Alternatives to the 15% Rule

Modified Screens and Validation

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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) is supporting 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.

This CSI RD&D project has completed the tasks of collecting data from the three utilities, clustering feeder characteristic data to attain a sample range of feeders, detailed modeling of the 16 sample feeders, and analysis of PV impacts to those feeders. In this report, gaps and limitations in the current screening process – California Rule 21 are identified. The improved screening methods are technically-based on the detailed analysis and are validated with six new feeders. A subsequent final report will highlight overall project findings.

Keywords
Application
Distributed PV
Interconnection
Screens
Solar

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) is supporting 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[3].

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, gaps and limitations in the current screening process – California Rule 21[4] are identified. Technical-based methods to improve Rule 21 are made along with a validation of these methods.

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 are a key factor in whether issues 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.[5]

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

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

[5] 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

Project Goal

This project is part of the third solicitation of the California Solar Initiative Research, Development and Demonstration program created by the California Public Utilities Commission in 2006 to support solar research in California. 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 including PV location, aggregate PV effects, and most importantly specific feeder characteristics such as voltage class, voltage regulation schemes, and operating criteria.

Benefits

The results of this effort are improved methods to 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 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 is 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.[6]
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.[7]
3. Collect high-resolution solar output data for validation of feeder models, definition of scenarios for high-penetration PV output, and verification of screening methods with empirical data.
4. Complete detailed feeder electrical modeling of 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.[8]
6. *Develop practical screening criteria for evaluating new interconnection results.*
7. *Conduct formal validation process to determine accuracy of screening methodology*.

This report highlights the improved screening methods based on the high-penetration detailed analysis (6) and provides validation of those methods with six separate feeders (7).

[6] 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.
[7] Clustering Methods and Feeder Selection for California Solar Initiative. EPRI, Palo Alto, CA: 2014. 3002002562.
[8] Alternatives to the 15% Rule: Modeling and Hosting Capacity Analysis of 16 Feeders. EPRI, Palo Alto, CA: 2015. 3002005812.

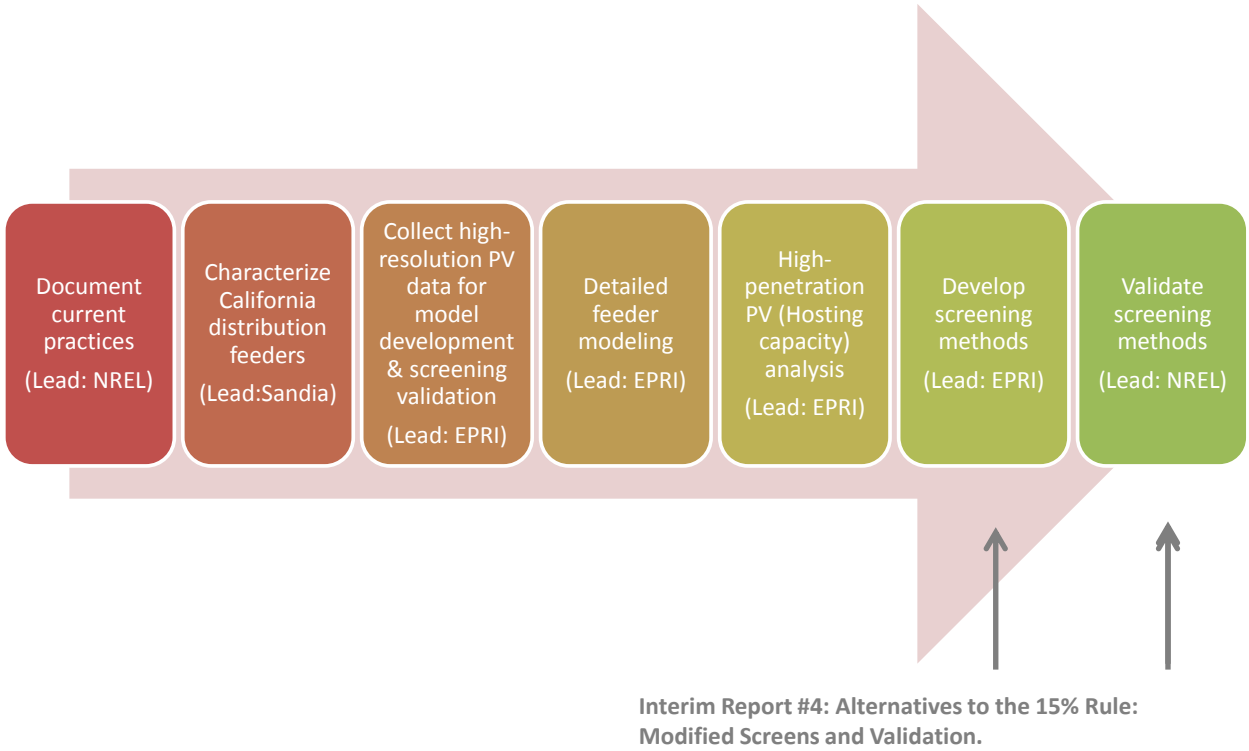

Figure 1
Project Breakdown and Task Leads

Results

The detailed feeder impact analysis performed in the previous project task identified when potential issues from aggregate distributed generation are not properly detected and when a feeder is capable of accommodating considerably higher levels of distributed generation. The centralized PV hosting capacity determined from the detailed analysis are shown in Figure 2a and Figure 2b for two different feeders. The hosting capacity depends on the feeder issue analyzed. The colors indicate the ability to accommodate/host PV by illustrating the impact to each issue as below/near/above the impact threshold. The dashed lines indicate 15% of peak load. In Figure 2a, the 15% load screen does not capture the potential adverse impacts from distributed generation since the feeder minimum hosting capacity (transition from green to yellow) is lower than the 15% peak load for several issues. Alternatively, as results show in Figure 2b, the 15% peak load screen can considerably limit the amount of PV allowed on the feeder.

