California Solar Initiative

RD&D: Research, Development, Demonstration and Deployment Program

GO solar CALIFORNIA

Final Project Report:

Alternatives to the 15% Rule

Grantee:

ELECTRIC POWER RESEARCH INSTITUTE (EPRI)

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http://www.calsolarresearch.ca.gov/Funded-Projects/

Preface

The goal of the California Solar Initiative (CSI) Research, Development, Demonstration, and Deployment (RD&D) Program is to foster a sustainable and self-supporting customer-sited solar market. To achieve this, the California Legislature authorized the California Public Utilities Commission (CPUC) to allocate **$50 million** of the CSI budget to an RD&D program. Strategically, the RD&D program seeks to leverage cost-sharing funds from other state, federal and private research entities, and targets activities across these four stages:

- Grid integration, storage, and metering: 50-65%
- Production technologies: 10-25%
- Business development and deployment: 10-20%
- Integration of energy efficiency, demand response, and storage with photovoltaics (PV)

There are seven key principles that guide the CSI RD&D Program:

1. **Improve the economics of solar technologies** by reducing technology costs and increasing system performance;
2. **Focus on issues that directly benefit California**, and that may not be funded by others;
3. **Fill knowledge gaps** to enable successful, wide-scale deployment of solar distributed generation technologies;
4. **Overcome significant barriers** to technology adoption;
5. **Take advantage of California's wealth of data** from past, current, and future installations to fulfill the above;
6. **Provide bridge funding** to help promising solar technologies transition from a pre-commercial state to full commercial viability; and
7. **Support efforts to address the integration of distributed solar power into the grid** in order to maximize its value to California ratepayers.

For more information about the CSI RD&D Program, please visit the program web site at www.calsolarresearch.ca.gov.

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Alternatives to the 15% Rule: Final Project Summary. EPRI, Palo Alto, CA: 2015. 3002006594.

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ABSTRACT

The third solicitation of the California Solar Initiative (CSI) Research, Development, Demonstration and Deployment (RD&D) Program established by the California Public Utilities Commission (CPUC) supported the Electric Power Research Institute (EPRI), National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL) with collaboration from Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E), in research to improve the Utility Application Review and Approval process for 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.[1]

This CSI RD&D project accomplished the tasks of collecting data from the three utilities, clustering feeder characteristic data to attain a sample set of feeders, detailed modeling of 16 sample feeders, analysis of PV impacts to those feeders, refinement of current screening processes, and validation of those suggested refinements.

The detailed feeder impact analysis performed identified when potential issues from aggregate distributed generation were not properly identified and also when a feeder was capable of accommodating considerably higher levels of distributed generation. The “Alternatives to the 15% Rule” found in this project more properly address the impacts from distributed generation and were not dependent on load level alone. The improvements suggested included:

- Add an Initial Review screen that addresses if the feeder has line regulators
- Modify the Initial Review to always address aggregate generation
- Add Supplemental Review equations to be used as a guideline to address the voltage and protection impacts from aggregate generation

This report summarizes all components of the overall project.

Keywords
Application
Distributed PV
Interconnection
Screens
Solar

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

EXECUTIVE SUMMARY

The third solicitation of the California Solar Initiative (CSI) Research, Development, Demonstration and Deployment (RD&D) Program established by the California Public Utilities Commission (CPUC) supported the Electric Power Research Institute (EPRI), National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL) with collaboration from Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E), in research to improve the Utility Application Review and Approval process for 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.[2]

This CSI RD&D project has completed the tasks of collecting data from the three utilities, clustering feeder characteristic data, detailed modeling of 16 sample feeders, and analysis of PV impacts to those feeders. In this report each task is summarized to produce a final summary of all components of the overall project.

Industry Challenge

Various incentive programs have increased the number of solar PV system interconnection requests to levels never before seen. Utilities must evaluate these interconnection requests to ensure proper operation of the grid is maintained. To assist utilities in quickly evaluating these systems, certain "screens" have been developed over the years that help identify when issues may or may not arise. The most common screening method takes into account the ratio of solar PV to peak load (15%), however it does not take into account the locational impact of PV nor the feeder-specific characteristics that can strongly factor in to whether issues may occur. EPRI has shown that a feeder's hosting capacity for accommodating PV is strongly determined by location of PV as well as a specific feeder's characteristics.[3]

Project Goal

The objective of this project, entitled *Screening Distribution Feeders: Alternatives to the 15% Rule*, was to develop a screening methodology that efficiently evaluates new interconnection requests while taking into account PV and feeder-specific factors. The method not only considered the peak load levels, but also other critical factors including PV location, aggregate PV effects, and most importantly specific feeder characteristics such as voltage class, voltage regulation schemes, and operating criteria.

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

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

The modifications suggested for CA Rule 21 are made based on the technical analysis conducted within this project's detailed PV impact study. The recommendations are based on PV while Rule 21 is inclusive of all forms of distributed generation.

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 sought to provide utilities in California (CA) with a useable and accurate way to determine the available capacity for PV generation on existing distribution feeders. The overall project approach was accomplished via the key tasks outlined in Figure 1. This report will highlight each of the main tasks:

- Document current practices for screening PV interconnections both inside and outside of CA.4
- 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.5
- Complete detailed feeder electrical modeling of selected test group of feeders across CA.9
- 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 formal validation process to determine accuracy of screening methodology. [10]

[4] Current Utility Screening Practices, Technical Tools, Impact Studies, and Mitigation Strategies for Interconnecting PV on the Electric Distribution Systems. EPRI, Palo Alto, CA: 2014. 3002003277.
[5] Clustering Methods and Feeder Selection for California Solar Initiative. EPRI, Palo Alto, CA: 2014. 3002002562.
[6] Alternatives to the 15% Rule: Modeling and Hosting Capacity Analysis of 16 Feeders. EPRI, Palo Alto, CA: 2015. 3002005812.
[7] Alternatives to the 15% Rule: Modified Screens and Validation. EPRI, Palo Alto, CA: 2015. 3002006594.

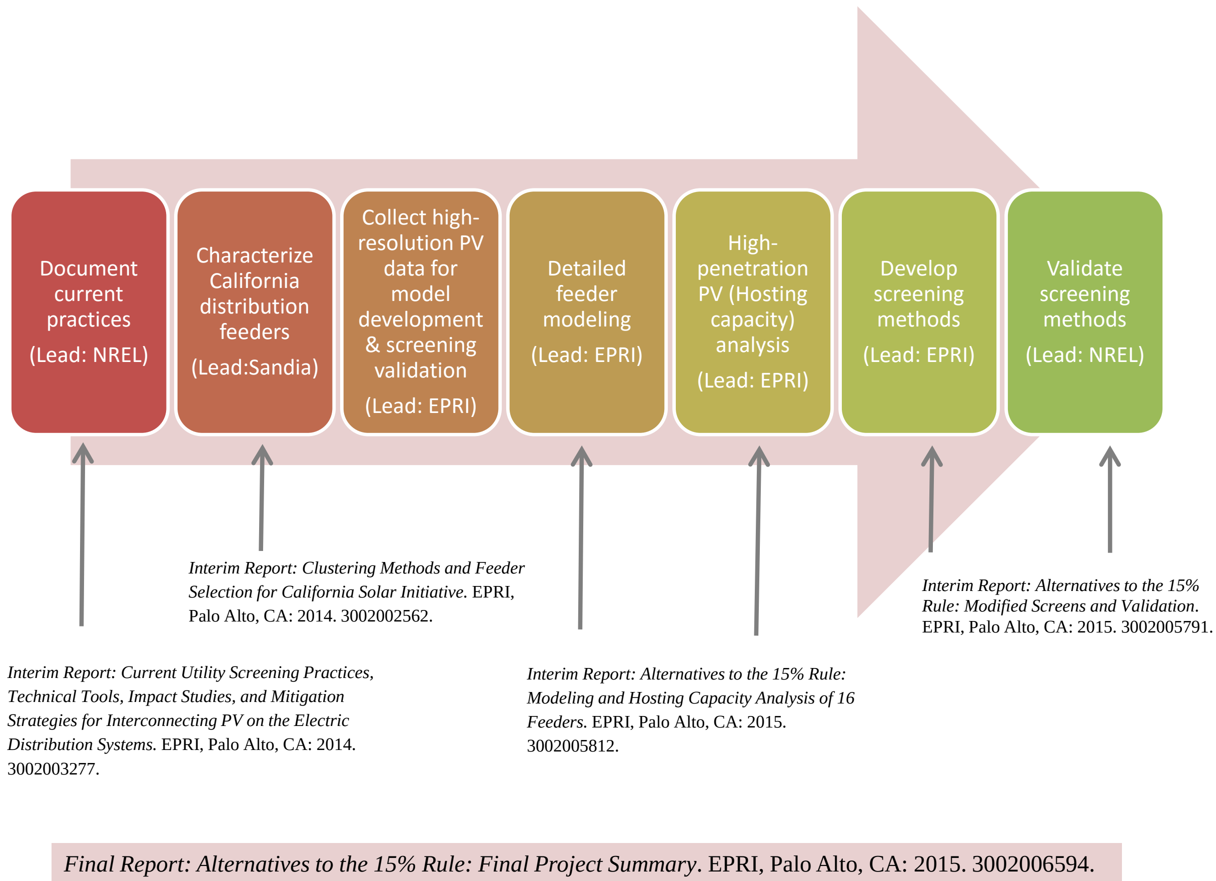

Figure 1
Overall Project Approach and Interim Task Reports

Project Summary

Rule 21 is an interconnection procedure for California utilities to follow for distributed generation application reviews. Utilities have the opportunity to go above and beyond where necessary but at a minimum must consider the contained screening methods. The interpretation and application of Rule 21 screens is based on planning procedures and the ability to conduct certain analyses. Most CA utilities have commented that even though Project Task 1 (Documentation of Current Practices) identified that the screening process can take well longer than the allotted time if supplemental and detailed review are necessary, their proficiency in the review process is considerably better than most utilities due to the number of interconnection requests encountered to date.

Each task of this project helped progress to the final goal of improving CA Rule 21 as penetration levels and interconnection requests continue to increase. The majority of the effort in this project consisted of selecting the feeders for detailed analysis as well as performing that analysis, suggesting updates to Rule 21, and validating those updated methods.

The selection of the utility feeders was based on the results of a comprehensive clustering analysis where each feeder from the three CA investor-owned electric utilities was characterized and grouped into sets. The samples chosen from each set do not suggest all feeders within the set will have a similar response to distributed generation, but the sets allow selection of several feeders that will have considerably different characteristics and responses to DER. These sample feeders from each utility were placed into two groups. One group of 16 for detailed analysis and another group of six for screening validation.

A detailed feeder model was developed for each of the selected feeders. The models were based on the utility planning model and converted into the OpenDSS distribution software. The OpenDSS distribution software was used such that detailed analysis can be performed similarly across the different utilities even though the original models come from different software platforms.

The analysis of the models was conducted with PV as the distributed energy resource. Rule 21 is inclusive of all distributed generation types, but this project specifically analyzed distributed PV. The hosting capacity analysis determined the amount of PV that can be accommodated on a distribution feeder without impacts exceeding predefined utility guided thresholds. The hosting capacity for each feeder is unique for voltage and protection issues.

The detailed feeder impact analysis performed identifies when potential issues from aggregate distributed generation are not properly identified and also when a feeder is capable of accommodating considerably higher levels of distributed generation based upon where it is located. The “Alternatives to the 15% Rule” found in this project more properly address the impacts from distributed generation and are not dependent on load level alone.

The improvements suggested to Rule 21 are illustrated in Figure 2 and include:

- An additional Initial Review screen that addresses if the feeder has line regulators
- A modification to the Initial Review to always account for aggregate generation
- Supplemental Review equations to be used as a guideline to address the impacts of aggregate generation for issues not solely dependent on load

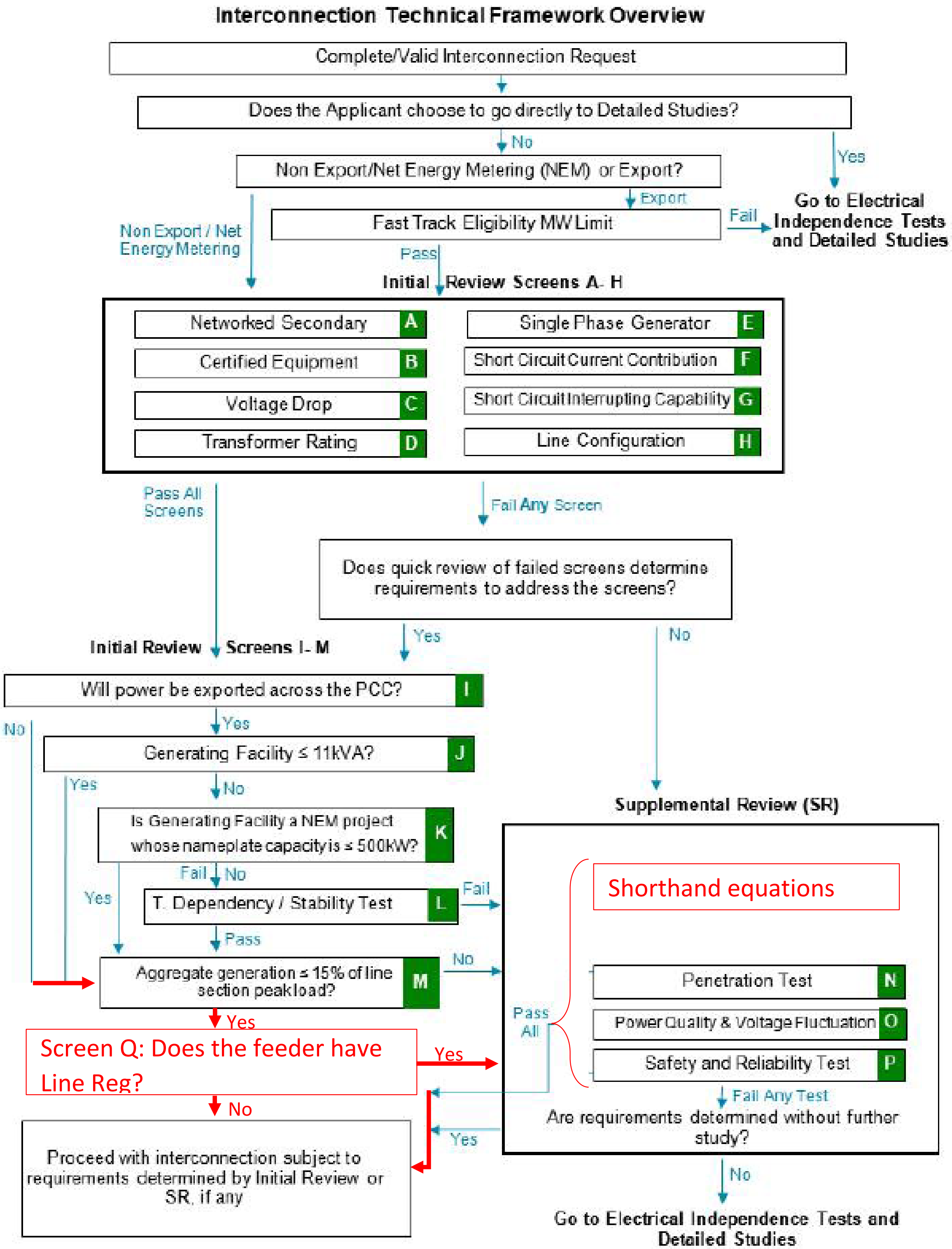

Figure 2.
Suggested Modifications to CA Rule 21

The modified screens were then applied to the validation feeders to observe and verify the new recommendations. Results from the proposed changes and short-hand equations indicated close approximation to the minimum hosting capacity values found through the detailed analysis. Minimum hosting capacity is defined as the lowest amount of PV that causes the first violation on a feeder. Therefore, the short-hand equations prove to be effective at estimating PV impact to the grid. When the short-hand equation solutions were considerably different than the minimum hosting capacity, the error tended to result in values less than the feeder minimum hosting capacity. This was acceptable given that simple "fast" screens such as these should be conservative in nature since limited analysis was performed at that stage. Results indicated the proposed modifications to the Initial Review and Supplemental Review processes could improve screening interconnection requests.

