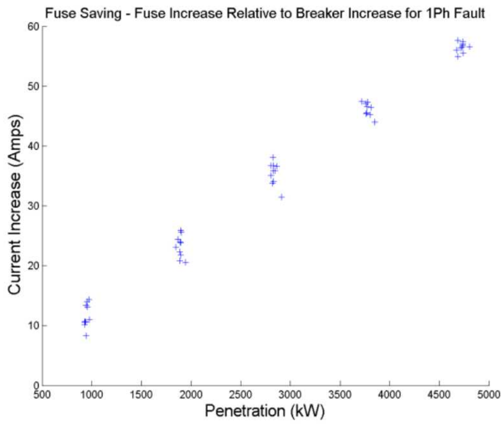

a) b)

**Figure A-108**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**

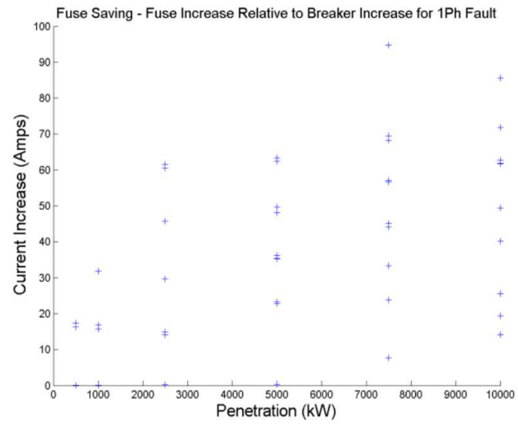



a) b)

**Figure A-109**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**



a)



b)

**Figure A-110**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

## Feeder 3999

The studied 33 kV feeder peak load is 19.6 MW. There are 25.2 primary feeder miles that extend linearly a maximum length of 18 miles from the substation within a semi-rural/industrial warehouse area. The feeder load is dominated by only 4 industrial customers. There are approximately 3 residential customers, 3 agricultural customers and 4 industrial customers on the feeder. Due to the predominance of industrial customers and the very low residential customer counts this circuit was not evaluated for small-scale (residential/commercial) PV deployment. There are no capacitors, regulators, or LTC on this feeder. A feeder voltage profile plot at peak load is shown in Figure A-111a. A schematic illustrating system impedance is shown in Figure A-111b.