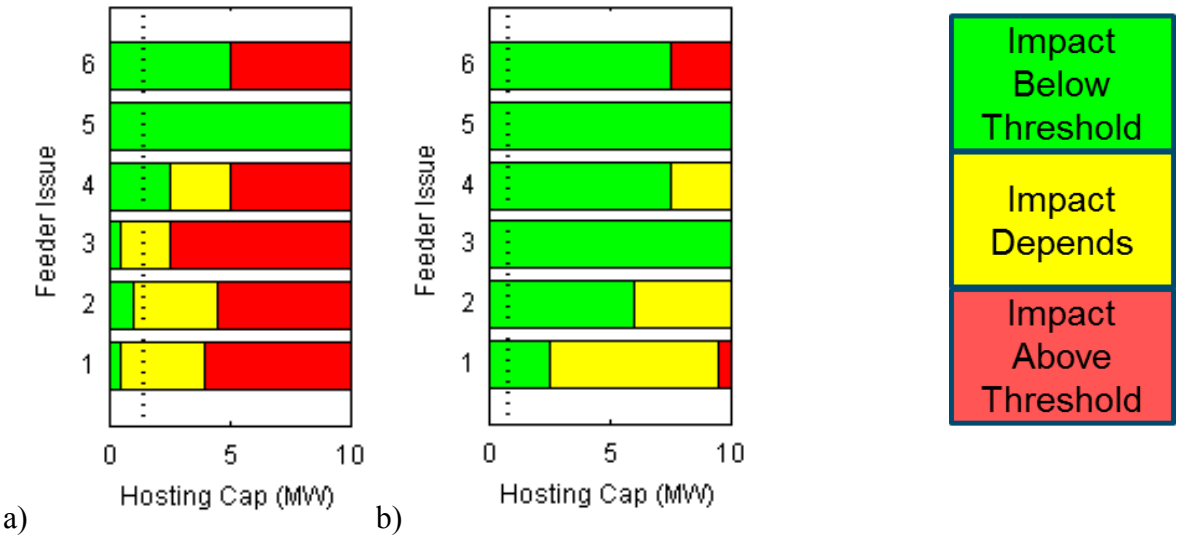

Figure 2.
Detailed Impact Analysis for Two Different Feeders where the 15% Load Screen a) Does not Properly Identify Adverse Impacts b) Incorrectly Limits Hosting Capacity
***Dashed lines indicate 15% peak load screen**

These findings inform the development of improved screens in CA Rule 21 which more accurately address the impacts from PV and aggregate generation. A simple illustration of CA Rule 21 illustrating the Initial and Supplemental Review within the Fast Track process is shown in Figure 3. The "Alternatives to the 15% Rule" found in this project address the impacts from distributed PV and are not dependent on load level alone. The improvements 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 guidelines to address the impacts of aggregate generation for issues not solely dependent on load

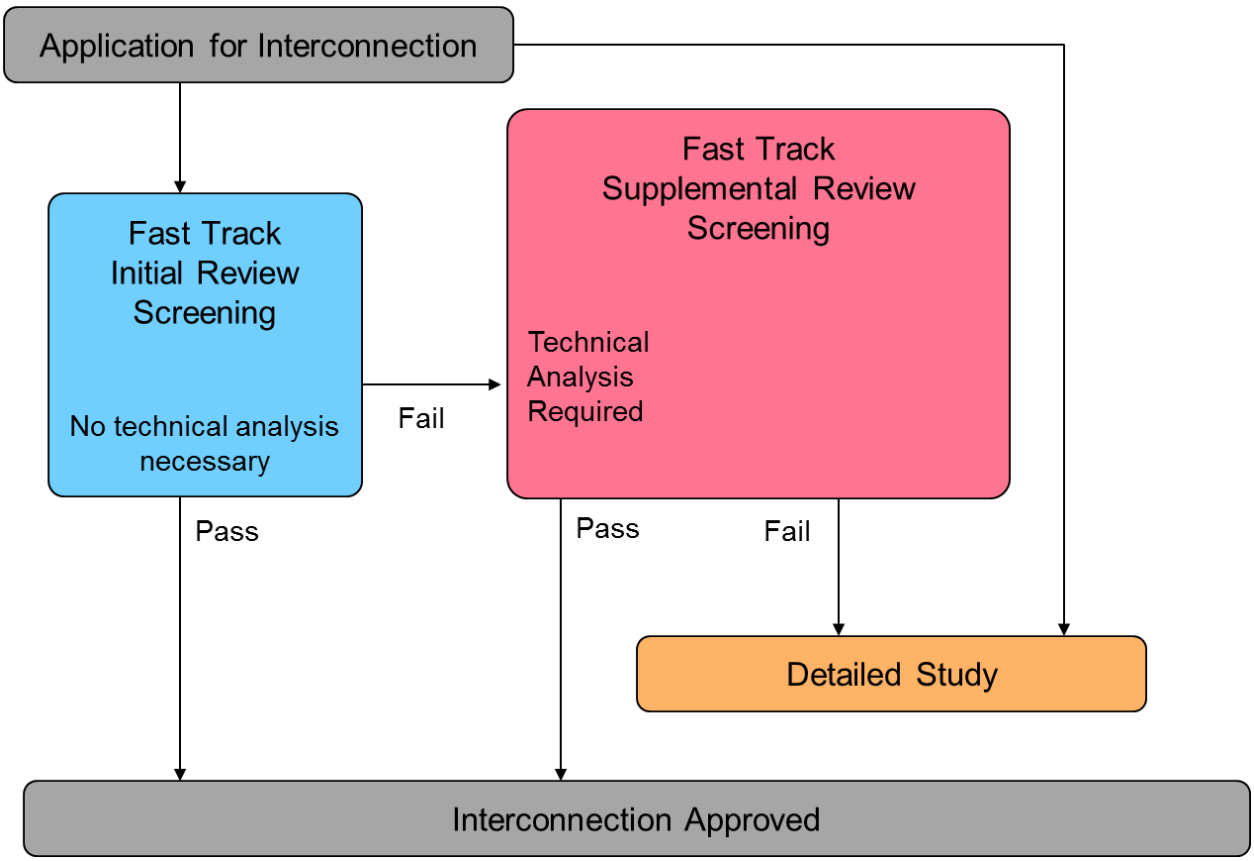

Figure 3.
Basic California Rule 21 Screening Process

Sixteen feeders, referred to as the "study feeders", have been analyzed in detail to develop the proposed Rule 21 modifications. The results of PV hosting capacity analysis for six new feeders have not been considered during the development of the proposed Rule 21 modifications. These six new feeders are used to validate the proposed modifications.

Figure 4 illustrates the Initial Review and Supplemental Review results on two of the validation feeders for centralized PV hosting capacity. The bar charts are shown for each of the six feeder issues considered, labeled as SR1-SR6.

The asterisks on each bar chart show the calculated PV hosting capacity using the proposed shorthand equations which can be implemented in the Supplemental Review process. The short-hand equations are intended to provide guidance to utilities and allow quick calculations to be performed using limited time and data, but also considering the unique feeder response due to the PV. Finally, the vertical dashed lines demark the loading level equal to 15% of the peak feeder load.