In a parallel effort during the course of this project, the CPUC mandated that the utilities develop Distribution Resource Plans (DRP) to prepare for future growth of distributed energy resources. The DRP is not a replacement for interconnection studies or Rule 21, however the DRP can be used to further improve the analysis of aggregate generation as is done in this project (illustrated in Figure 3). If the DRP analysis is not conducted on the feeder under study, the shorthand equations can still help to better estimate aggregate PV limits for a feeder.

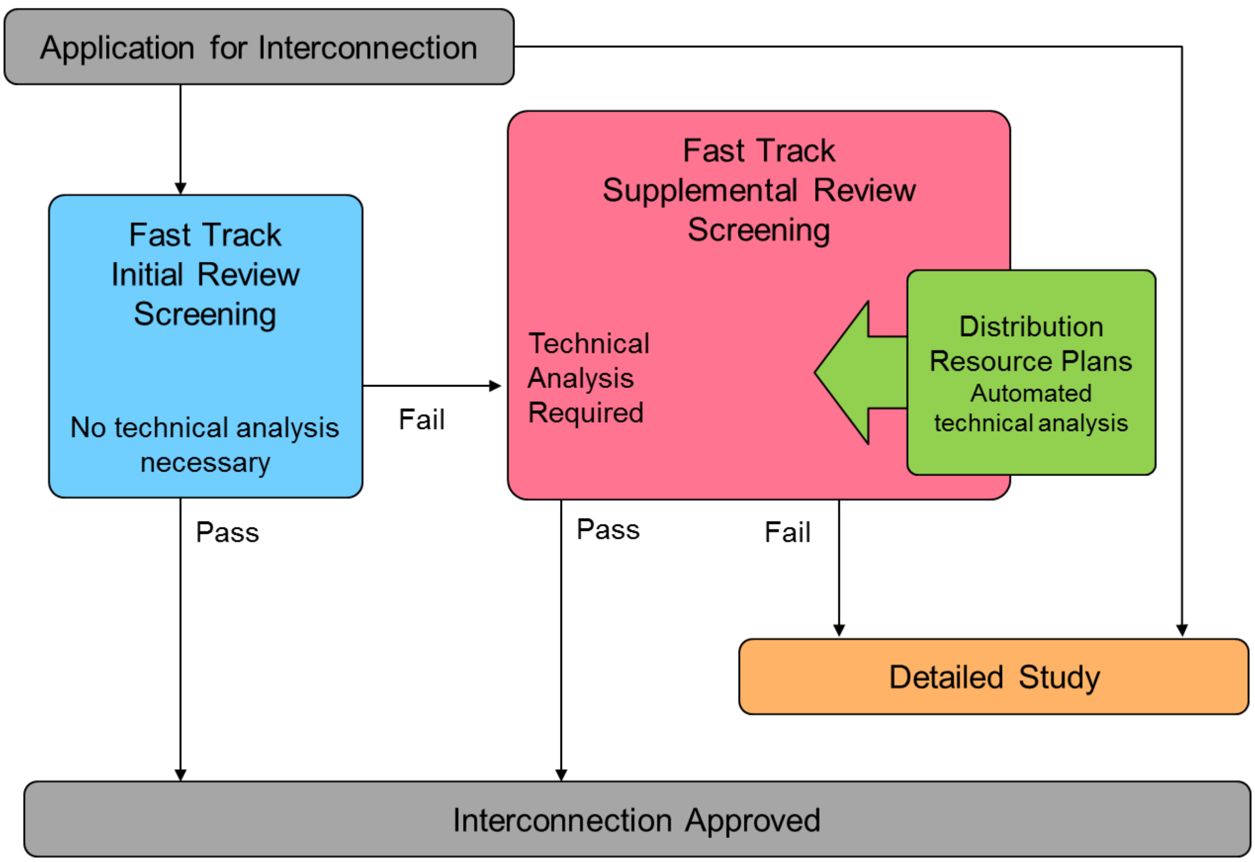

Figure 3.
Screening in Coordination with Distribution Resource Plan

Project Team

This CPUC/CSI project combines the experience of individuals across the industry, including:

- Electric Power Research Institute - Project Lead
- National Renewable Energy Laboratory – Project partner
- Sandia National Laboratories – Project partner
- Itron – Grant Manager

Utility Partners:

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

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INTRODUCTION

The third solicitation of the California Solar Initiative (CSI) established by the California Public Utilities 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.

Working with the three investor-owned utilities, the project team evaluated the impacts of PV on the distribution system through detailed hosting capacity analysis. The results of this analysis led to the identification of additional Fast Track Initial and Supplemental Review screens that could be applied alongside the existing California Electric Rule 21 screens. These new screens were derived directly from the technical analysis and more appropriately predict the amount of PV that can be accommodated on a feeder regardless of its loading. The recommendations were based on PV while Rule 21 is inclusive of all forms of distributed generation.

The focus was on PV due to the proliferation of interconnection requests utilities are faced with. In 2013 alone, there were approximately 155,000 interconnection requests accepted in the US with 94% connected to the distribution system. Even more applications are received, but not approved due issues found in the interconnection review process.

Current Practices

The California P.U.C. Rule 21 Interconnection Technical Framework is illustrated at a high level in Figure 1-1. The Utility Application Review and Approval process is currently the most time-consuming of any step on the path to generating power on the distribution system[8] [9]. The process includes two main pieces that will be referenced in the report. The highlighted sections indicate the Fast Track Initial Review process (blue) and Fast Track Supplemental Review process (red). All applicants enter the application process and are either directed to the Fast Track process upon eligibility or are directed to detailed studies. Once in the Initial Review process, a failure of a screen could direct the applicant's review to Supplemental or Detailed Analysis. Supplemental Review is part of the Fast Track process but an intermediate step between Initial Review and Detailed Analysis. Each process deeper in the review requires more thorough analysis and requires additional details.

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

[9] Current Utility Screening Practices, Technical Tools, Impact Studies, and Mitigation Strategies for Interconnecting PV on the Electric Distribution Systems. EPRI, Palo Alto, CA: 2014. 3002003277.

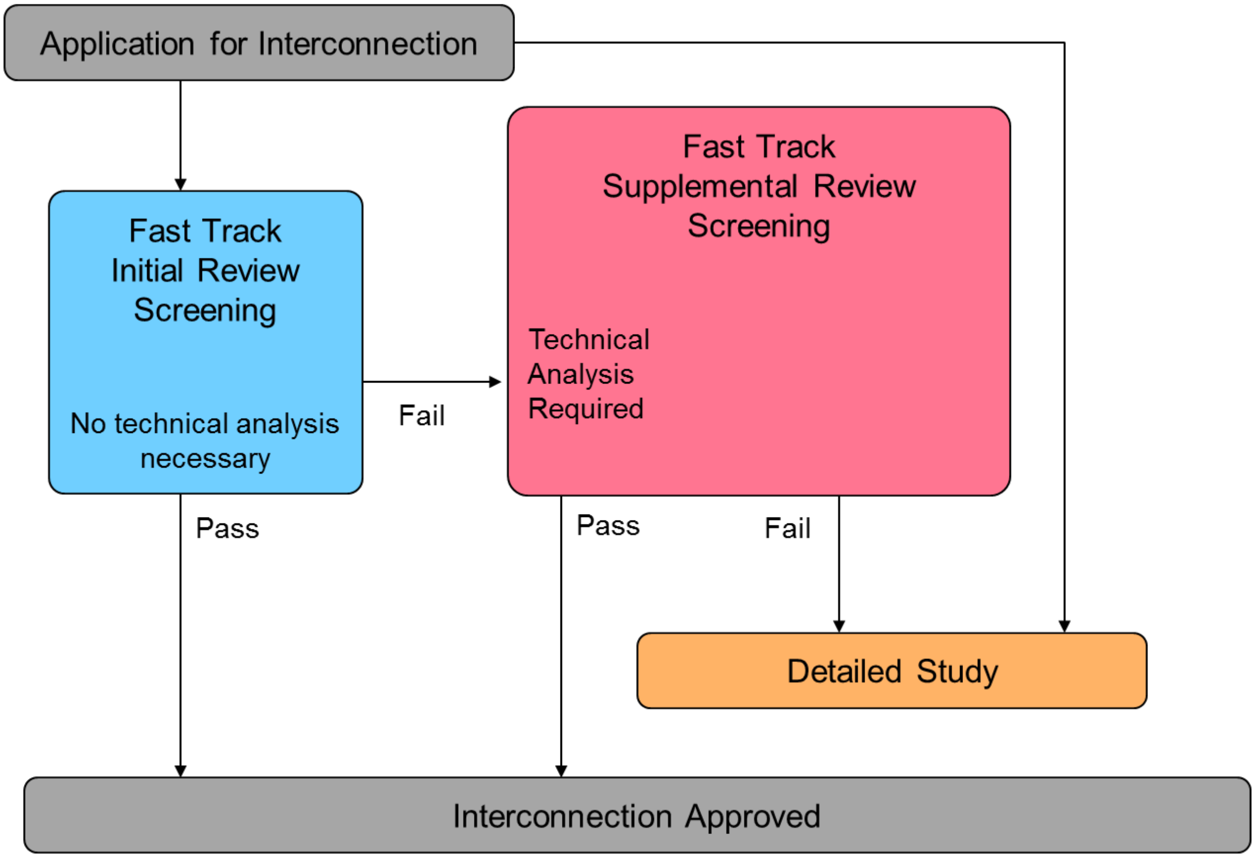

Figure 1-1.
Basic California Rule 21 Screening Process

The application process allows utilities approximately 15 business days to perform Initial Review 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 screens, detailed impact studies are preformed within less than 120 calendar days. Interconnection requests primarily fall into one of the two following categories: (1) those that are granted based on Initial Review 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.

As a supplement to the Rule 21 process a number of the utilities in California have developed additional PV screening methods and criteria to expedite the PV interconnection process and to avoid requiring detailed studies of systems that don’t warrant such analysis. The utilities and the entity requesting the PV interconnection are served best when detailed studies are only required when some form of impact mitigation needs to be defined (e.g. changing the control settings on a line regulator, reconductoring a portion of the feeder, etc.).

Improving Current Practices

Adequate consideration of PV throughout the interconnection process is necessary and a key focus of this project. PV is considered as the primary form of DER because of the amount of interconnection requests as well as the variability of the resource. Based on the Measurement Task[10], Figure 1-2 shows that various locations throughout California have daily solar variability that can span the range from low to high variability.

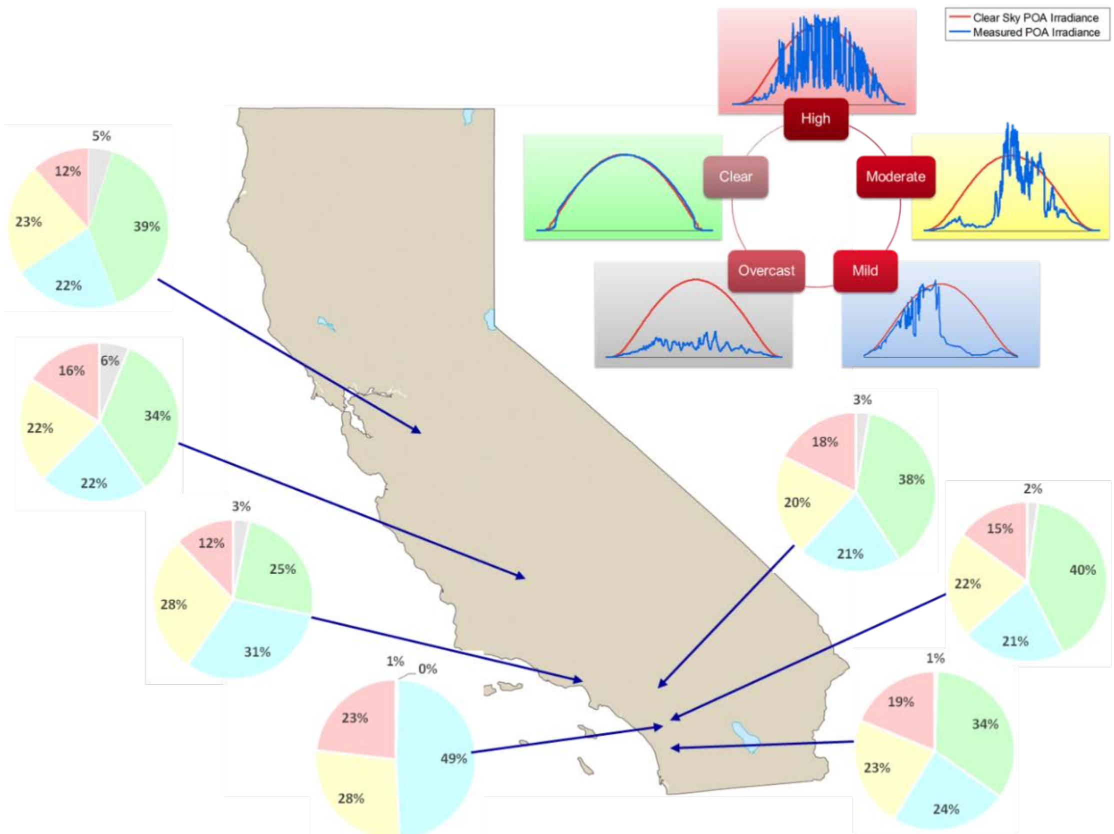

Figure 1-2.
Solar Variability in California (pie chart colors correlate to the solar day-type)

The improvement to the Fast Track process came from identifying gaps where incorrect approval could occur as well as suggesting simple calculations to more accurately determine a feeder's ability to accommodate PV. This would improve and expedite the application review and approval process.

This final report highlights the findings from each key task. Chapter 2 examines the current utility practices. Chapter 3 characterizes utility feeder data and clusters them to identify approximately five feeder groups for each utility. Chapter 4 details the selected feeder from each group and performs a detailed PV impact analysis on each modeled feeder. These impact results then inform the additional screens and enhancements to the current California P.U.C. Rule 21 that are derived and validated in Chapter 5.