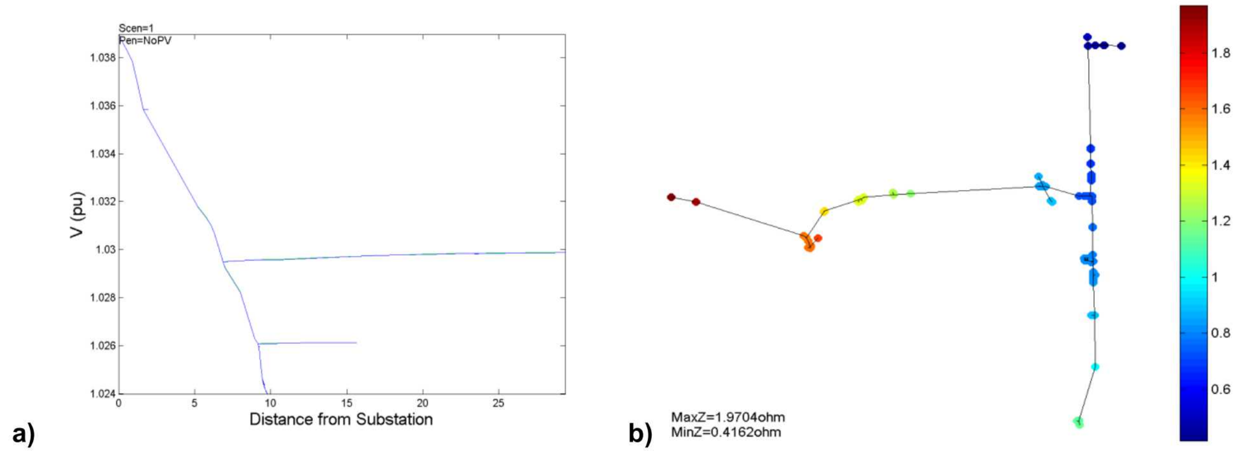



**Figure A-111**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

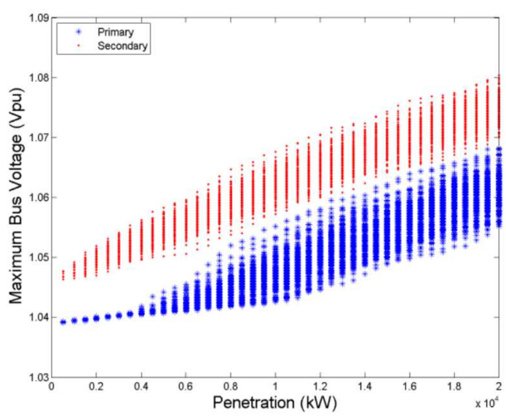



**Figure A-112**
**Primary Overvoltage Trends: Large-Scale PV**

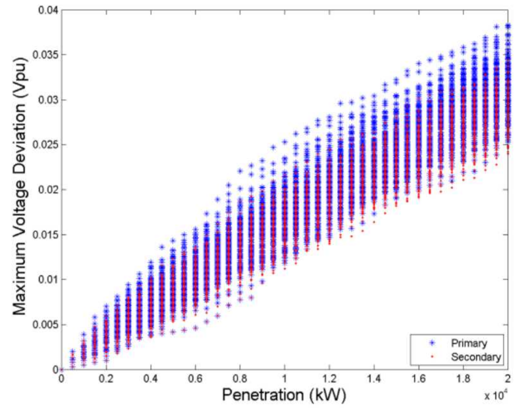



**Figure A-113**
**Primary Voltage Deviation Trends: Large-Scale PV**

## *Protection*

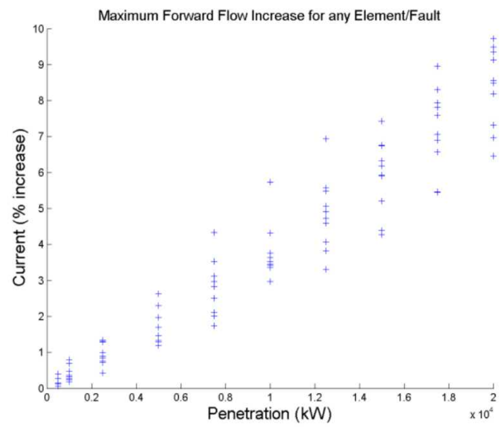



**Figure A-114**
**Element Fault Current Trends: Large-Scale PV**

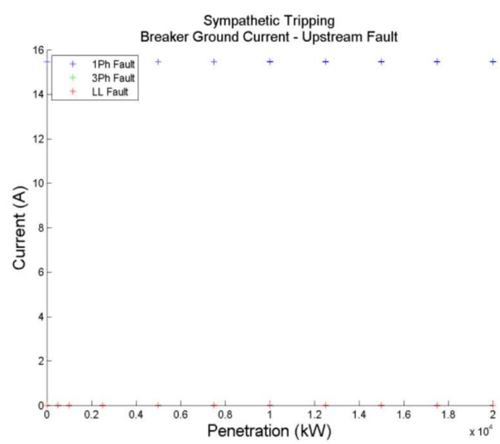



**Figure A-115**
**Breaker Ground Current Trends: Large-Scale PV**

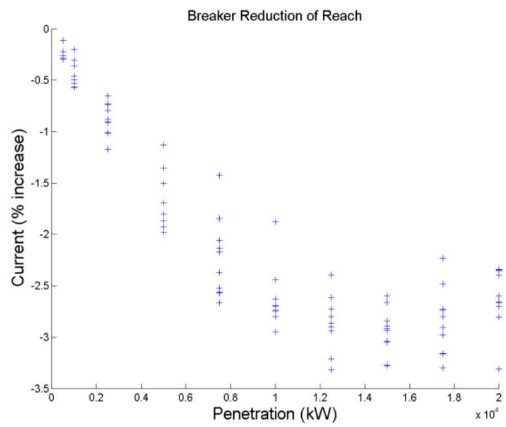



**Figure A-116**
**Reduced Breaker Sensitivity Trends: Large-Scale PV**

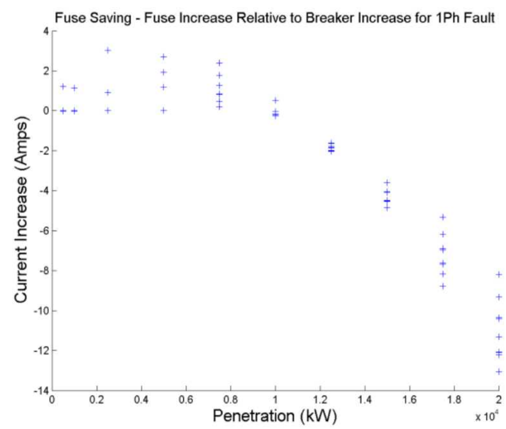



**Figure A-117**
**Fuse Current Trends: Large-Scale PV**

## Feeder 420

The studied 12 kV feeder peak load is 5.6 MW with an existing 890kW of PV. There are 11.2 primary feeder miles that extend a maximum length of 3 miles from the substation within an older downtown urban residential and commercial retail area. There are approximately 1956 residential customers and 6 commercial customers on the feeder. There is one operating feeder capacitor totaling 1200 kvar compensation on time-bias voltage control. The one time-bias voltage controlled bank has a daytime schedule 121/124.5V on/off and nighttime 118/121.5 V on/off (all voltages referenced to 120V nominal base). There are no regulators or LTC on this feeder. A feeder voltage profile plot at peak load is shown in Figure A-118a. A schematic illustrating system impedance is shown in Figure A-118b.