Feeder 679 does not contain a line regulator, and as expected, hosting capacities are above the 15% load limit. Feeder 514 does contain a line regulator, and as expected, hosting capacities are below the 15% load limit. The feeder with the regulator would be subjected to the Supplemental Review process immediately as opposed to allowing PV deployment up to 15% of peak load and then implementing the Supplemental Review. At some point, the aggregate generation on the

feeder will cause adverse impact, thus aggregate generation should always be considered during interconnection requests. After determining the approximate hosting capacity with the Supplemental Review equations (asterisks), the feeders' ability to accommodate PV is shown to be independent of load level and better matches the detailed analysis.

Results from the short-hand equations compared to the detailed hosting capacity analysis indicate close approximation to the minimum hosting capacity. Recall that minimum hosting capacity is defined as the lowest amount of PV that causes the first violation on the feeder. Therefore, the short-hand equations prove to be effective at estimating PV impact to the grid. When in error, the error tends to result in values less than the feeder minimum hosting capacity. This is acceptable given that simple "fast" screens such as this should be conservative by nature since limited analysis is being performed at that stage.

Results indicate the proposed modifications to the Initial Review and Supplemental Review processes can improve screening interconnection requests.

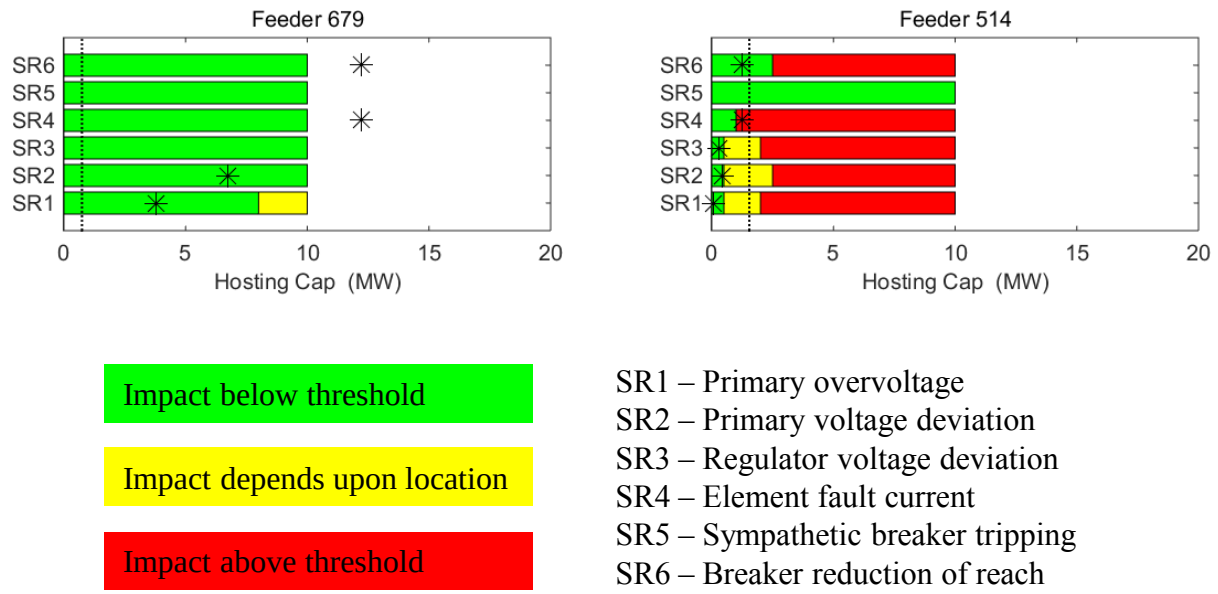

Figure 4.
Centralized PV hosting capacity for Validation Feeders
***Dashed lines indicate 15% peak load**
***Asterisks indicate alternatives to estimating hosting capacity**

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
- Sandia National Laboratories
- Itron

Utility Partners:

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

CONTENTS

***1* INTRODUCTION 1-1**

California Rule 21 1-1

Initial Review Process 1-4

Supplemental Review Process 1-4

Modified Screens 1-4

Improvements to Initial Review 1-4

Improvements to Supplemental Review 1-4

Validation 1-5

Initial Review Validation 1-5

Supplemental Review Validation 1-5

***2* MODIFIED SCREENS 2-1**

Detailed Analysis Results 2-2

Improvements to Initial Review Process 2-4

Line Voltage Regulators 2-5

Aggregate Generation 2-5

Improvements to Supplemental Review 2-5

Shorthand Analysis 2-6

Primary Voltage Headroom & Sensitivity 2-6

Detailed Analysis with Shorthand Hosting Capacity Calculations 2-7

Shorthand Equations 2-9

SR1 – Primary Overvoltage 2-10

SR2 – Primary Voltage Deviation 2-11

SR3 – Regulator Voltage Deviation 2-11

SR4 – Element Fault Current 2-12

SR5 – Sympathetic Breaker Tripping 2-12

SR6 – Breaker Reduction of Reach 2-13

Revised Screen 2-13

***3* VALIDATION 3-1**
Methodology 3-1
Initial Review 3-2
Supplemental Review 3-2
Validation Result 3-3
Initial Review 3-3
Supplemental Review 3-6

***4* CONCLUSION 4-1**

LIST OF FIGURES

Figure 1-1. Basic California Rule 21 Screening Process 1-2

Figure 1-2. Detailed Rule 21 Screening Process.....1-3

Figure 2-1. Residential/Commercial Rooftop PV Detailed Hosting Capacity (Dashed lines indicate 15% of breaker peak load) *Note: Feeder 3999 is a solely industrial circuit and is not included in hosting capacity analysis for residential/commercial PV deployment. *Vertical dashed lines indicate 15% of peak load. 2-3

Figure 2-2. Utility-Scale PV Detailed Hosting Capacity (Dashed lines indicate 15% of breaker peak load) *Vertical dashed lines indicate 15% of peak load. 2-4

Figure 2-3. Sensitivity to Determine Best Method to Estimate Primary Overvoltage Hosting Capacity a) Feeder with No Line Regulators b) Feeder with Line Regulators 2-7

Figure 2-4. Residential/Commercial Rooftop PV Short-Hand Hosting Capacity *Note: Feeder 3999 is a solely industrial circuit and is not included in hosting capacity analysis for residential/commercial PV deployment. 2-8