[10] http://calsolarresearch.ca.gov/funded-projects/88-screening-distribution-feeders-alternatives-to-the-15-rule

2
CURRENT APPLICATION SCREENING PRACTICES

Interconnection procedures and the various tools and techniques used to evaluate interconnection requests (applications) vary from utility to utility. Standardized interconnection procedures, permitting procedures, and building guidelines have been developed in California before other states began focusing on these topics. These procedures have been put in place to ensure that safety, reliability, and power quality are maintained throughout the grid. In the past few years, many of the utilities in California and elsewhere have worked diligently to improve their PV screening and study processes thereby reducing the costs and the total time from application through interconnection with the electrical distribution system.

This portion of the project focused on collecting the PV screening methods and interconnection practices from utilities currently seeing significant amounts of distribution-connected PV. The goal of the survey is to identify leading practices that might be considered by all utilities that have a large queue of proposed PV installations on their electric distribution systems, as well as those who are positioning themselves for new PV interconnection applications and installations. In this section the methods used to complete the survey are presented first followed by a summary of the survey findings.

Survey Methodology

Each utility that participated in the survey has been asked a series of detailed questions regarding interconnection processes, screens, tools, impact studies and mitigation methods. Some of the utility experts completed many of the questions prior to the completion of an in-person interview. Additionally, all utilities have been included in a conference call covering the same questions but with a broader participation (i.e. with multiple distribution engineers, managers, etc.).

The questionnaire used for the interviews and conference calls with each utility is developed with inputs from the CPUC, Itron, EPRI, IREC, and NREL. The details of the specific questionnaire are provided in the full report on this part of the project[11]. The primary focus of the questionnaire is designed to determine the types of impact studies, distribution modeling methodologies, and the mitigation approaches used at each utility, as well as any unique tools or methods currently being used to screen PV interconnection requests.

Southern California Edison (SCE), Pacific Gas and Electric (PG&E), San Diego Gas and Electric (SDG&E) and the Sacramento Municipal Utility District (SMUD) were interviewed between December, 2012 and January 2013.

[11] Current Utility Screening Practices, Technical Tools, Impact Studies, and Mitigation Strategies for Interconnecting PV on the Electric Distribution Systems. EPRI, Palo Alto, CA: 2014. 3002003277.

Summary

The four utilities interviewed for the survey illustrated a number of "best practices" based on the experiences of the utility personnel interviewed. An immediate and clear finding is that each utility processes interconnection applications differently, and utilizes a myriad of distribution modeling software tools, impact study types and various mitigation strategies when a PV system is identified as creating a significant impact on a distribution feeder.

There are a number of best practices highlighted when working with the four California utilities. The identified best practices in California for the interconnection of PV systems onto distribution systems determined through the survey and interviews are:

- Use of state-wide interconnection procedure (Rule 21 in CA) provides transparent and consistent process
- Use of online interconnection applications for PV developers and utility customers
- Online tracking of PV application for both utility workers and PV stakeholders (e.g. PowerClerk)
- Use of industry standard screening processes to identify Fast Track PV applications for quick approval
- Use of national standards to ensure power quality and safety (UL1741 and IEEE1547)
- Use of supplemental screens or individual reviews for interconnection agreements that fail Fast Track screens but may still qualify for quick approval
- Use of "no study solutions" (fully avoiding the cost of a detailed modeling study) to mitigate potential problems with known approaches that are often low-cost (e.g. changing service transformer or voltage regulator controls)
- Use of GIS systems to track distribution system components for use in modeling efforts
- Tracking of all DG and PV systems on GIS for fast analysis of new interconnection agreements (this includes timely updates to GIS systems with PV that are attached to the correct area in the distribution system and with significant detail on the size and type of technology)
- Use of a standard distribution-modeling platform for evaluating all DG on a circuit (while no single platform currently conducts all types of impact studies, those that can perform several studies are preferred)
- Standard application fees for PV interconnection applications and limited yet reasonable times necessary to perform analysis

As utilities in California, as well as states such as Arizona, Massachusetts, Hawaii, New Jersey, and Colorado, have seen large numbers of interconnection applications in the past five years, they are already developing better and more efficient methods to screen PV interconnection requests and ultimately aid in the more expeditious deployment of PV in a safe, reliable and cost-effective manner within their respective service territories. Additionally, public utility commissions in some states have developed their own methods for interconnection, such as the California Rule 21. As many states have yet to adopt a uniform approach for interconnection they are in a good position to adopt the most accurate and timely PV interconnection screening techniques in the near future. The more compatible these adopted state level PV interconnection regulations can be the less complex the PV interconnection landscape will be for all PV stakeholders – utilities and PV developers alike.

Clearly there are processes that have been developed by many electric utilities to manage the large numbers of interconnection applications. The best interests are served when PV applications can be approved quickly or moved to impact studies quickly, and done so with the safety, reliability, and cost-effectiveness of the utility system in mind.

3
CHARACTERIZING DISTRIBUTION FEEDERS

In order to determine alternative screening methods that can be used, the range of feeders that the PV systems might be connecting to must be evaluated. The feeder characterization task consisted of two parts: 1) characterize 8,163 distribution feeders by developing a database of feeder characteristics to determine the range of feeder configurations and 2) determine a set of sample feeders to be used in the project by analyzing the statistical range/distribution of feeder configurations, types, and electrical characteristics. The primary goal of this task was to understand the overall statistical feeder population, cluster the feeders into representative groups, and then select specific sample feeders for study/analysis.

Feeder Data

This task identified feeder characteristics that represent the known range of feeder types in California and are known to affect hosting capacity. Extensive experience with distribution impact studies and familiarity with utility databases was utilized to compose a set of feeder characteristics to describe the variation in the feeder population. The set of feeder characteristics were selected based on their likelihood to affect hosting capacity of the feeder for voltage, thermal and protection impacts. The groups of characteristics identified include:

1. Nominal voltage level (e.g., 4kV, 13kV, 25kV, etc.)
2. Feeder length and main conductor type
3. Three-phase vs. single-phase feeder length
4. Voltage regulation schemes (load tap changers, feeder regulators, switched capacitor banks)
5. Load mix (residential, commercial, industrial)
6. Load shape (peak, minimum load, seasonality)
7. Existing DG and PV deployment levels (kW)
8. Utility operational practices (e.g. use of conservation voltage reduction schemes)
9. System protection devices

Key Differences

The characteristics of the feeder data received vary significantly within a utility and even more among the different utilities. Figure 3-1 shows the distribution of feeder voltage class for all three utilities. The majority of feeders for Utility 1 and Utility 2 have a nominal voltage of 12 kV. Utility 3 provided data only for 12 kV feeders which is the voltage class for the majority of their feeders.

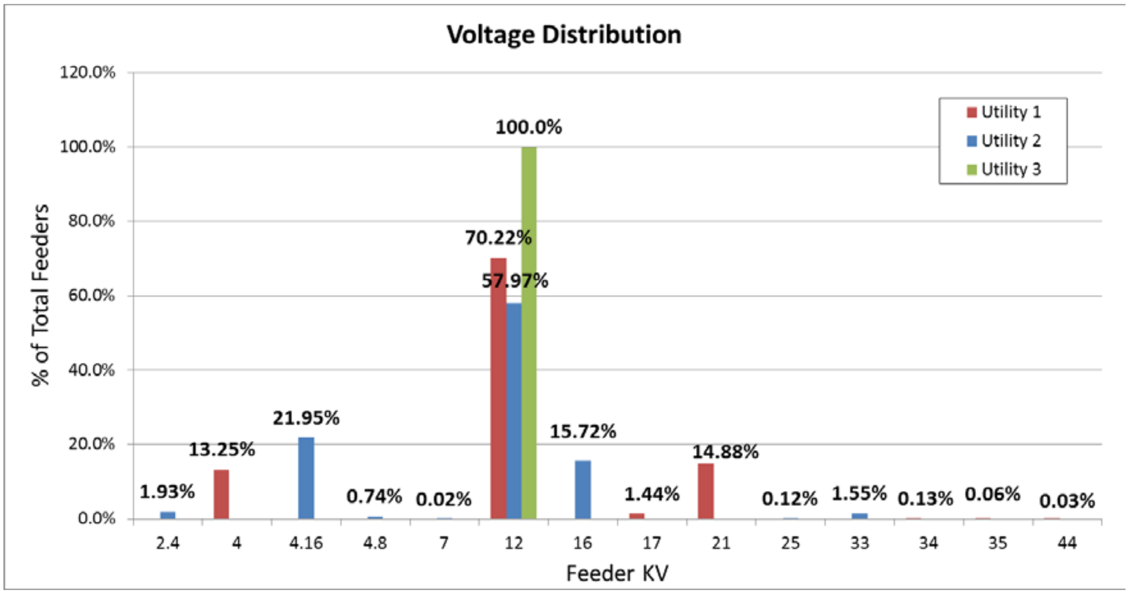

Figure 3-1
Voltage Class Distribution for All Three Utilities

Figure 3-2 shows the distribution of three-phase line length for all three utilities. The three-phase length distribution was defined as the sum of all three-phase sections within the feeder. Utility 1 has long feeders with several over 80 miles in length. The majority of three-phase feeders for Utility 2 and Utility 3 are less than 20 miles in length and all of them are less than 80 miles in length.

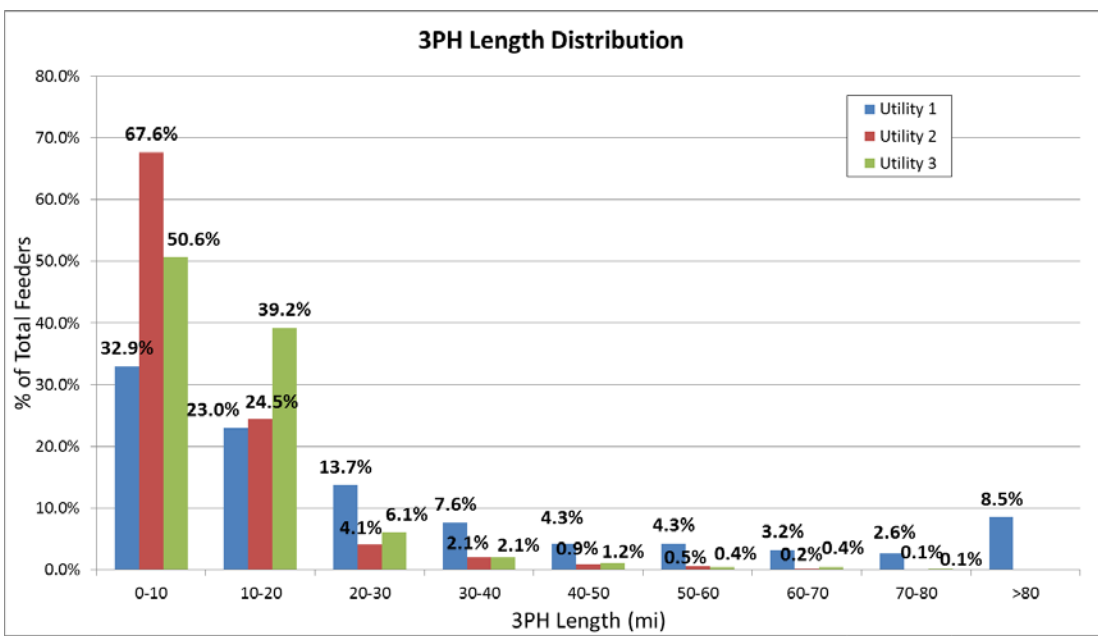

Figure 3-2
Three-Phase Line Length Distribution for All Three Utilities

Figure 3-3 shows the distribution of voltage regulators for all three utilities. Less than 10% of the feeders within Utility 2 and Utility 3 have voltage regulators. Utility 1 uses regulators more often.

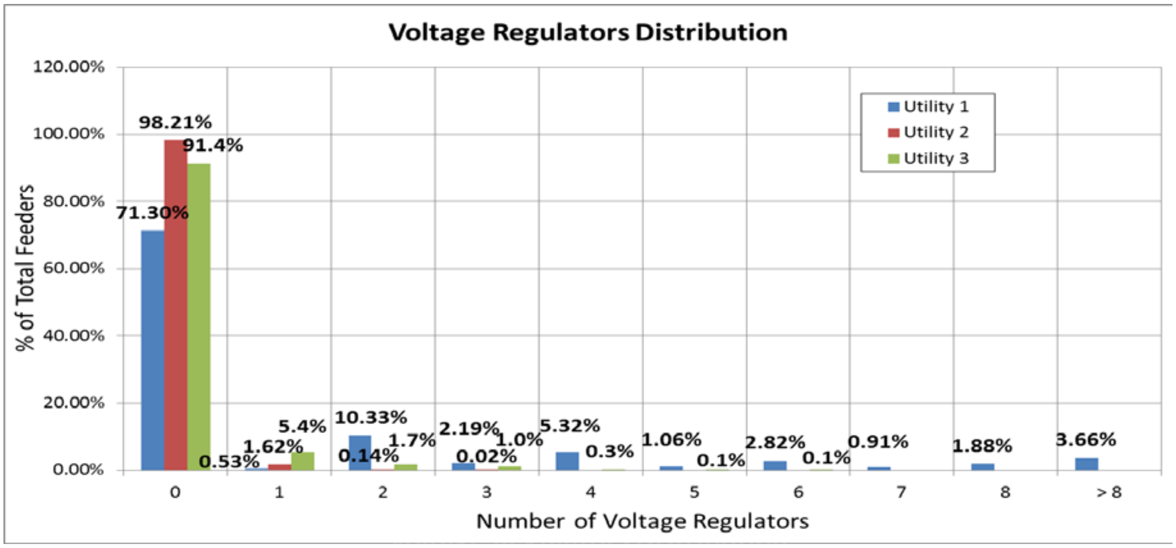

Figure 3-3
Voltage Regulator Distribution for All Three Utilities

Clustering Approach

The goal of this task was to develop a method to classify distribution feeders into clusters and to select sample feeders from each cluster. The K-means clustering methodology was used for grouping distribution feeders and the Cubic Clustering Criterion (CCC) was used for determining the optimum number of clusters. One of the main advantages of the K-means algorithm was its quick convergence for large data sets (greater than 200 elements) making it more popular than hierarchical clustering approaches. For this project the K-means expectation-maximization algorithm (used by SAS JMP[12]) was used as it is known for its ability to accommodate clusters of variable size much better than the original K-means algorithm.

Initial Data Review and Cleanup

Although the same data request was sent to all utilities, data received differed due to availability and ease of retrieval. The review process consisted of the following steps:

- *Histogram generation.* Histogram plots can be found in the *EPRI RD&D Solicitation Three Feeder Database and User's Guide*[13] for each utility.
- *Data clarification.*
- *Outlier identification.*
- *Boundary definition.*
- *Data anomaly documentation.*
- *Data set preparation.*

[12] More information on SAS JMP can be found at http://www.jmp.com
[13] http://www.calsolarresearch.org/component/option,com_sobipro/Itemid,0/pid,54/sid,88/.