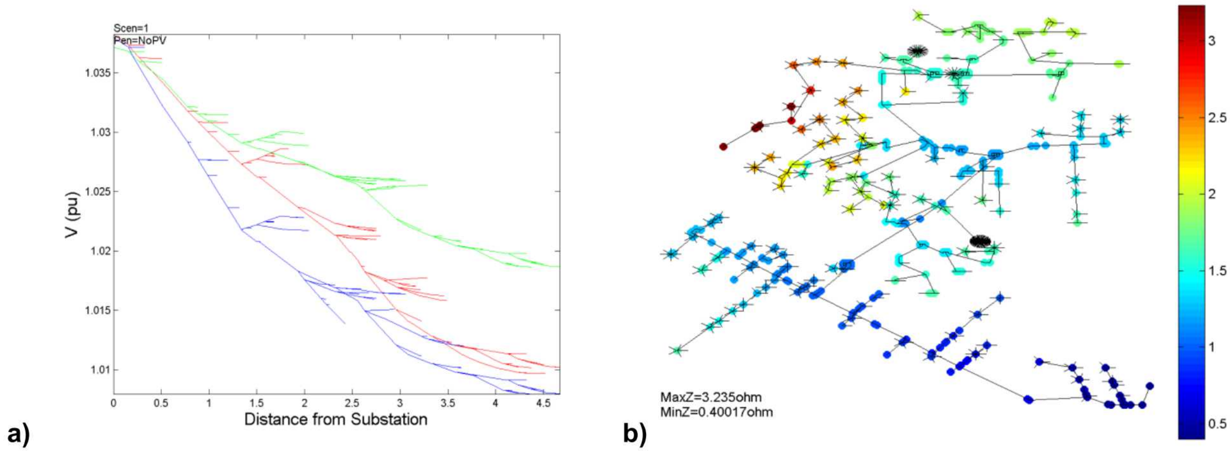



**Figure A-118**
**Feeder a) Peak Load Voltage Profile b) Schematic/Impedance**

### *Voltage*

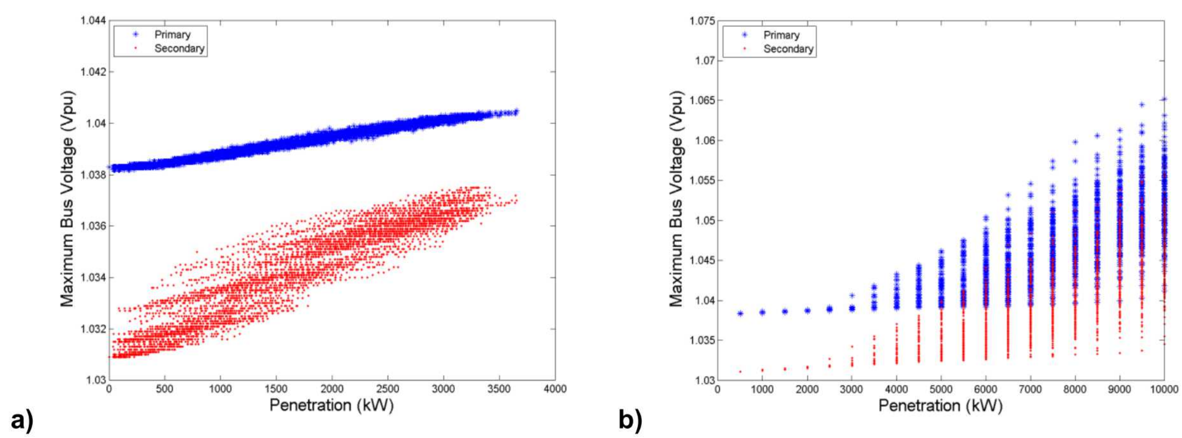



**Figure A-119**
**Primary Overvoltage Trends a) Small-Scale PV b) Large-Scale PV**

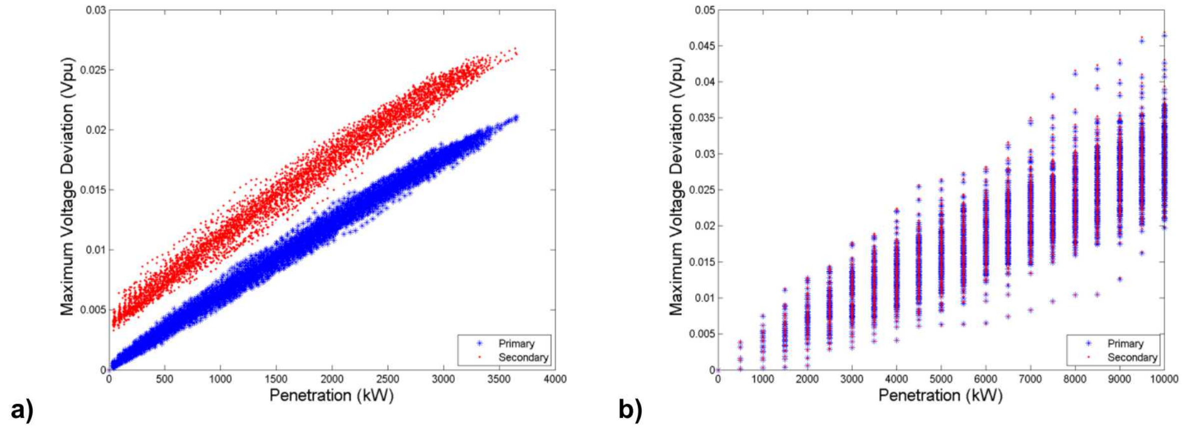