Figure 2-5. Utility-Scale PV Short-Hand Hosting Capacity 2-9

Figure 2-6. Suggested Modifications to CA Rule 21 2-14

Figure 3-1. Characteristics of the Six Validation Feeders 3-3

Figure 3-2. Residential/Commercial Rooftop PV Detailed Hosting Capacity (Dashed lines indicate 15% of peak load) 3-4

Figure 3-3. Utility-Scale Centralized PV Detailed Hosting Capacity (Dashed lines indicate 15% of peak load) 3-5

Figure 3-4. Maximum Resistance to Last Three-phase Primary Node on Validation Feeders.....3-6

Figure 3-5. Primary Voltage Headroom of Validation Feeders.....3-6

Figure 3-6. Residential/Commercial Rooftop PV Hosting Capacity (Dashed lines indicate 15% of breaker peak load) 3-7

Figure 3-7. Utility-Scale PV Hosting Capacity (Dashed lines indicate 15% of breaker peak load) 3-8

1
INTRODUCTION

The third solicitation of the California Solar Initiative (CSI) Research, Development, Demonstration and Deployment (RD&D) program 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. Currently this process is the most time-consuming of any step on the path to generating power on the distribution system[9].

The process allows utilities approximately 15 business days to perform Fast Track 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 Initial Review and Supplemental Review, 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.

An outcome of this CSI RD&D solicitation three project is to improve the review and approval process in both the Initial Review and Supplemental Review. The improvement to the Initial Review 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. Identifying overly-conservative results can prevent lengthier Supplemental Review or transfer to detailed impact analysis. All of the above will improve and expedite the application review and approval process.

The project had several steps to reach this outcome. 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 are 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 formulate the additional screens and enhancements to current California P.U.C. Rule 21 as discussed and validated in this report.

California Rule 21

California P.U.C. Rule 21 is a guideline established to manage distributed generation (DG) interconnection requests. The Technical Framework of Rule 21 is illustrated at a high level in

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

Figure 1-1. A more detailed version of the process is shown in Figure 1-2. 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 DG applicants enter the application process and either enter the Fast Track process upon eligibility or are directed to detailed studies. Once in the Initial Review process, a failure of a screen will direct the application to Supplemental Review or Detailed Analysis. Supplemental Review is an intermediate process between Initial Review and Detailed Analysis. Each process deeper in the review requires more thorough analysis and requires additional details and data.