Selecting Variables for Clustering

Initial variables were selected based on the impact they might have on differentiating feeder types and on DG hosting capacity. The initial variables varied among utilities as needed to account for differences in availability of data from each utility. These initial variables were analyzed using a correlation map to show the degree of correlation among all variables. Because the optimum number of clusters was more accurately achieved when the chosen variables were independent of each other, pairs of highly correlated variables are examined more closely to determine if it was beneficial to remove one of the variables before clustering. The degree of correlation was used to develop a list of candidate pairs for evaluation. For example, *Total 3-Phase Circuit Miles* and *Total 3-Phase Overhead Circuit Miles* had a strong positive correlation. Therefore one of these two variables was removed before clustering. Once an optimal clustering was obtained, no further variables were removed.

Removing Outliers

Feeders labeled as outliers were those not representative of the overall data set. K-means clustering algorithms can be very sensitive to outliers, especially if the initial cluster means are chosen based on the outliers, which is often the case since many algorithms start by choosing initial cluster means as far apart from each other as possible. Therefore, when using K-means as the clustering technique, removing outliers can help improve convergence speed and will make the clustering more reliable. Outliers in the dataset were identified by *Distance* – a multivariate calculation that is a measure of how similar a particular feeder is to its closest neighbor. Although two feeders may share similar characteristics (and thus have a small distance between them) they themselves may be unique among the dataset. Therefore, rather than basing outlier removal on the distance between a feeder and its closest neighbor, a distance measure from each feeder to its twelve closest neighbors was computed and these distances were used to compute an average distance. If the average distance were above a certain threshold (different for all utilities) the feeder was considered an outlier and removed from the clustering process.

Cubic Clustering Criterion

The optimum number of clusters can be derived from a cubic clustering criterion value based on minimizing the within-cluster sum of squares. Although not a mathematical law and more of a rule of thumb that has been accepted in the statistical community, the optimal number of clusters can be determined by plotting the CCC value against the number of clusters and finding a local maximum after the CCC rises above 2 and before it drops below 2. Statistical analysis was performed using the SAS JMP software tool to calculate the CCC value for each cluster number.

As discussed previously, the variables selected for clustering were down selected from a larger set by excluding certain highly correlated variables. The down-select process for the variables to be used in the clustering algorithm helped with selecting the optimum number of clusters for a given data set as shown below in Figure 3-4. Two example CCC plots are shown below in Figure 3-4. In Figure 3-4 (left) all of the original variables were used in the clustering algorithm to compute the CCC value. As the number of clusters increased, there was a continual rise in the CCC value with no definitive peaks up until 22 clusters. The CCC value never dropped back below 2. Figure 3-4 (right) shows a CCC plot using the down-selected variables based on correlation. There was a definitive peak occurring at 12 clusters, followed by a drop in the CCC value that goes below 2. This indicated that the ideal number of clusters for this data set was 12.

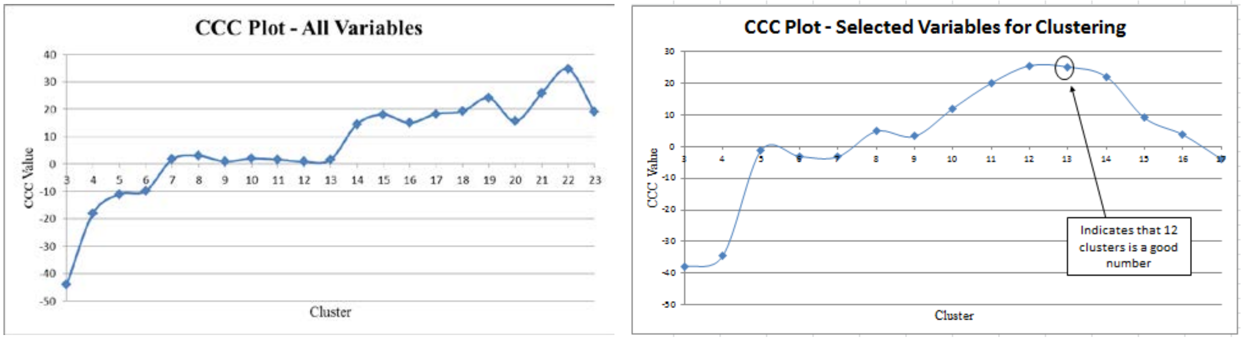

Figure 3-4
CCC Plot with All Variables (left) and with Selected Variables (right)

Feeder Selection

Figure 3-5 shows an example of a biplot for the feeders within a single cluster. The multiple data dimensions were reduced using Principle Component Analysis (PCA) to the two dominant aspects of variation. The *'90% radius'* depicted in Figure 3-5 is the length from the cluster's center to a circle that captures 90% of the feeders. This radius represents how tightly grouped the feeders were within the cluster. Feeder selection from within the cluster was accomplished by sorting the feeders based on their distance from the center and selecting feeders that were closest to the center of the cluster (therefore highly representative of the cluster). Other important parameters used to make final feeder selection included significant PV system presence and the existence of feeder SCADA data. These parameters were critical for developing the accurate feeder models needed for analysis.

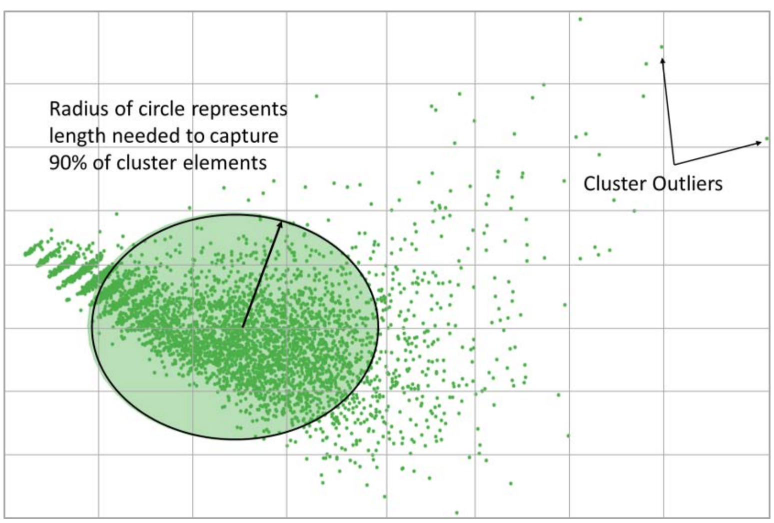

Figure 3-5
Example of Cluster Biplot

Summary

This task identified feeders to be used in the development of a modified screening method. Ideally, one feeder would be chosen from each identified cluster to represent all of the three participating utilities appropriately, however, more than sixteen total clusters were identified. The clusters were further examined to determine similar primary characteristics to reduce the number of clusters from which feeders were chosen for detailed analysis.

One of the primary characteristics to manually reduce clusters was voltage class. The utility feeder clusters represented a wide range of voltage classes from 4 kV to 33 kV. The majority of the feeders fell into the 12 kV class, therefore, the majority of the feeders chosen for analysis were selected from that voltage class. Three clusters were used to represent outlying voltage classes such as 4 kV and 33 kV.

There were twenty two feeders selected from those identified in the clustering. The final set included sixteen feeders for detailed analysis and development of the screening methodology, while six feeders were reserved for validation of the methodology.

4
FEEDER MODELING AND ANALYSIS

Utilizing the sixteen feeders selected in the clustering, detailed feeder modeling and analysis was performed to understand the PV impacts. How a feeder responds to photovoltaic generation was dependent on the individual feeder's characteristics. Although feeder characteristics were a key factor in the feeder response from distributed PV, additional factors include the PV size, location, and power output. The distribution of connected PV will ultimately mold the overall feeder response.

The main characteristics of each feeder analyzed are shown in Figure 4-1. 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 were equally important.

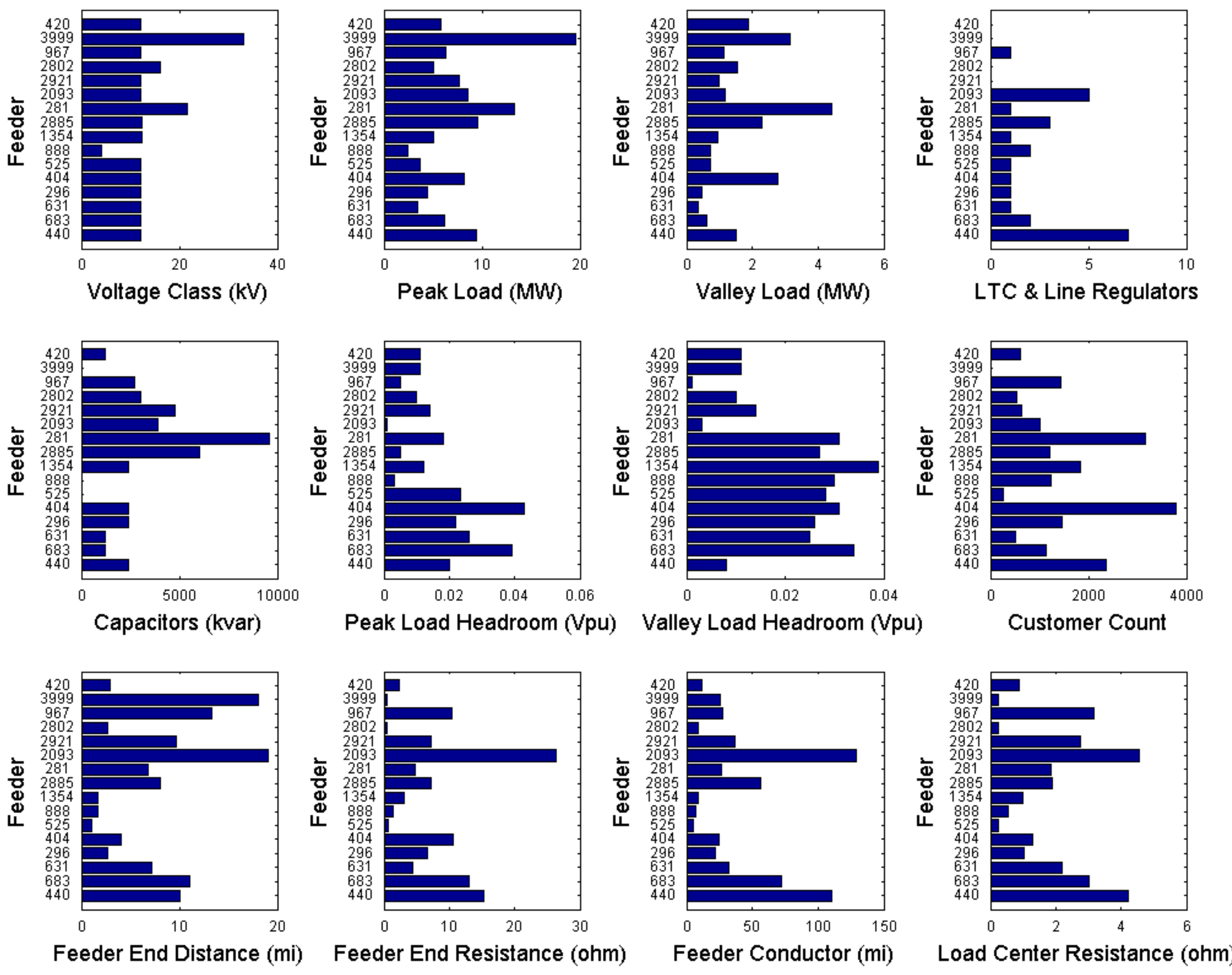

Figure 4-1.
Characteristics of Analyzed Feeders

Detailed Hosting Capacity Method

Every distribution feeder is rather unique due to the endless combinations of voltage class, conductor type, topology, and other feeder characteristics. The feeder design itself provides part of the uniqueness, but the customer dynamics also play a role. As a result of this diversity, all feeders will have a unique response to distributed photovoltaics and therefore a unique amount of PV that can be accommodated before facing an adverse impact.

Hosting capacity is defined as the amount of DER that can be accommodated without adversely impacting power quality or reliability under existing control and infrastructure configurations. This feeder hosting capacity will be dependent on the feeder, PV deployments, and specific utility-established thresholds. The hosting capacity method is rooted in two key areas that are critical for ensuring effective DER integration:

- Voltage – the voltage analysis considers over and under voltages (primary and secondary), voltage regulation, changes to equipment operation (regulators & load tap changers (LTCs), switched capacitor banks), and
- Protection – the protection analysis considers protection coordination issues due to changes in fault current including: relay desensitization, sympathetic tripping, and increased fault duty.

When applied, the hosting capacity method provides a range of possible aggregate penetration scenarios that determine both a more and a less conservative hosting capacity (minimum and maximum hosting capacity). Figure 4-2 provides an example of this application when considering maximum primary feeder voltage as a function of total PV on the feeder. Each marker indicates the absolute maximum primary feeder voltage for a unique PV deployment. There are also three regions (A,B,C) identified in the figure.

Region A includes PV deployments, regardless of individual PV size or location, with primary voltages below the ANSI 105% voltage threshold (threshold shown by horizontal 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 that causes adverse impact. The rightmost side of Region B defines the Maximum Hosting Capacity where all PV deployments, regardless of individual PV size or location, begin to cause primary voltages in excess of the threshold. Region C continues with all deployments exceeding the threshold regardless of individual PV size or location.