**Figure A-120**
**Primary Voltage Deviation Trends a) Small-Scale PV b) Large-Scale PV**

## *Protection*

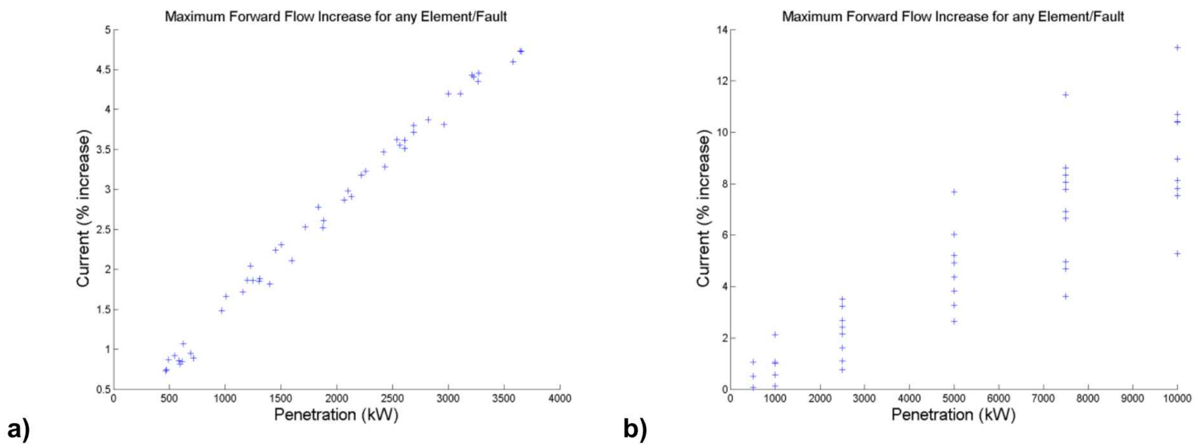



**Figure A-121**
**Element Fault Current Trends a) Small-Scale PV b) Large-Scale PV**

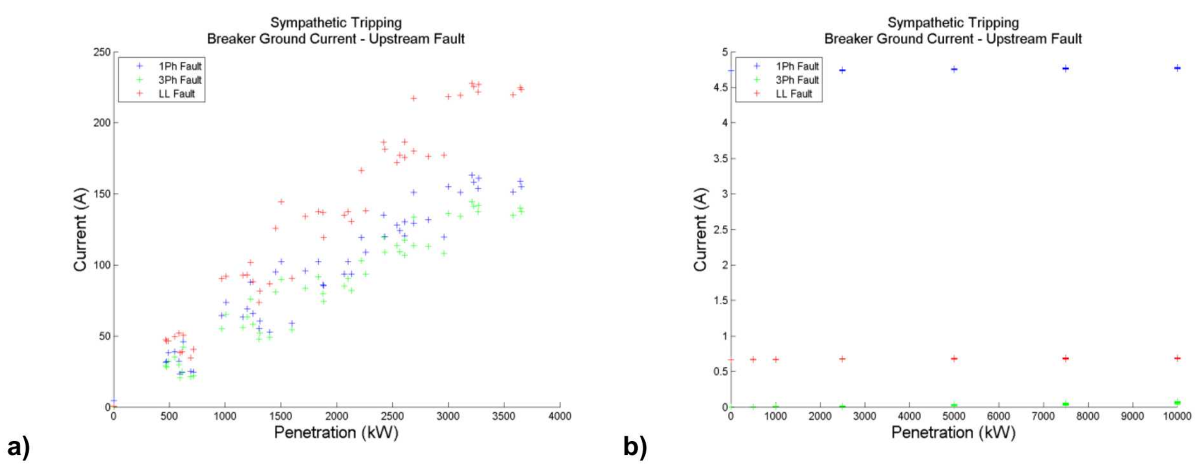
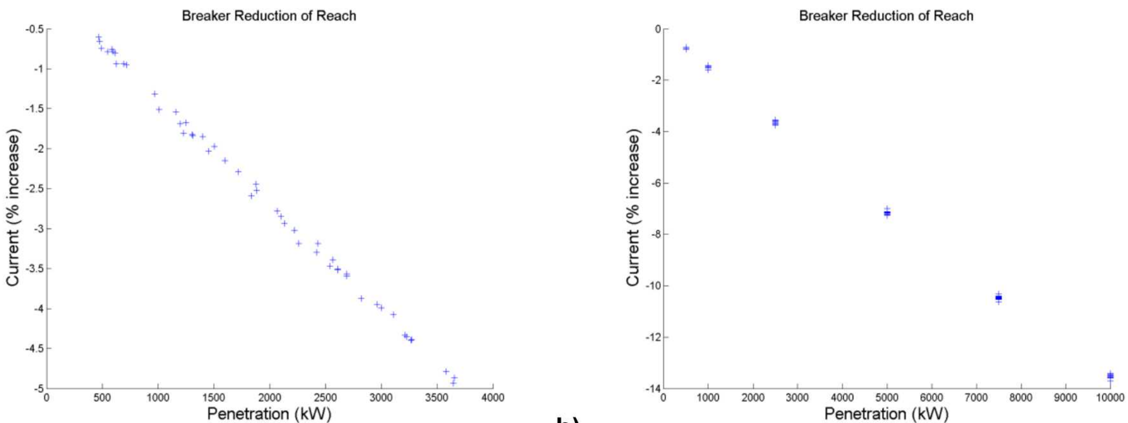
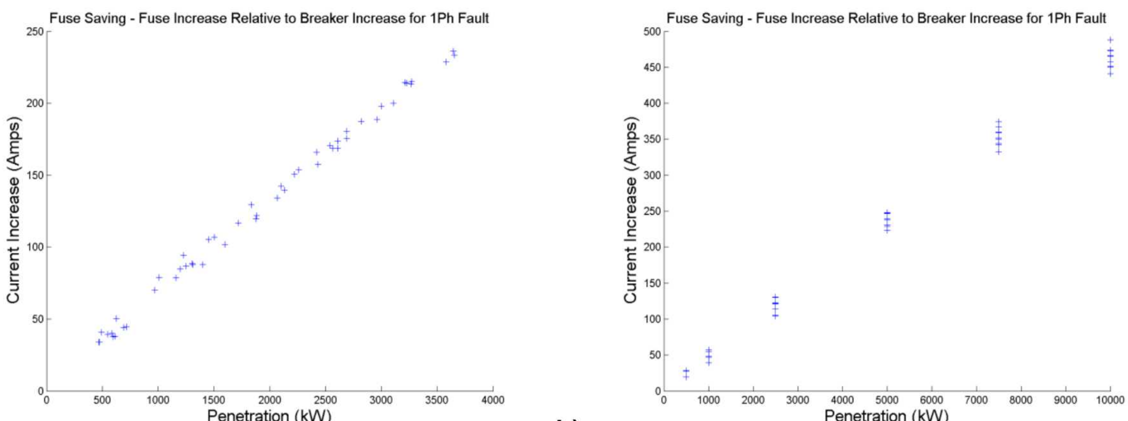



**Figure A-122**
**Breaker Ground Current Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-123**
**Reduced Breaker Sensitivity Trends a) Small-Scale PV b) Large-Scale PV**




a) b)

**Figure A-124**
**Fuse Current Trends a) Small-Scale PV b) Large-Scale PV**

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**Electric Power Research Institute**
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com