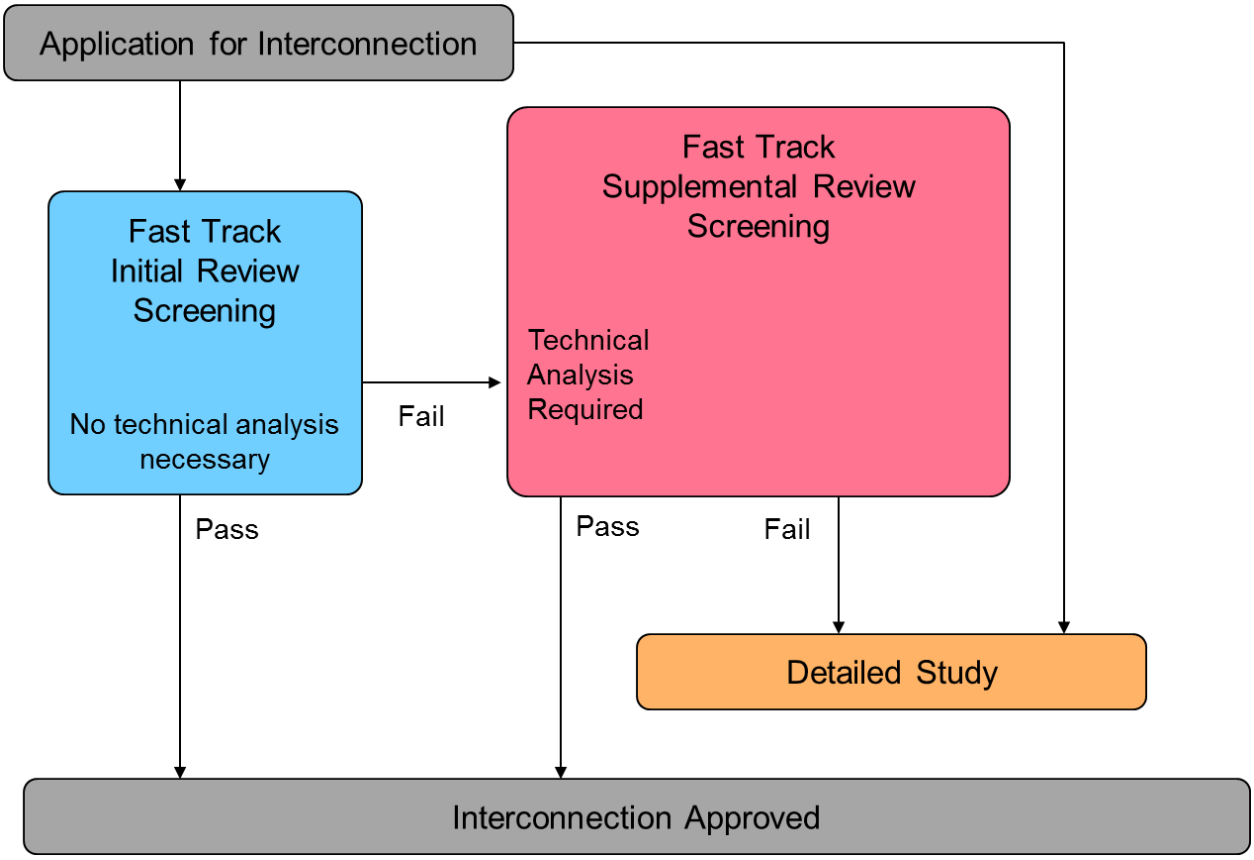

Figure 1-1.
Basic California Rule 21 Screening Process

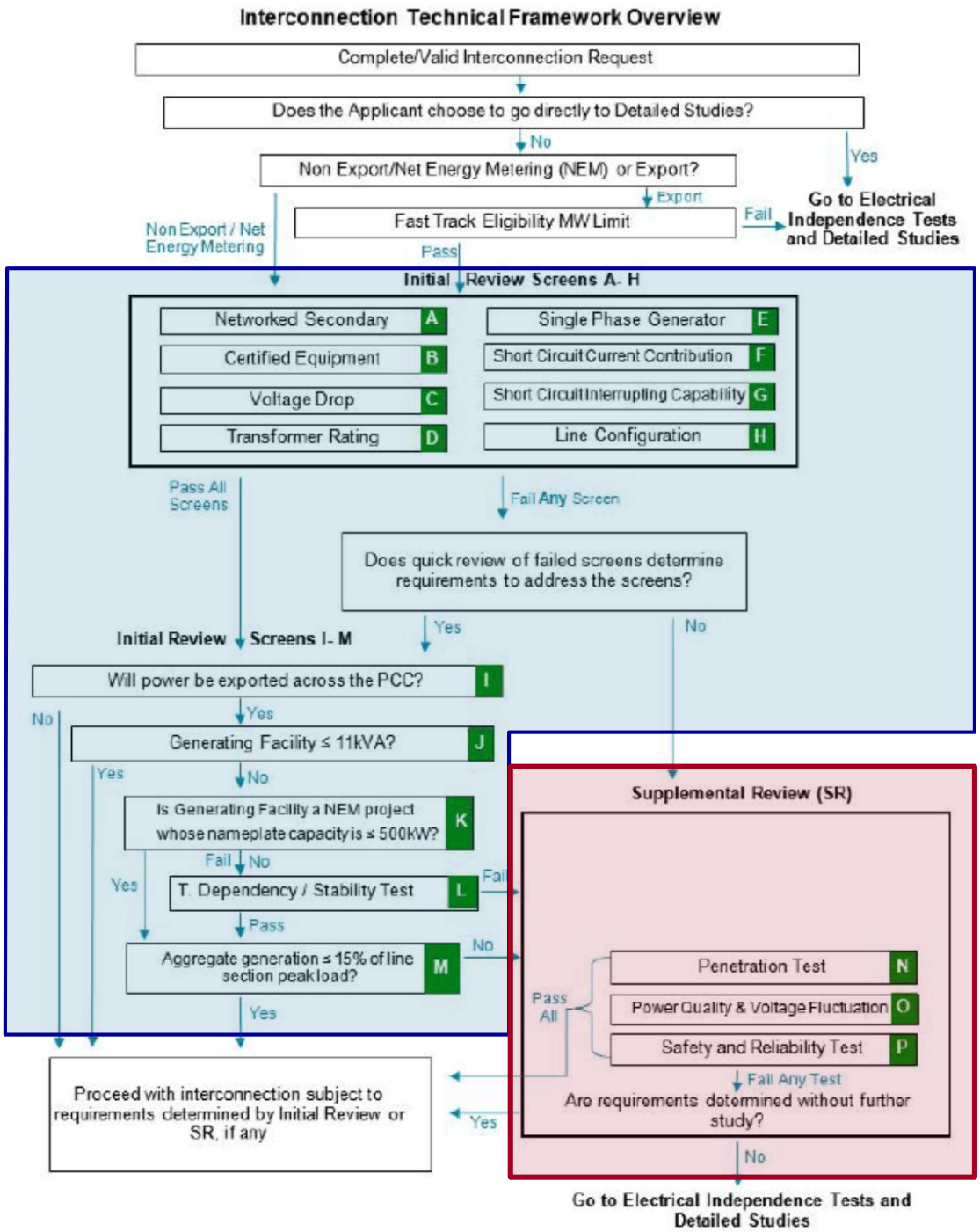

Figure 1-2.
Detailed Rule 21 Screening Process[10]

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

Initial Review Process

Initial Review is conducted with little to no technical analysis. The failure of an Initial Review screen can direct the application to Supplemental Review. There are three ways to enter the Supplemental Review from the Rule 21 Initial Review. Additionally, there are three ways to move directly into interconnection acceptance. Early failure or acceptance can prevent all Initial Review screens from being analyzed.

Supplemental Review Process

The Supplemental Review requires a slightly more technical analysis but is not meant to be a detailed study. There are only three screens currently listed within Supplemental Review. Those screens are meant to capture the range in possible impacts from interconnecting distributed generation and also the range in the ways utilities might analyze those impacts.

Modified Screens

The current version of CA Rule 21 has been analyzed to identify gaps and areas where improvement can be made. These gaps and improvements are made based on the inspection of the Rule as it is currently written. It should be acknowledged that some of the recommendations suggested may already be applied by the utilities based on their extensive use of Rule 21 and planning practices currently in place. However, Rule 21 should be thorough such that it can be easily interpreted by other utilities establishing their own screening criteria.

The majority of the improvements recommended in this report address the implications from aggregate generation on the feeder. Most of the screens currently in Rule 21 address the single generator interconnect request. This is likely due to the Rule originally designed for low penetration, however, as penetration continues to increase, the aggregate impacts must be properly addressed.

Improvements to Initial Review

Improvements to the Initial Review must not require technical analysis. An additional screen to identify a potential problematic scenario is if the feeder is weak. An indication of a weak feeder, without model analysis, is if the feeder contains line regulators. This characteristic typically occurs on feeders that currently have existing voltage regulation problems and is common among feeders that have lower hosting capacities.

Another problematic scenario depends on the amount of DG already connected to the feeder. One of the primary drivers that allow expedited acceptance of distributed generation is based on the size of the generating facility. Relatively small systems or when the DG is less than the local minimum load, can be immediately accepted based on the several early screens. An improvement to the Initial Review process is to always acknowledge the aggregate penetration already on the feeder. Detailed analysis of high aggregate DG penetration indicates that adverse impact may still occur even if the individual systems are relatively small.

Improvements to Supplemental Review

The Supplemental Review process can be improved by providing additional guidance about the ability to accommodate PV. Although a more technically based analysis, the Supplemental

Review is not meant to be a full detailed study. Simple methods and equations are suggested to determine a conservative aggregate feeder hosting capacity for PV.

Validation

Validation of the modified interconnection request process is completed on a set of six new distribution feeders. This allows validation to proceed with feeders whose hosting capacity characteristics had not been considered during the formulation of the modified screens. For validation, the detailed hosting capacity analysis is completed on the validation feeders. Then the modified Initial Review and Supplemental Review are applied to determine

- If all problematic PV scenarios are identified
- If a more accurate aggregate hosting capacity can be calculated.

Initial Review Validation

The Initial Review modifications are validated by comparing if the presence of a line regulator limits the ability to accommodate DG below 15% of peak load as seen in the test feeder analysis. All feeders with line regulators should immediately enter Supplemental Review. For all other feeders, no issues should occur when the aggregate penetration is below 15% of peak load. When the aggregate penetration level exceeds 15% of peak load, Supplemental Review is mandatory. By forcing this procedure, a potential scenario should not occur where higher aggregate penetration is allowed without more thorough analysis.