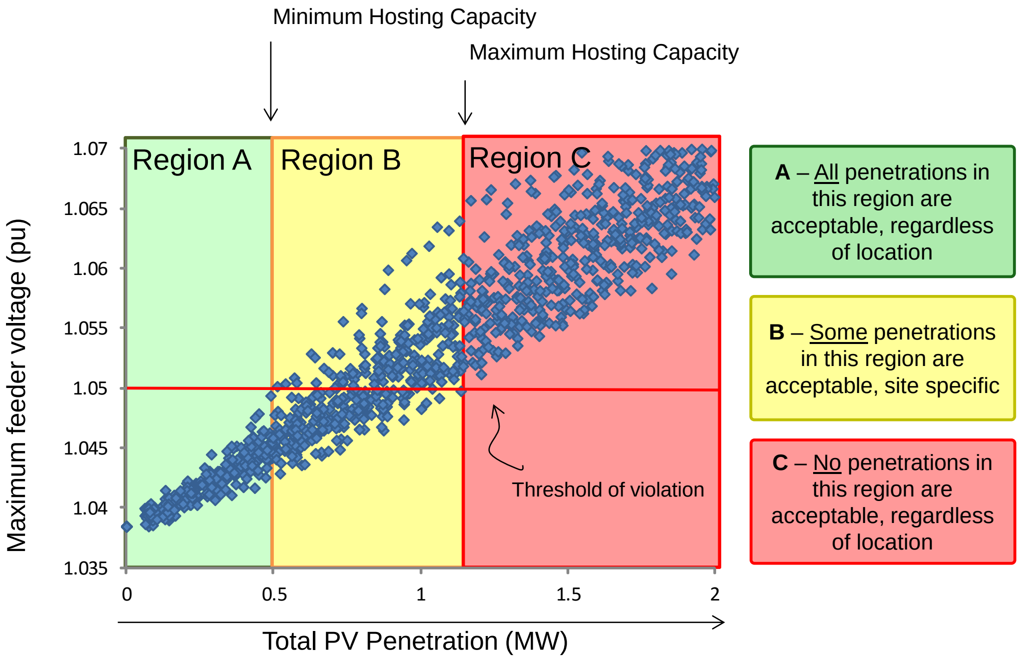

Figure 4-2
Example of the range of possible aggregate penetration scenarios considering maximum primary feeder voltage as a function of total PV on the feeder

EPRI has published many papers and reports on the subject of hosting capacity and at the end of this chapter are a number of references the reader can refer to. A high-level overview is provided as well.[14]

Hosting Capacity Results

The hosting capacity method was applied to all 16 feeders. Hosting capacity values were calculated separately for each potential issue on each feeder. The summary of hosting capacity for each feeder is provided in this section. The primary issues used to identify aggregate feeder hosting capacity include:

1. Primary Overvoltage: If voltages might exceed ANSI limits
2. Primary Voltage Deviation: If the variable resource could impact sensitive equipment or cause unacceptable fast voltage fluctuations
3. Regulator Voltage Deviation: If additional tapping might occur
4. Secondary Voltage Deviation: If the variable resource could impact sensitive equipment or cause unacceptable fast voltage fluctuations
5. Secondary Overvoltage: If voltages might exceed ANSI limits
6. Sympathetic Breaker Tripping: If the breaker might inadvertently trip on ground current due to a parallel feeder fault

[14] *Distribution Feeder Hosting Capacity: What Matters When Planning for DER?* EPRI, Palo Alto, CA: 2015. 3002004777

7. Breaker Reduction of Reach: If the breaker may lose visibility to remote feeder faults
8. Breaker/Fuse Coordination: If variable resource could cause mis-coordination between fuses and other automatic protection devices
9. Element Fault Current: If protection devices may need to be rated higher due to additional fault current

The feeders identified from each utility for modeling and analysis have been chosen based on their different characteristics – a goal of the clustering analysis. These characteristics inherently make each feeder more/less susceptible to impact from distributed generation. The range of impact based on hosting capacity is shown in Figure 4-2 for both residential/commercial rooftop PV and utility-class centralized PV. Each colored region represents no issues (green), issues dependent upon PV location (yellow), and issues regardless of PV location (red).[15]

The residential/commercial PV analysis looked at behind-the-meter PV while the utility-class PV analysis examined large PV systems interconnected behind dedicated interconnect transformers. There are two separate scenarios in the utility-scale analysis that examined two types of interconnect transformers that have different impacts during feeder faults. 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/commercial PV scenario was limited by the total load on the feeder, while the maximum utility-class PV was based on the voltage class of the feeder (10/20 MW below/above 15 kV, respectively).

Hosting capacities for each feeder between the residential/commercial and utility-scale PV scenarios was different due to the possible PV locations. In the utility-scale analysis, the deployed PV could be located close to the start-of-circuit (i.e. the substation) or could be located in the extremities of the feeder whereas in the residential/commercial analysis the PV location was more dependent on the customer location.

The key takeaway from this figure is that no two feeders have the same ability to accommodate PV without the need to modify the feeder or implement mitigation measures (i.e. the initial PV hosting capacity of the feeder). This was expected based on the feeders chosen from clusters of different characteristics.

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[15] *Alternatives to the 15% Rule: Modeling and Hosting Capacity Analysis of 16 Feeders.* EPRI, Palo Alto, CA: 2015. 3002005812.

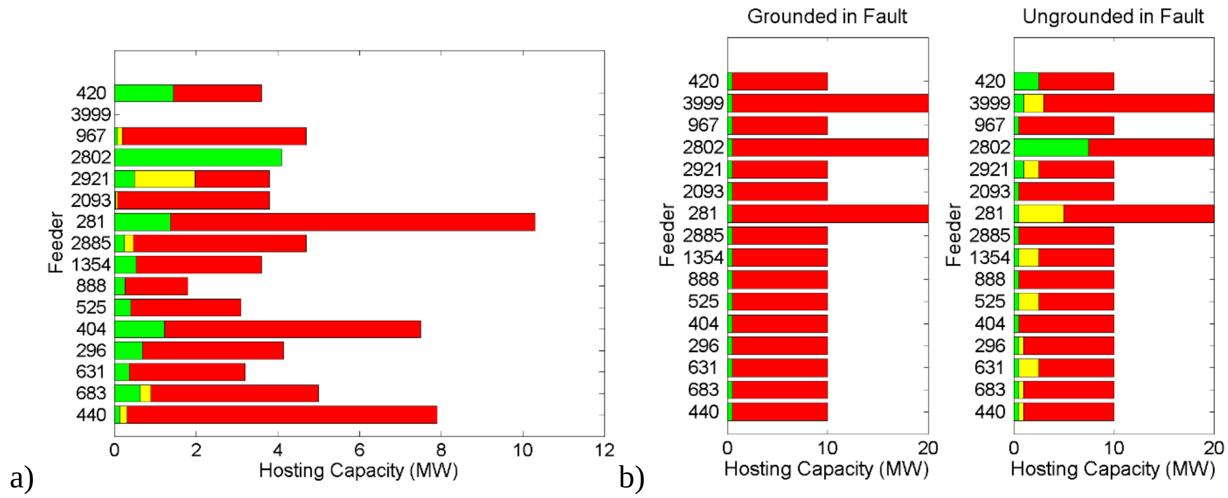

Figure 4-3.
Detailed Hosting Capacity for Analyzed Feeders a) Residential/Commercial PV[*] b) Utility Class PV Grounded and Ungrounded

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

Residential/Commercial Rooftop PV

The issue specific results shown in Figure 4-3 illustrate the range in hosting capacity across the three utilities. The results also showed that even though high impact/low hosting capacity feeders can be identified with the clustering analysis, two feeders that had lower minimum hosting capacities could accommodate different levels of PV. This was easily ascertained from the results for feeder 440 and 2093. The issue specific hosting capacities were considerably different for several issues. Additionally, the low hosting capacity feeder 967 had high hosting capacity with regards to protection.

A similar comparison between two feeders that have similar characteristics (967 and 683) showed that the hosting capacities were 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.

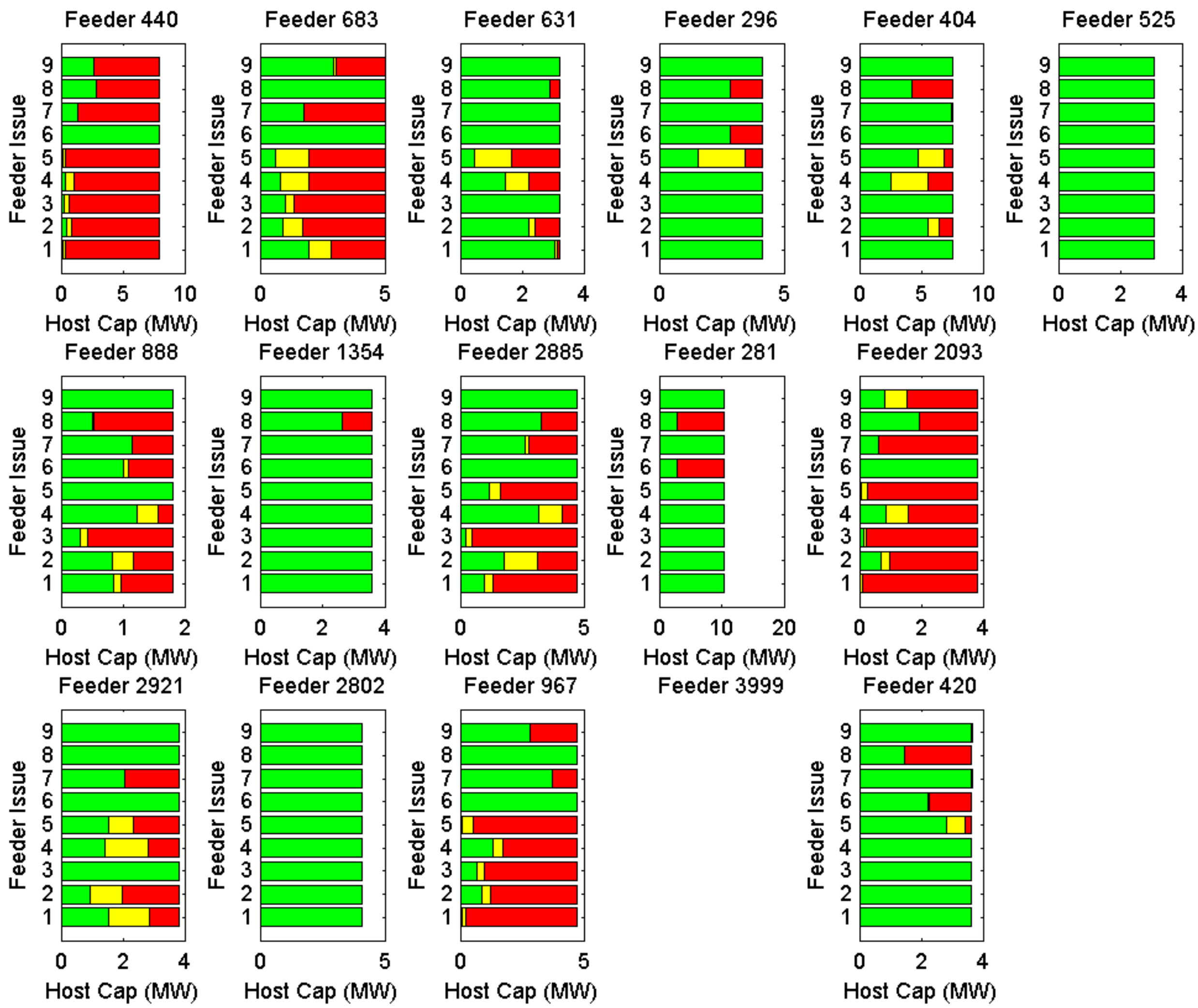

Figure 4-4.
Issue Specific Residential/Commercial Rooftop PV Hosting Capacity

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

Utility-Scale PV

The issue specific utility-scale PV hosting capacity results were shown for all feeders in Figure 4-4. The protection related issues shown were based on Grounded Wye-Grounded Wye interconnect transformers. The different feeders had drastically different hosting capacities. Across the different utilities, analyzed feeders such as 683 and 967 fell into a similar cluster, however, the hosting capacities were still different.

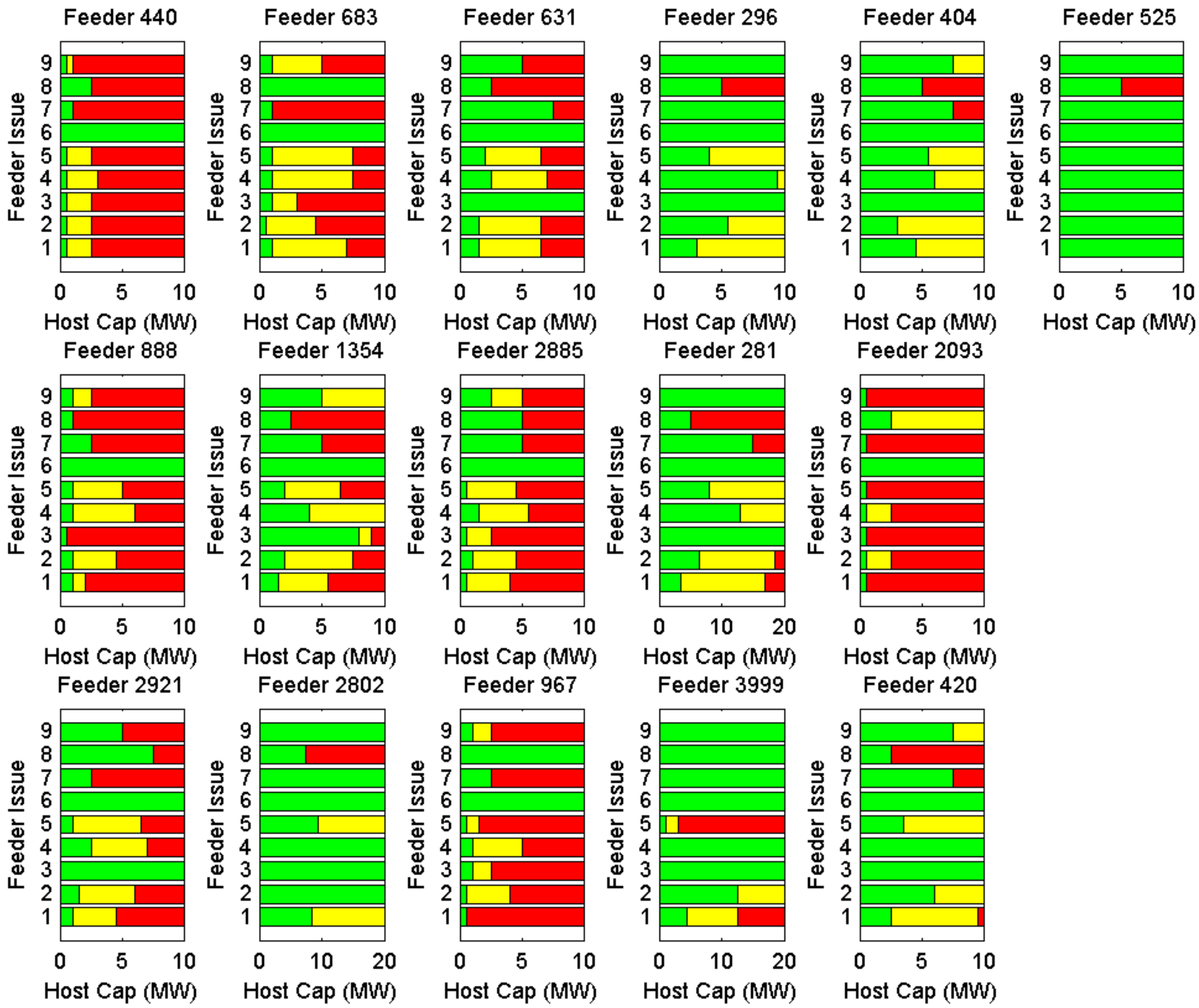

Figure 4-5.
Issue Specific Utility-Scale PV Hosting Capacity

Summary

The detailed feeder analysis showed that the specific characteristics of the feeder under study had 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. 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 were also dependent on the feeder and how PV interacts with all elements.

The main factors influencing feeder impact from PV included:

- Feeder voltage class
- Feeder resistance

- Feeder regulators
- PV system electrical location

The feeder impact from aggregate PV based on 15% of peak or 100% of minimum daytime load was typically less than what the feeder can truly accommodate. However, there were also instances where a feeder can accommodate considerably less.

The results determined through the detailed feeder analysis played a direct role in the improvement to the existing California P.U.C. Rule 21. Additional feeder characteristics will be used to update the Initial Review screening process to identify when interconnection requests should be examined more closely in Supplemental Review. Updates to Rule 21 Supplemental Review also identified when higher levels of PV could be accommodated without initiating the detailed review process. The updates would 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.

References

This section provides references for readers interested in the details regarding the hosting capacity method, application, and sample results.

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

Rylander, M., Smith, J., “Comprehensive Approach for Determining Distribution Network Hosting Capacity for Solar PV”, 2nd International Workshop on Integration of Solar Power Into Power Systems, Lisbon, Portugal, Nov 2012.

Rylander, M., Smith, J., "Stochastic Approach for Distribution Planning with Distributed Energy Resources", 2012 CIGRE Grid of the Future Symposium, Kansas City, MO, 2012

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

Rylander, M., Smith, J., Lewis, D., Steffel, S., "Voltage Impacts from Distributed Photovoltaics on Two Distribution Feeders", IEEE PES, Vancouver, Canada, 2013

Distributed Photovoltaic Feeder Analysis: Preliminary Findings from Hosting Capacity Analysis of 18 Distribution Feeders. EPRI, Palo Alto, CA: 2013. 3002001245.

5
MODIFIED SCREEN AND VALIDATION

The modifications suggested for CA Rule 21 are made based on the technical analysis conducted within this project's detailed PV impact study. The recommendations are based on PV while Rule 21 is inclusive of all forms of distributed generation (DG). The changes suggested are primarily applicable to all forms of generation in the Initial Review process. In the Supplemental Review process, some of the recommendations could be ignored when not applicable.

The technical analysis conducted in this project was also not inclusive of all potential impacts from PV. Most of the Initial Review Screens A-H in Rule 21 are applicable to the single generation interconnection request. The current version of Rule 21 does a good job screening for the impacts of a single generator on a feeder. However, the Rule lacks detail and fails to properly address the impacts of aggregate generation on a feeder. This has been less problematic as long as there are only a few generators, but with time the number of distributed generators on single feeders will increase and require adequate aggregate generation screening.

The current screens contained within the Rule were retained since they are still applicable. The modifications suggested in this report are geared toward the improvement of Rule 21 for "Alternatives to the 15% Rule." The modifications also address the need to examine the distributed (aggregate) PV impact.

Modified Screens

The suggestions to improve the Initial Review and Supplemental Review in CA Rule 21 are shown in Figure 5-1. These suggestions targeted the methods to analyze the impact of aggregate generation and specifically provided "Alternatives to the 15% Rule." The improvements were based on the technical analysis and included:

- Adding an Initial Review screen that addresses if the feeder has line regulators
- Modifying the Initial Review to always address aggregate generation
- Adding Supplemental Review equations to be used as a guideline to address the impacts of aggregate generation

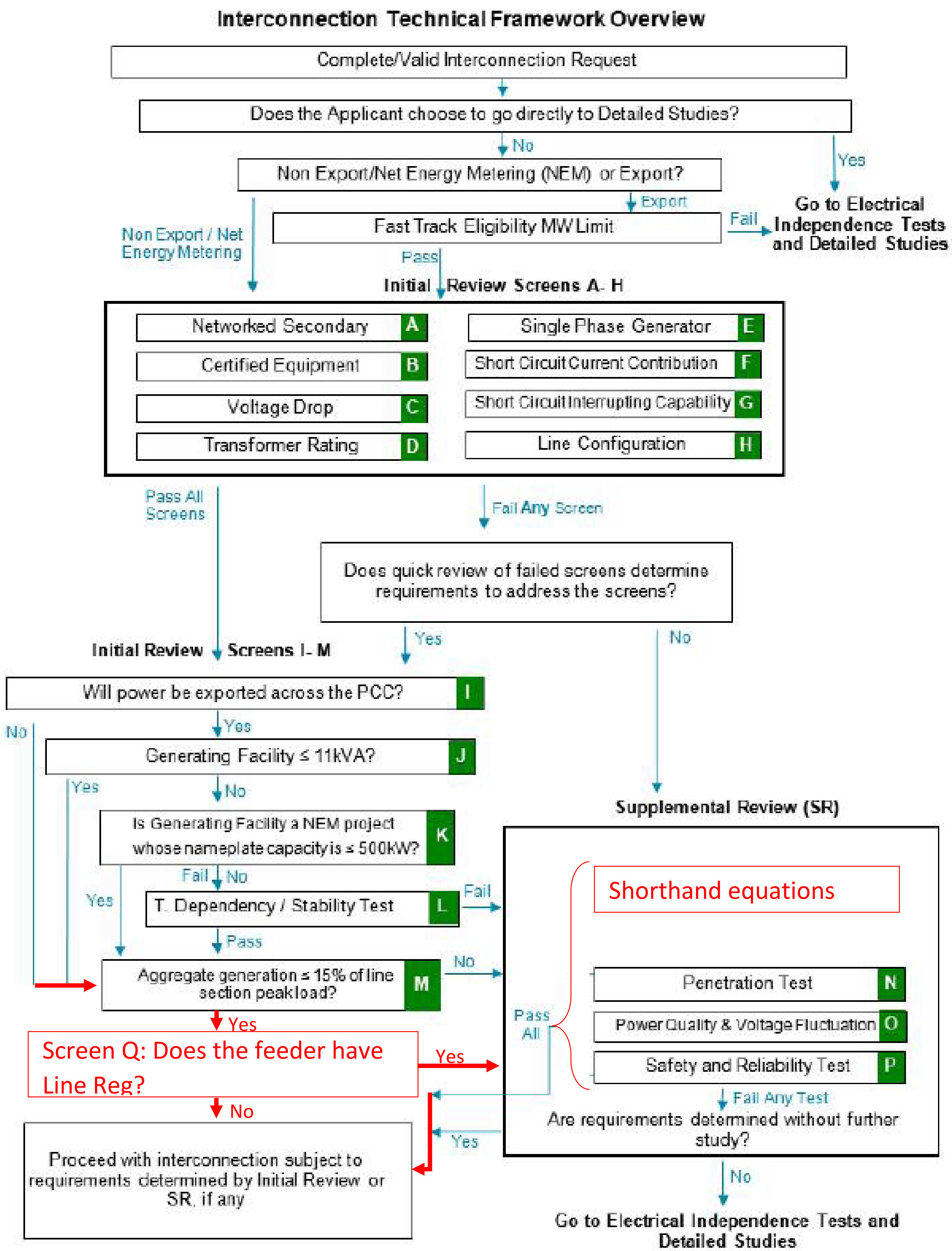

Figure 5-1.
Suggested Modifications to CA Rule 21

Improvements to Initial Review

In the Initial Review, the aggregate penetration of PV becomes a factor if Screen M (15% peak load) is applied. Screen M is a main aggregate penetration test currently contained within the Rule (aggregate impact is also addressed in Screen F for fault current contribution). The Screen M aggregate penetration test is based on peak load at an automatic sectionalizing line section and is designed to provide conservative penetration limits. Commonly, the only line section load data available is at the feeder breaker. Using the peak feeder load for Screen M, the value to pass/fail is identified and plotted as the dashed vertical line on the detailed hosting capacity results shown in Figure 5-2.

The feeder issues in which aggregate generation hosting capacity are shown include the following list. The first three are geared toward voltage issues while the last three focus on protection issues.

1. Primary Node Overvoltage
   a. If voltages might exceed ANSI limits
2. Primary Node Voltage Deviation
   a. If the variable resource could impact sensitive equipment or cause unacceptable fast voltage fluctuations
3. Voltage Regulation Node Voltage Deviation
   a. If additional tapping might occur
4. Element Fault Current
   a. If protection devices may need to be rated higher due to additional fault current
5. Sympathetic Breaker Tripping
   a. If the breaker might inadvertently trip on ground current due to a parallel feeder fault
6. Breaker Reduction of Reach
   a. If the breaker may lose visibility to remote feeder faults

The green regions indicate aggregate penetration where adverse impact does not occur. The yellow regions indicate that issues may occur due to the aggregate generation. Whether or not issues occur in this range is dependent on the location of individual PV systems. Impact dependency on individual system location primarily occurs for voltage issues. Location is less of a factor for protection issues since inverter-based generators are typically constant power/current limited devices. Aggregate penetration in the red region indicates adverse impact despite individual system location. Adverse impact is defined as the feeder response deviating - from the base case operation without generation - greater than a specified threshold. Thresholds applied are based on utility guided input.

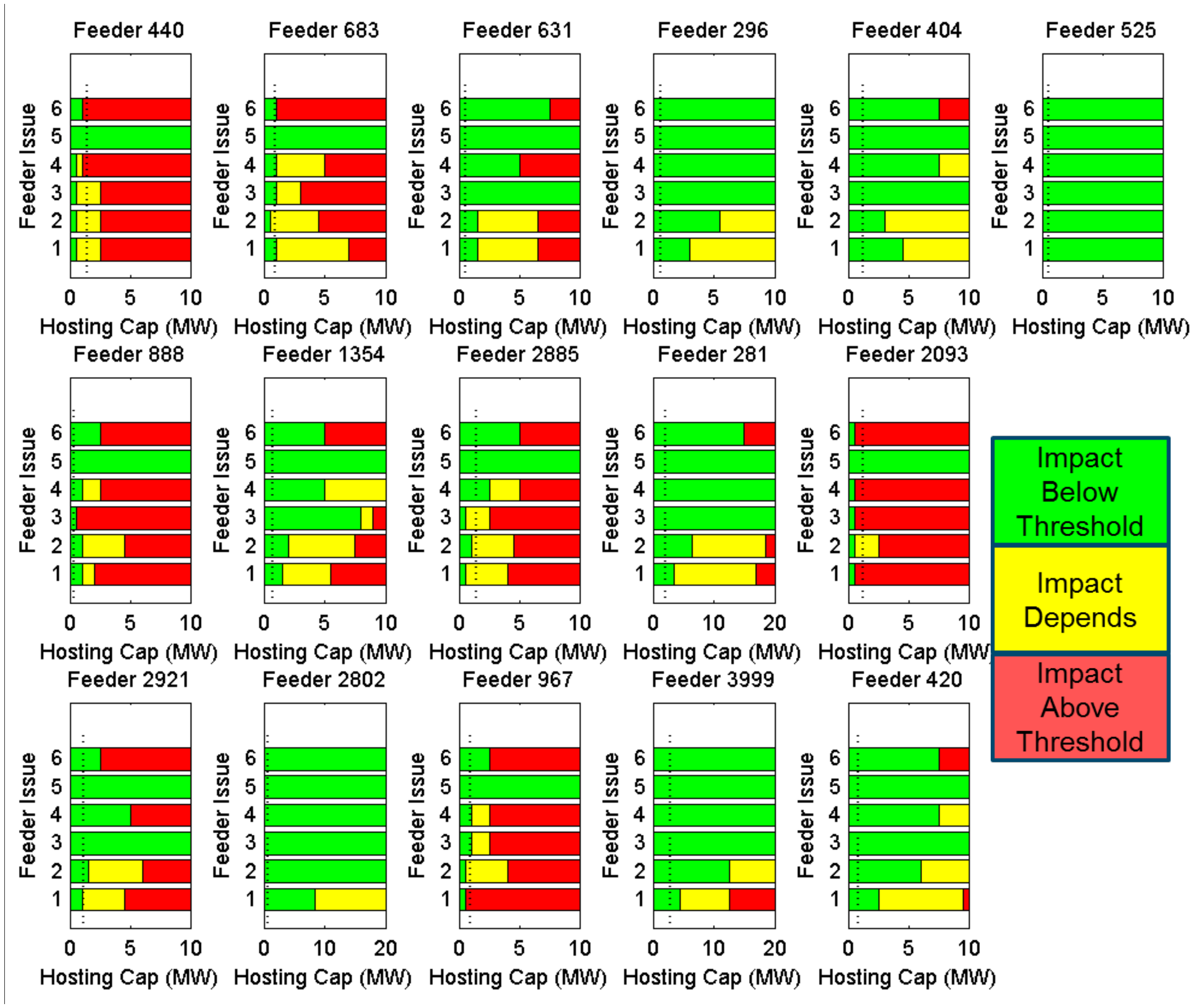

Figure 5-2.
Utility-Scale PV Detailed Hosting Capacity (Dashed lines indicate 15% of breaker peak load)

Line Voltage Regulators

The feeders that had hosting capacities lower than that determined from Screen M all have line regulators (Feeders 440, 683, 2885, 2093, 967). A suggestion to improve the Initial Review screening process for aggregate generation was to include a screen dedicated to line regulators. Line regulators are commonly an indication that there are voltage regulation issues already on the feeder. If line regulation exists on a feeder under review, the application would be directed to Supplemental Review.

Aggregate Generation

The aggregate generation test Screen M is not always considered especially if Screen I (non-exporting) or Screen J (small system) are satisfied. This identifies a major gap in the Initial Review process where the aggregate generation test can be bypassed. For example, if all PV systems interconnecting to the feeder are less than 10 kW, the impacts from aggregate distributed generation would not be addressed through Screen M. Therefore, it was suggested that screen I and J must still go through Screen M before a decision is made. Obviously, it will not be the final 10 kW system that ends up causing a violation, but at some point prior to reaching that limit, potential feeder impacts could be identified.

Improvements to Supplemental Review

The next limitation of Rule 21 is that many feeders can host considerably more PV than identified by Screen M (15% peak load) as shown in Figure 5-2. Screen N (100% minimum load) is actually the Supplemental Review screen that can limit the overall hosting capacity as identified in Rule 21, but Screen N is still based on line section loading and commonly produces similar values to Screen M. The implications of failing Screen N are that 1) there may be reverse power flow such that all inline devices should be bi-directional and 2) that islanding issues could occur.

What is not addressed explicitly in the Supplemental Review are the intermediate steps to address impact to voltage and protection issues. The recommended modifications should provide these steps to clearly identify the aggregate hosting capacity of a feeder. These recommendations were the “Alternatives to the 15% Rule.” These recommended screens should be simple such as shorthand equations since the Supplemental Review is not a detailed study.

Shorthand Analysis

With limited additional information in the Supplemental Review, a more accurate yet still conservative feeder hosting capacity limit could be calculated using simple equations. For each of the issues shown previously, a shorthand equation was derived.[16] The shorthand equation for each issue should show a hosting capacity within the green region of the detailed analysis results. Therefore the equations still produced conservative hosting capacity values that described an aggregate PV scenario worse than any analyzed in the detailed analysis. The data needed for the additional Supplemental Review equations included:

- MaxR: Resistance to last/furthest/most remote three-phase primary node
- MaxZ: Impedance to last/furthest/most remote three-phase primary node
- FeederkVLL: Feeder line-line primary voltage class of the feeder. For feeders with multiple voltage classes, use the main voltage class.
- Regulators (optional):
  - Bandwidth: in Volts
  - RtoReg: Short-circuit resistance to the regulator in ohms at feeder voltage base
  - Line Drop Compensation Settings (if applicable)
    - Rsetting
    - NCT: CT rating
    - NPT: PT ratio

[16] Alternatives to the 15% Rule: Modified Screens and Validation. EPRI, Palo Alto, CA: 2015. 3002005791.

- FaultIpv: Fault current contribution in PU of rated current
- Thresholds:
  - Primaryheadroom: Voltage headroom (in percent).
  - VoltageDeviationTreshold: Allowable Primary Voltage Deviation (in percent)
  - PercentIncreaseThreshold: Allowable per unit increase in fault current
  - BreakerSensitivityThreshold: Allowable per unit decrease in breaker sensitivity
  - SympatheticTrippingThreshold: Allowable current rise on breaker ground relay

Figure 5-3 shows an asterisk for each issue at the calculated amount of allowable utility-scale PV on the feeder. One thing to note from the figure is that the simple equations seldom overestimate the hosting capacity (asterisks rarely falling in the red region). Most of the asterisks fell near the transition from green to yellow or green to red (transition produced by the worst-case condition analyzed in the detailed analysis). The hosting capacity from the detailed analysis could be higher (wider yellow region) because there were more optimal PV scenarios. The asterisk also occasionally fell well within the green region. One reason that this could occur was due to the actual feeder topology providing lateral diversity. The simple equations did not account for lateral diversity and thus provided more conservative hosting capacities.