Supplemental Review Validation

The validation for the modifications proposed for the Supplemental Review process compares the detailed feeder minimum hosting capacities to the values derived from proposed simple equations. The equations are a function of worst-case DG placement on the feeder, thus the results should provide conservative hosting capacities similar to the minimum hosting capacities from the detailed analysis which also occur from worst-case DG placement.

2 MODIFIED SCREENS

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.

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 screening.

The current screens contained within the Rule are 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. The technical recommendations provided from this project are also not inclusive of all potential aggregate impacts from PV.

Detailed Analysis Results

The detailed analysis conducted in this project is used to determine the feeder impacts and hosting capacity for issues not specifically identified in Rule 21. The impacts examined can be caused by the aggregate amount of PV on a feeder and are not a function solely of load.

The detailed hosting capacity analysis results for residential/commercial (rooftop) PV are shown in Figure 2-1 while the detailed hosting capacity for utility-scale (centralized) PV is shown in Figure 2-2[11].

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

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 slow variation flicker
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.

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

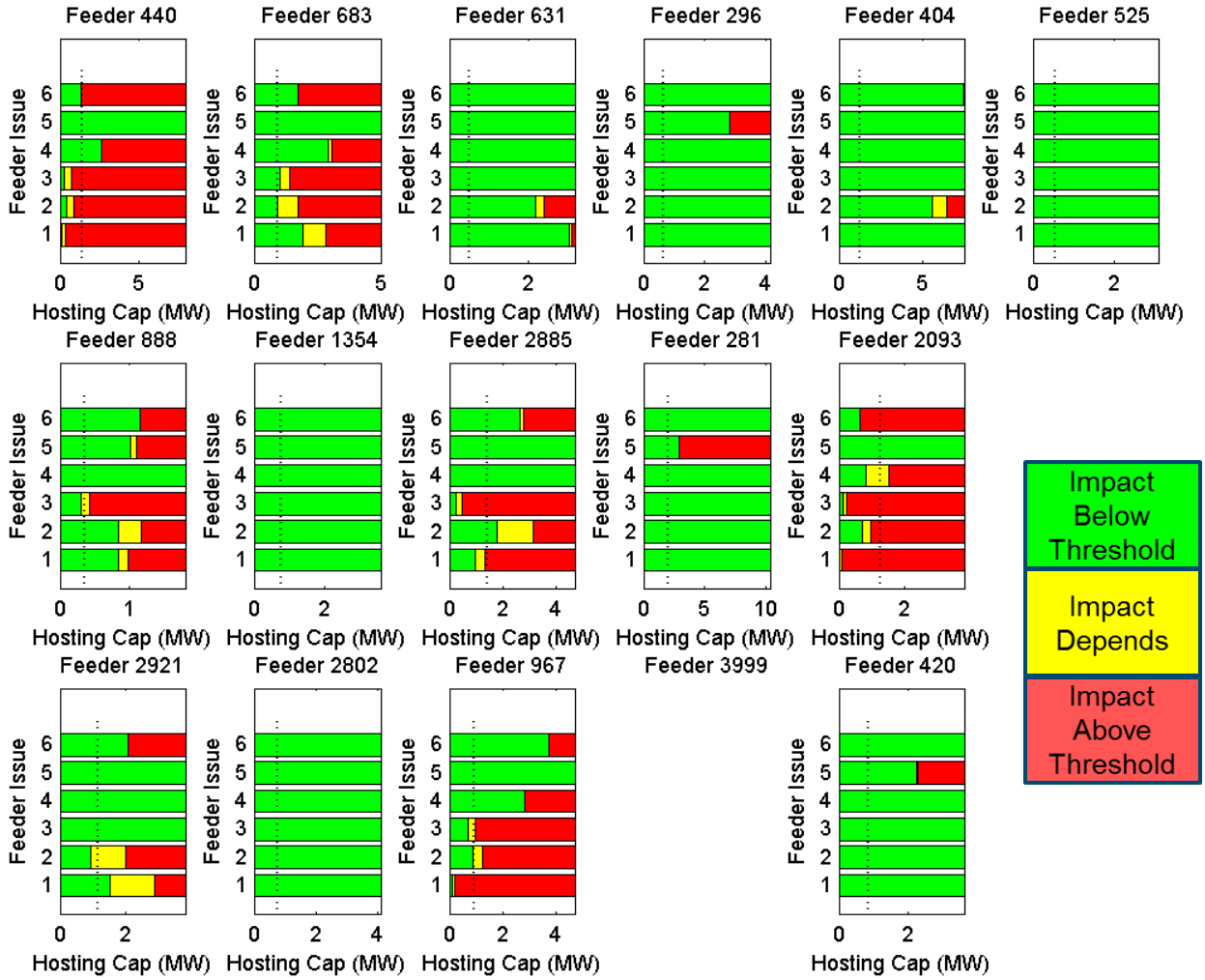

Figure 2-1.
Residential/Commercial Rooftop PV Detailed Hosting Capacity (Dashed lines indicate 15% of breaker peak load)
***Note: Feeder 3999 is a solely industrial circuit and is not included in hosting capacity analysis for residential/commercial PV deployment.**
***Vertical dashed lines indicate 15% of peak load.**