The main objective was to show where hosting capacity can be higher than the hosting capacity determined based on load. The values calculated for a feeder would be compared to the actual aggregate PV on the feeder after the interconnection request. If the calculated values were higher, then the interconnection request would have a better chance passing Supplemental Review with regards to the issues analyzed.

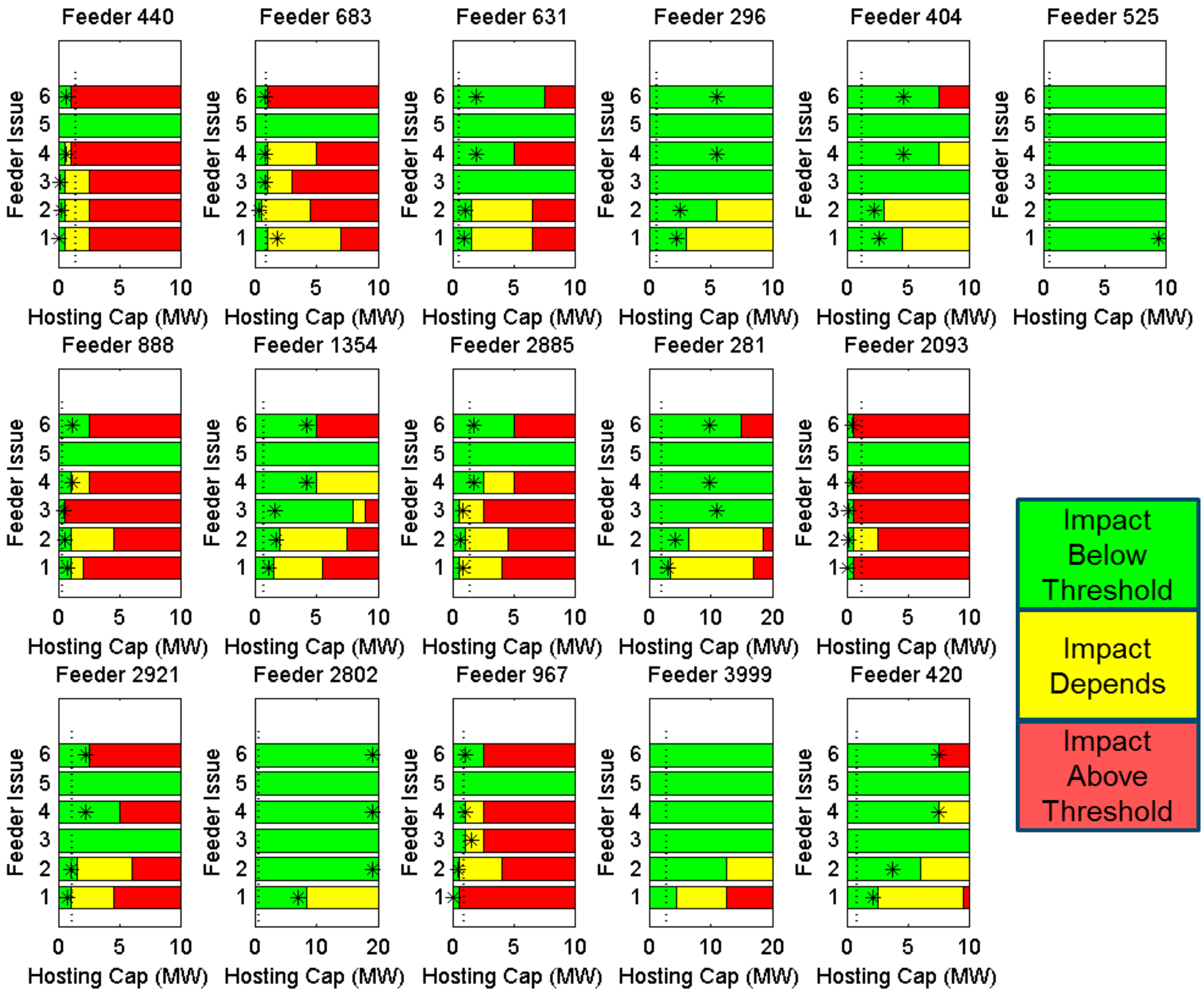

Figure 5-3.
Utility-Scale PV Short-Hand Hosting Capacity

The one feeder that failed the shorthand equations was Feeder 3999 where all five loads were modeled as capacitive. The distributed load capacitance causes significant voltage rise when the distributed generation was greater than local load. The voltage rise was greater than that predicted with the shorthand equations. This scenario was an anomaly but does represent a condition that can be more problematic for distributed generation.

Validation

The proposed modifications to CA Rule 21 were validated based on their application to the project's validation feeders. These modifications included changes to the Initial Review process as well as the Supplemental Review process. The goal of the validation was to determine if the modified screening process more accurately identified aggregate PV system impacts than the current Rule 21 framework. More effective screening allowed higher levels of overall PV interconnection through the proposed Initial Review or Supplemental Review processes while correctly identifying when the hosting capacity should be lower.

Validation of the modified interconnection request process was completed on a set of six distribution feeders that were reserved for such purposes at the beginning of the study. This allowed validation to proceed with feeders whose hosting capacity characteristics were not considered during the formulation of the modifications/improvements to the screening process. For validation, the Initial Review and Supplemental Review modifications were implemented within the distribution system analysis framework that was used for the detailed analysis completed on the 16 study feeders, while identical hosting capacity analysis was completed on the validation feeders.

Figure 5-4 showed the detailed hosting capacity of the validation feeders for utility-scale PV. The six feeder issues analyzed are indicated by SR1, SR2, … SR6. The green regions indicate when aggregate penetration does not cause adverse impact, the yellow regions indicate when aggregate penetration may cause adverse impact, and the red regions indicate when aggregate penetration will cause adverse impact. The dashed line is added to denote 15% of peak load.

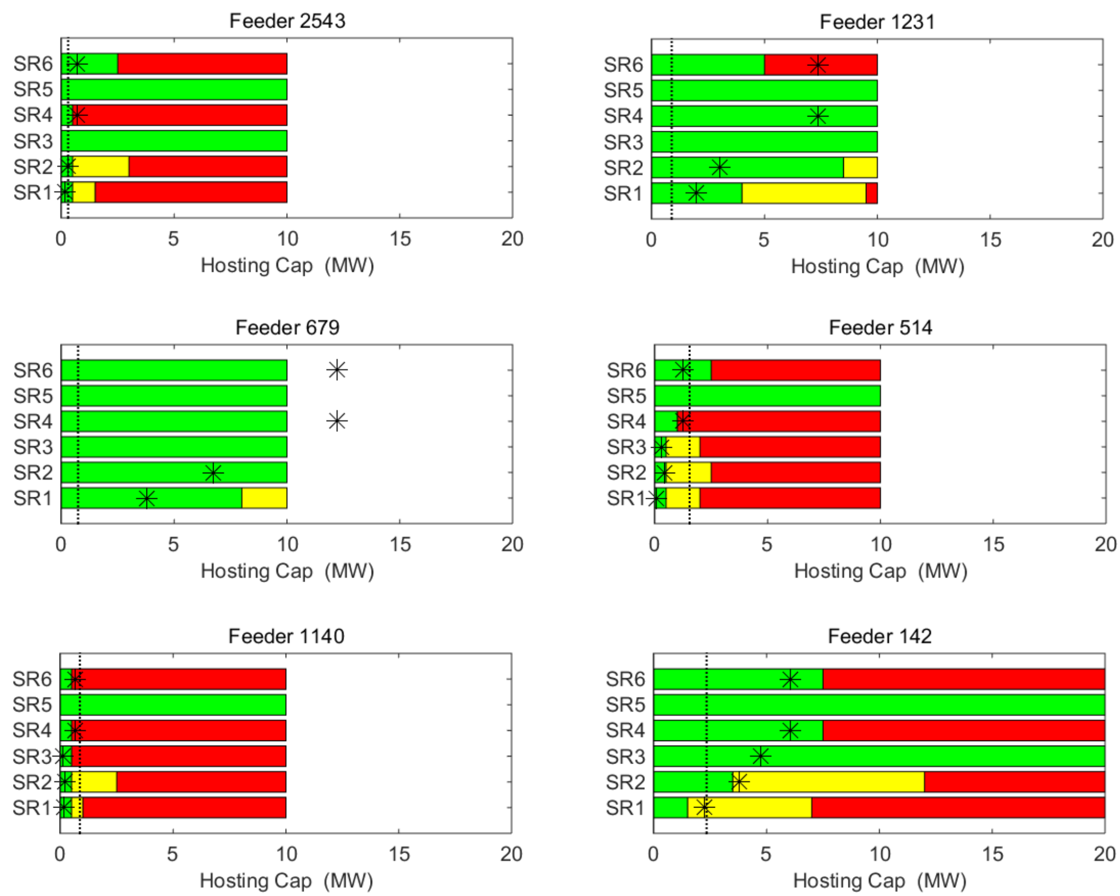

Figure 5-4.
Utility-Scale PV Hosting Capacity (Dashed lines indicate 15% of breaker peak load)

The feeders with line regulators (514, 1140) had adverse impacts when the aggregate penetration was lower than 15% peak load. Thus, it was validated that the existence of line voltage regulators indicates a high likelihood of adverse impact.

Validation feeders that do not have a line regulator (2543, 1231, 679, 142) generally could accommodate at least 15% of peak load without adverse feeder impact. However, feeder 142 did have a detailed hosting capacity for SR-1 slightly below 15% peak load. This showed that load was not the best indication of hosting capacity. Therefore, the Supplemental Review could better estimate the hosting capacity for those feeders.

Supplemental Review shorthand equations were applied to the six validation feeders to approximate the hosting capacities, and the solutions were then shown on the detailed analysis results. The asterisk in each bar was the hosting capacity estimation computed using Supplemental Review shorthand equations. If the asterisk was not shown on the plot, the shorthand hosting capacity was greater than the range displayed.

Except for the asterisks in feeders 1231 and 679 exceeding the simulation data limit, all other asterisks in all validation feeders were within green areas or near the transition from green to yellow/red. Thus, it proved that shorthand equations could give a good and conservative estimation of PV hosting capacity.

Summary

The detailed feeder impact analysis performed in the previous project task identified when potential issues from aggregate distributed generation were not properly indicated and also when a feeder was capable of accommodating considerably higher levels of distributed generation. These findings allowed for the development of improved screens in CA Rule 21 which more accurately address the impacts from aggregate generation.

The “Alternatives to the 15% Rule” found in this project more properly addressed the impacts from distributed generation and were not dependent on load level alone. The improvements were based on the detailed technical analysis and included:

- Adding an Initial Review screen that addresses if the feeder has line regulators
- Modifying the Initial Review to always address aggregate generation
- Adding Supplement Review equations to be used as a guideline to address the voltage and protection impacts of aggregate generation

These improvements were based on the detailed analysis of 16 test feeders that span a wide range of characteristics. The modified screens were then applied to a new set of 6 feeders to observe and validate the new recommendations. The application of the modified screens showed that the aggregate impact can be better determined for the issues analyzed.

6
DISTRIBUTION RESOURCE PLANS

In parallel to this CSI RD&D project, the CPUC mandated that the three large California investor owned utilities develop Distribution Resource Plans (DRP) to prepare for future growth of distributed energy resources. The DRP is not a replacement for interconnection studies or Rule 21, however the DRP can be used to further improve the analysis of aggregate generation as has been analyzed in this project. If the DRP analysis has not been conducted on the feeder under study, the Supplemental Review shorthand equations can still help to better estimate aggregate PV limits for a feeder.

Figure 6-1 shows how the DRP can be used to further improve Rule 21. In place of the shorthand equations outlined in this document for Supplemental Review, the DRP would already have the feeder hosting capacity calculated for each feeder on the system. From the DRP, the aggregate penetration limits of the feeder would already be known and used in place of the Supplemental Review shorthand analysis.

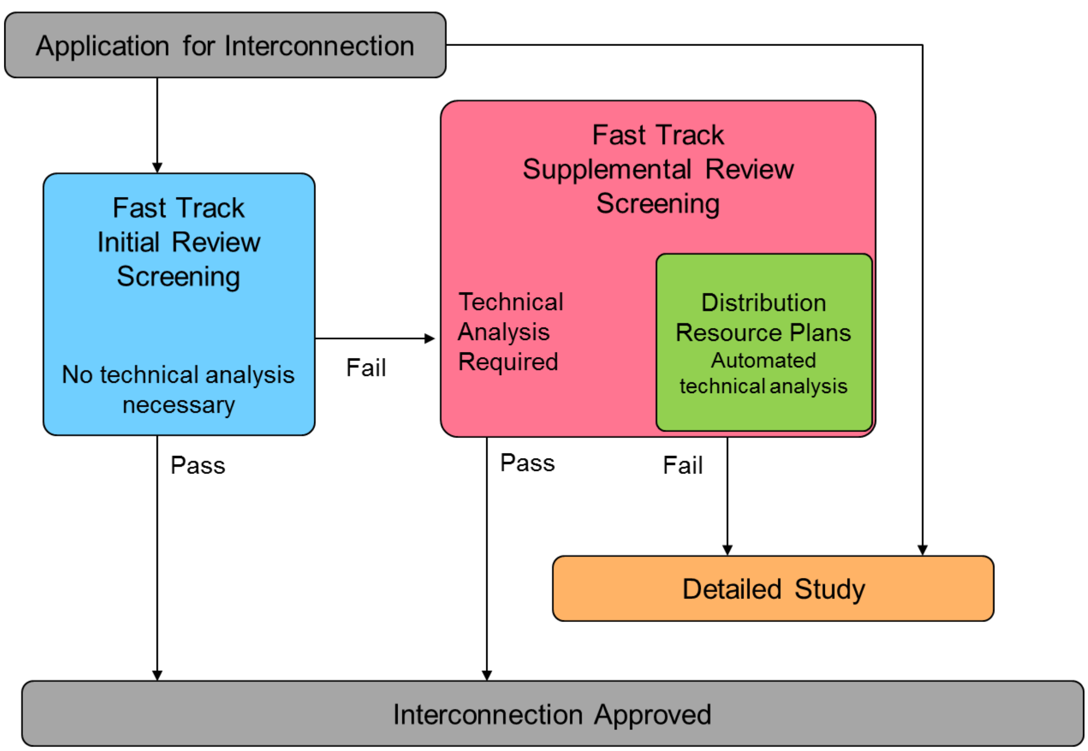

Figure 6-1.
Screening in Coordination with Distribution Resource Plan

A DRP could effectively be a detailed analysis on every feeder, however, as indicated from this project, the detailed analysis is very time intensive and would be less feasible. A DRP must be something that can be efficiently and effectively calculated. After several years of research, EPRI has created the Streamlined Hosting Capacity method that can be used as a form of DRP.