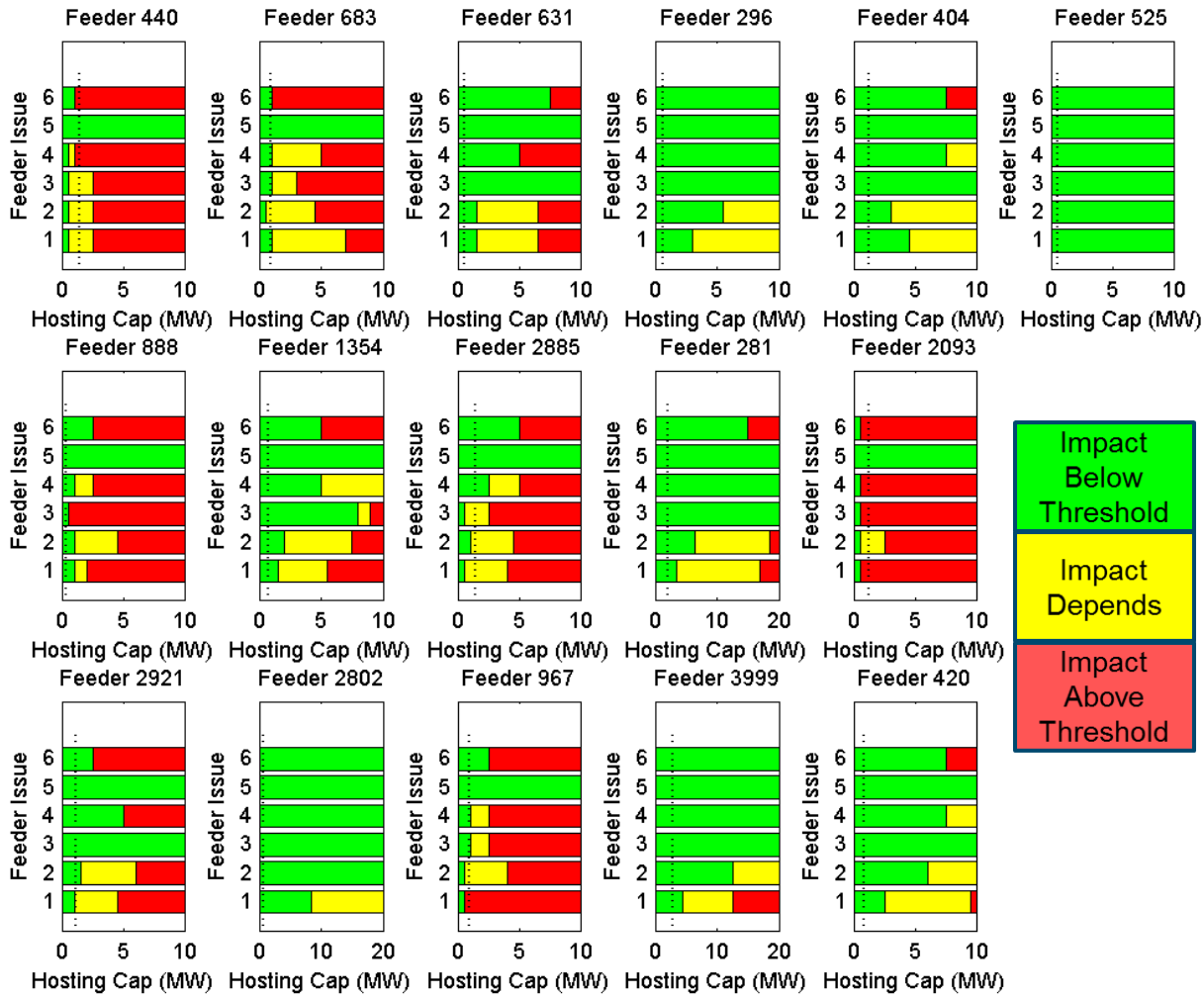

Figure 2-2.
Utility-Scale PV Detailed Hosting Capacity (Dashed lines indicate 15% of breaker peak load)
*Vertical dashed lines indicate 15% of peak load.

Improvements to Initial Review Process

In the Initial Review screening process, the aggregate penetration of PV becomes a factor if Screen M (15% peak load screen) is applied. Screen M is the main aggregate penetration test currently contained within the Rule (aggregate fault current issues also addressed in Screen F). 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 in Figure 2-1 and Figure 2-2. There are several instances where PV would be allowed to interconnect based on passing Screen M whereas the detailed analysis shows that the hosting capacity for the feeder can be lower.

Line Voltage Regulators

The feeders that have 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 is to include a screen dedicated to line regulators. Line regulators are commonly an indication that there are voltage regulation issues already on the feeder. The data needed to apply this screen would only be to know if the applicant is wanting to interconnect to a feeder that contains mid-feeder voltage regulation. If this occurs, the application would enter the Supplemental Review. A way to deem there is a low likelihood of adverse impact would be if the applicant's interconnection would be upstream from the line regulator.

Aggregate Generation

The aggregate generation test Screen M is not always considered especially if Screen I (non-exporting facility) or Screen J (≤ 11 kVA facility) are satisfied. This identifies a major gap in the Initial Review screening process where the aggregate generation test can be bypassed. For example, if all PV interconnecting to the feeder are less than 10 kW, the impacts from aggregate distributed generation would not be addressed through Screen M. Therefore, it is 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 the reaching that limit, potential feeder impacts would 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 as shown in Figure 2-1 and Figure 2-2. Screen N (100% minimum load screen) 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) when 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. Ultimately, there is a need to more accurately identify the aggregate hosting capacity of a feeder other than that based solely on load. These recommendations are the "Alternatives to the 15% Rule." These recommendations 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 hosting capacity limit can be calculated using simple equations. For each of the issues shown previously, a shorthand equation has been derived. The shorthand equation for each issue should show a hosting capacity within the green region of the detailed analysis results. Therefore the equations would still produce conservative hosting capacity values that describe an aggregate PV scenario worse than any analyzed in the detailed analysis. The data needed for the additional Supplemental Review equations include:

- MaxR: Resistance to last/furthest/most remote three-phase primary node
- MaxZ: Impedance to last/furthest/most remote three-phase primary node
- FederkVLL: 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
- 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

Primary Voltage Headroom & Sensitivity

The primary voltage headroom on a feeder can be a difficult value to define. There are several methods to approximate the value, so a sensitivity analysis has been conducted to determine the recommended methods and under what feeder conditions those methods should be applied. The method chosen is based on producing similar primary overvoltage hosting capacity results as in the detailed analysis. In the sensitivity, the midday minimum and midday maximum load are examined. Five methods for calculating headroom are also examined but the top two Methods are:

1. Highest voltage anywhere on the feeder, all nodes and phases considered
2. Average voltage of all nodes along the feeder while only considering the highest phase voltage at each node

The best approach to determine hosting capacity when regulators are not present is to use Method 2 as illustrated by hosting capacity (y-axis) in Figure 2-3a. Midday minimum load

typically produces a lower hosting capacity due to higher voltages and less headroom, except when line drop compensation exists as on this feeder. When line regulators are present (Figure 2-3b), Method 1 is used to calculate voltage headroom and hosting capacity. Due to line regulation, the hosting capacity shown is an order of magnitude lower than when regulators are not present (Figure 2-3a). Again, midday minimum load typically produces lower hosting capacities due to higher voltages and less headroom, except when line drop compensation exists as on this feeder.