The streamlined hosting capacity analysis has been applied to five of the 16 study feeders. Figure 6-2 shows primary node overvoltage-based hosting capacity determined from the DRP, detailed analysis, and shorthand equation (SR1). Using the detailed analysis as the baseline, the DRP produces results that are closer than the shorthand equation. Because the shorthand analysis is not performed with the full detailed model, the estimates can be slightly higher/lower than the detailed result while the DRP remains slightly lower. Ultimately, the DRP can be used in lieu of the shorthand equations for the interconnection issues identified in this project as well as others.

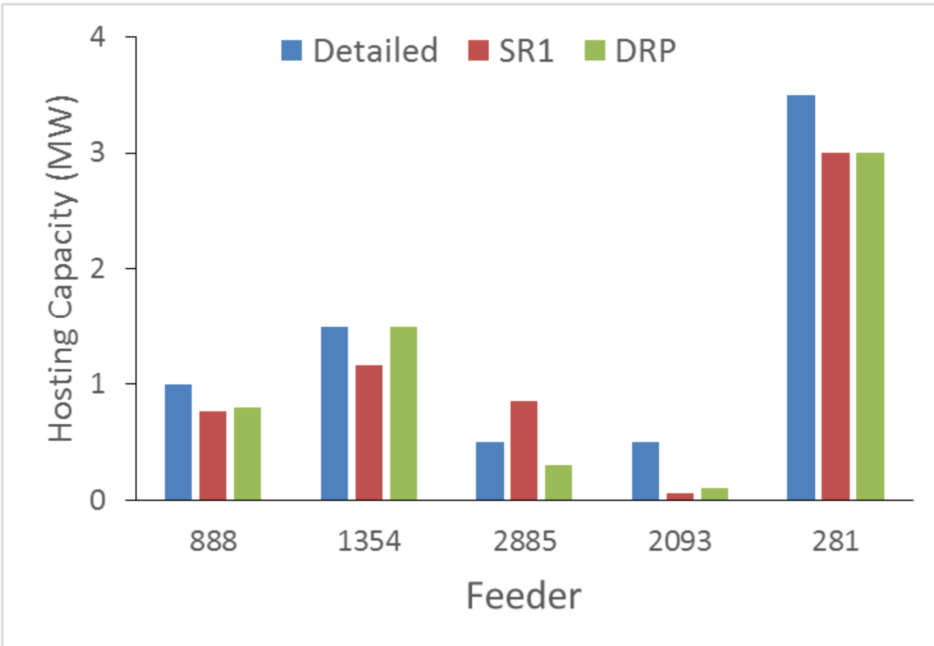

Figure 6-2.
Improving Overvoltage Hosting Capacity Prediction with Distribution Resource Plan

EPRI's Streamlined Hosting Capacity

The streamlined hosting capacity analysis has been created to better determine the system-wide ability to accommodate Distributed Energy Resources (DER) on the distribution system such as photovoltaics (PV) and energy storage. As described in Figure 6-3 detailed analysis would be more accurate but requires significantly longer analysis. Simple screens can be quick but are much less accurate. The streamlined analysis is a bridge between these two extremes and incorporates accuracy with speed.

Figure 6-3.
Streamlined Hosting Capacity Analysis Compared to Detailed Analysis and Screens

The fundamental design of the streamlined analysis is outlined in Figure 6-4. The method is granular and can be applied to every distribution feeder which is necessary because each feeder is unique. The method is repeatable with automated scripts so that the analysis can be re-applied as the system changes. It is efficient such that it is scalable to analyze the entire system. The method is transparent and documented.[17] It is proven based on detailed feeder analysis conducted by EPRI over the past several years and also with 3rd party methods. And finally, the method is in the process of becoming available in utility tools such as Cyme, Synergi, and Milsoft.

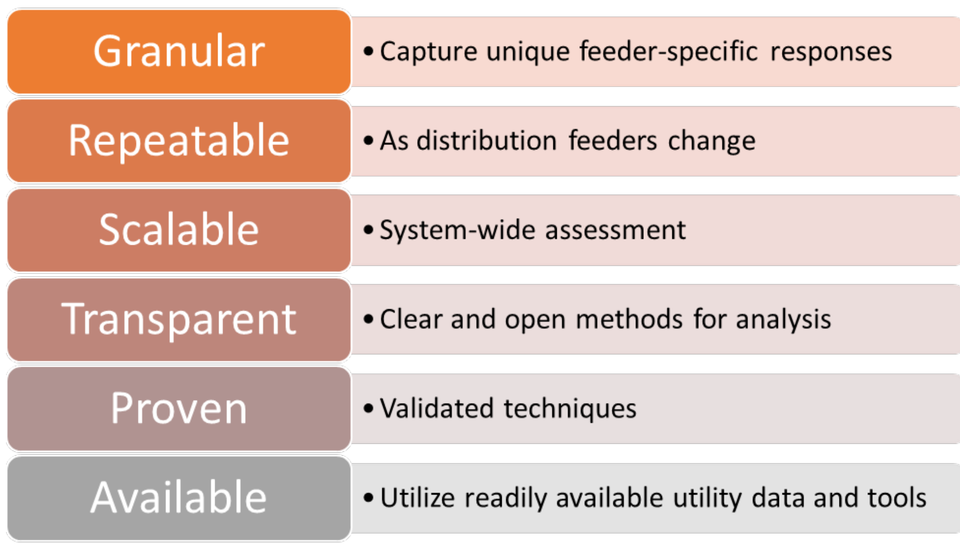

Figure 6-4.
Design of the Streamlined Hosting Capacity Analysis

The streamlined hosting capacity method and analysis has been developed through multiple years of research on distributed PV impact studies. The evolution of the methodology is shown in Figure 6-5. The method analyzed millions of potential PV deployments across more than 30 feeders while examining the impact to multiple issues. The simulations and impacts observed on specific feeders have been beneficial in determining how PV can impact the distribution system as well as providing the utility a screening criterion.

[17] A New Method for Characterizing Distribution System Hosting Capacity for DER: A Streamlined Approach for PV. EPRI, Palo Alto, CA: 2014. 3002003278.

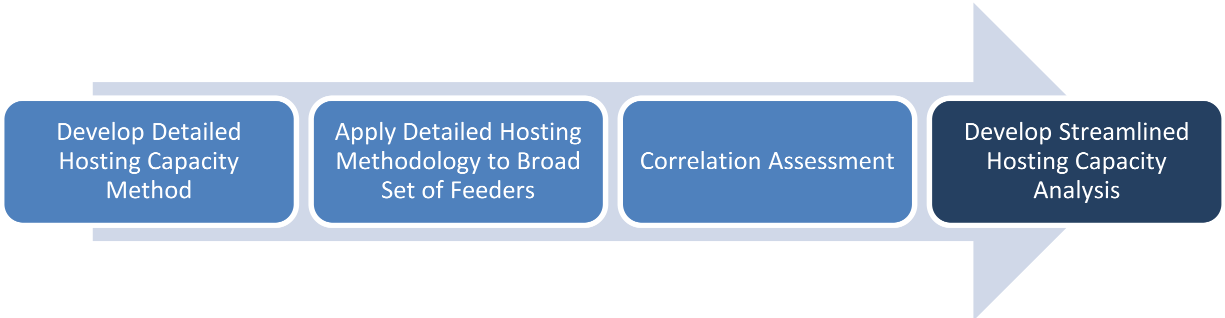

Figure 6-5.
Evolution of Hosting Capacity Analysis

The question that often arose during the detailed analysis is how the hosting capacity analysis on several test feeders could be extrapolated to the additional thousands of feeders within a service territory. Unfortunately, the response of each feeder is unique and the time and effort involved in the detailed study is too great to replicate on thousands of additional feeders. Therefore, the impact results found in the detailed study cannot be mapped directly to other feeders.

Although the results cannot be mapped to other feeders, there are correlations in the feeder response. These correlations allow the key characteristics to be derived and support the development of faster and easier methods to arrive at similar solutions. The overarching observation is that the location of PV matters and the feeder impact cannot be decoupled from the full range in characteristics/detail included in a feeder model.

The hosting capacity's ultimate dependency on the actual feeder model is the driving force to develop EPRI's streamlined method. Thus the streamlined method is rooted in the details and takes into consideration the full range in feeder characteristics by examining the model's power flow solution and short-circuit response. These two key data streams provide input to the overall method, and combined with a characterization of the feeder topology, form the basis of the streamlined hosting capacity methodology. The application of the EPRI's Streamlined Hosting Capacity Analysis applied to an entire system is shown in Figure 6-6.

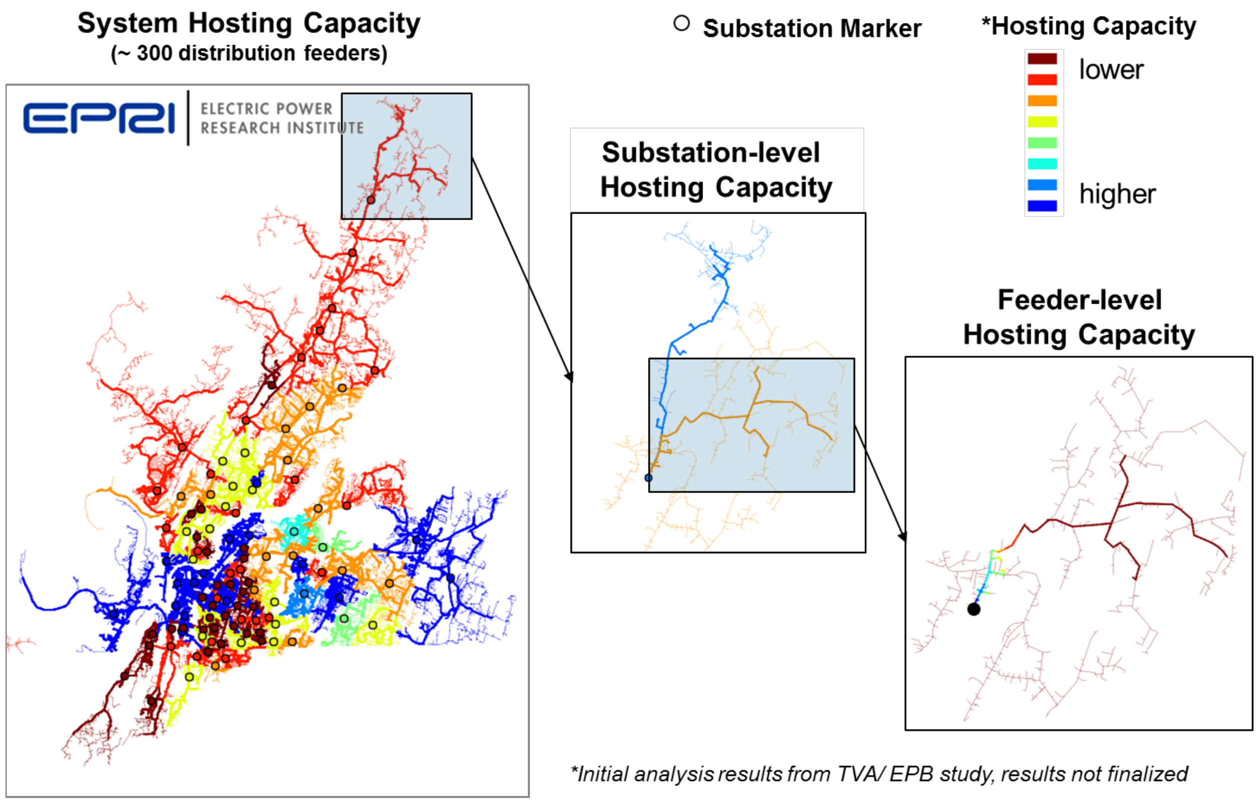

Figure 6-6.
Sample Results from System-Wide Analysis

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CONCLUSION

Rule 21 is an interconnection procedure for California utilities to follow for distributed generation application reviews. Utilities have the opportunity to go above and beyond where necessary but at minimum must consider the screening methods in the rule. The interpretation and application of Rule 21 screens is based on planning procedures and the ability to conduct certain analyses. Most CA utilities have commented that even though the screening process can take well longer than the allotted time if supplemental and detailed review are necessary, their proficiency in the review process is considerably better than most due to the number of interconnection requests encountered to date.

Each task of this project helped progress to the final goal of improving CA Rule 21 as penetration levels and interconnection requests continue to increase. The bulk of the project consisted of selecting the feeders for detailed analysis as well as performing that analysis, suggesting updates to Rule 21, and validating those updated methods.

The selection of the utility feeders was based on the results of a comprehensive clustering analysis where each feeder from the three CA investor owned utilities was characterized and grouped into representative sets. The representative sets were not suggesting all feeders within the set will have a similar response to distributed generation, but the sets allow selection of several feeders, one from each set, that will have considerably different characteristics. These representative feeders from each utility were placed into two groups. One set of 16 for detailed analysis and another set of 6 for validation.

A detailed feeder model was developed for each of the selected feeders. The models were based on the utility planning model and converted into the OpenDSS distribution software. The OpenDSS distribution software was used so that detailed hosting capacity analysis could be performed similarly across the different utilities even though the original models come from different software platforms.

The analysis of the models was conducted with PV as the distributed resource. Rule 21 is inclusive of all distributed resources, but this project specifically analyzed distributed PV. The hosting capacity analysis determined the amount of PV that could be accommodated on a distribution feeder without impacts exceeding predefined utility guided thresholds. The hosting capacity for each feeder was unique for voltage and protection issues.

Findings

The detailed feeder impact analysis performed identified when potential issues from aggregate distributed generation were not properly identified and also when a feeder was capable of accommodating considerably higher levels of distributed generation. The “Alternatives to the 15% Rule” found in this project more properly address the impacts from distributed generation and were not dependent on load level alone. The improvements suggested to Rule 21 included:

- Add an Initial Review screen that addresses if the feeder has line regulators
- Modify the Initial Review to always address aggregate generation
- Add Supplemental Review equations to be used as a guideline to address the voltage and protection impacts from aggregate generation

These improvements were based on the detailed analysis of 16 study feeders that span a wide range in characteristics. The modified screens were then applied to a separate set of 6 validation feeders to observe and verify the new recommendations. The application of the modified screens show that the aggregate impact could be better screened for the issues analyzed.

Recommendations

Based on the findings of this work, the suggested screening improvements can be used to provide a more detailed screening mechanism while the utilities are developing the DRP. The DRP is not a replacement for interconnection studies or Rule 21, but can further improve the analysis of aggregate generation as has been analyzed in this project. In the near term, the shorthand equations developed here can be used for Supplemental Review and more accurately assess the aggregate impact. In the long term, the DRP would have the feeder hosting capacity calculated for each feeder on the system and the aggregate penetration limits of the feeder would already be known and used in place of the Supplemental Review shorthand analysis.

Public Benefit

As the number of PV applications and installations increases, utilities are faced with a greater need to evaluate the aggregate impact of these systems. In most cases, it means an increased number of detailed impact studies or applications that do not get approved. The short hand calculations developed in this project provide a screening mechanism to potentially fast track some of the more complex applications during the Supplemental Review. Using these calculations, utilities may identify applications that can be approved for interconnection without requiring further study that may have gone to detailed study previously. The result - more timely and lest costly interconnection application processing.