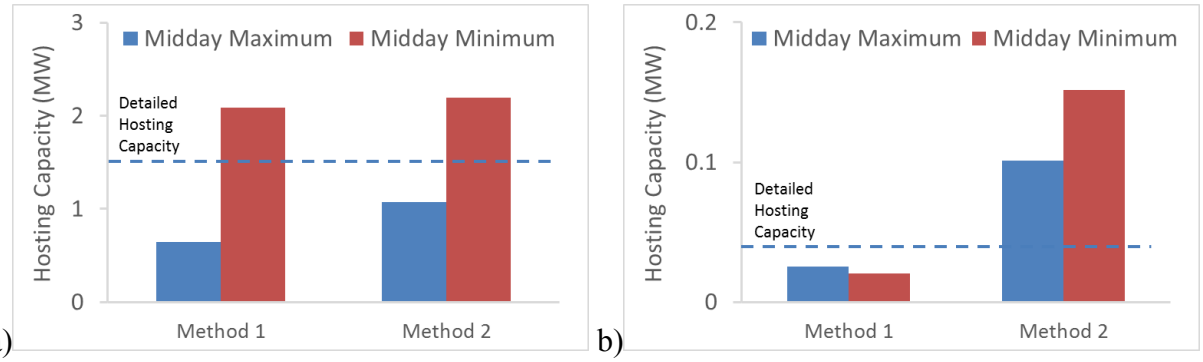

Figure 2-3.
Sensitivity to Determine Best Method to Estimate Primary Overvoltage Hosting Capacity a) Feeder with No Line Regulators b) Feeder with Line Regulators

Detailed Analysis with Shorthand Hosting Capacity Calculations

Each issue has a simple equation associated that can help the engineer determine the feeder hosting capacity under a worst-case aggregate PV scenario. There may be more optimal PV scenarios, but the result produced from the shorthand calculation is meant to be conservative. Figure 2-4 shows an asterisk for each issue at the calculated amount of allowable aggregate rooftop 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 fall 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 can be higher (wider yellow region) because there are more optimal PV scenarios. The asterisk also sometimes falls well within the green region. One reason that occurs is because there are beneficial factors of the feeder such as topology (lateral diversity) or the arbitrary location used in the short-hand equations is worse than those occurring randomly in the detailed analysis. Thus the simple equations provide conservative hosting capacities.

The main objective is to show where hosting capacity can be higher than that 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 are higher, then the interconnection request would have a better chance passing Supplemental Review with regards to the issues analyzed.

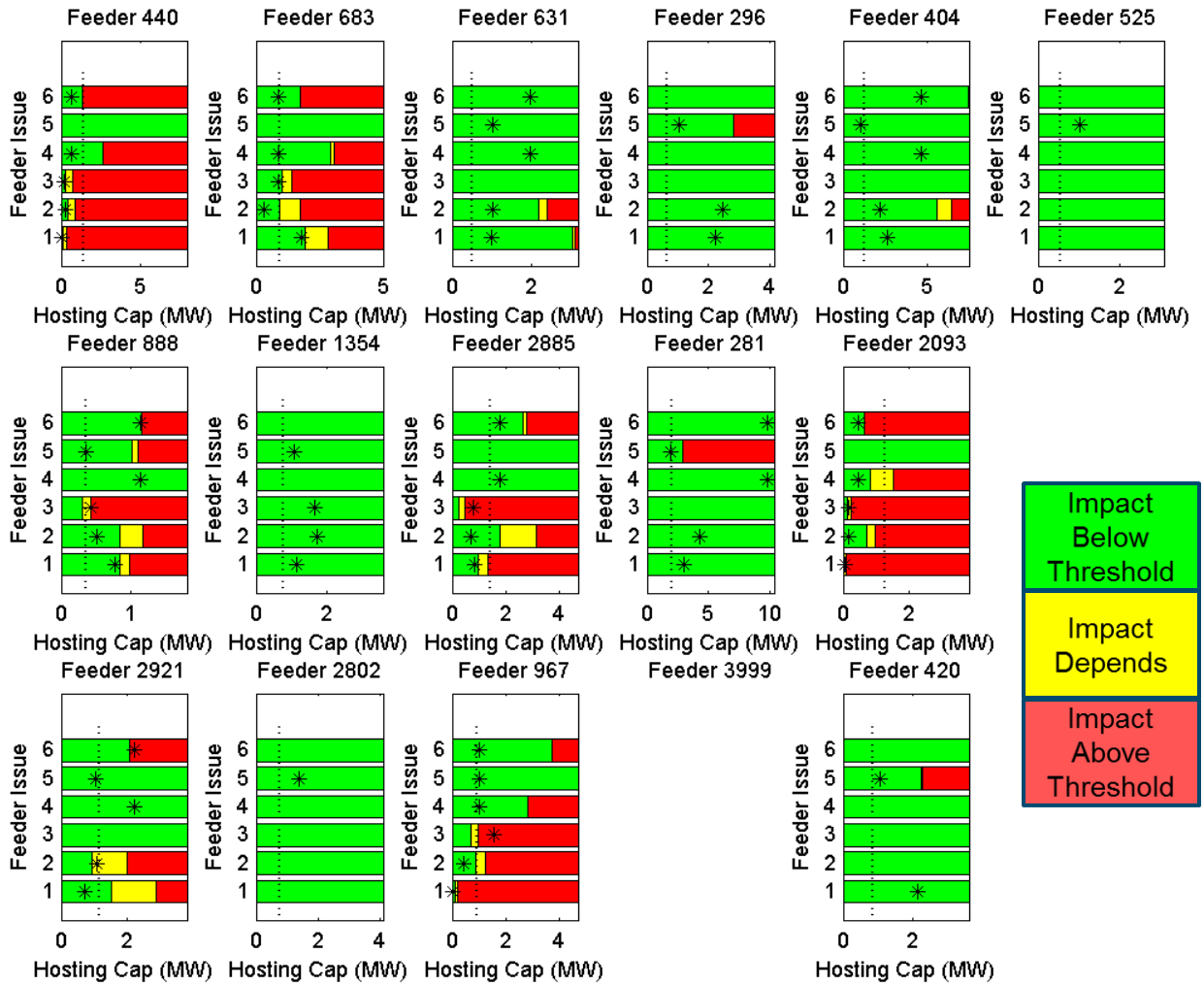

Figure 2-4.
Residential/Commercial Rooftop PV Short-Hand Hosting Capacity
***Note: Feeder 3999 is a solely industrial circuit and is not included in hosting capacity analysis for residential/commercial PV deployment.**

The shorthand hosting capacities are shown for utility-scale PV in Figure 2-5. Again, asterisks primarily fall near the green-yellow or green-red transitions. Many factors could lead to accommodating more PV, so a conservative hosting capacity estimate is provided from the simple equations.

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

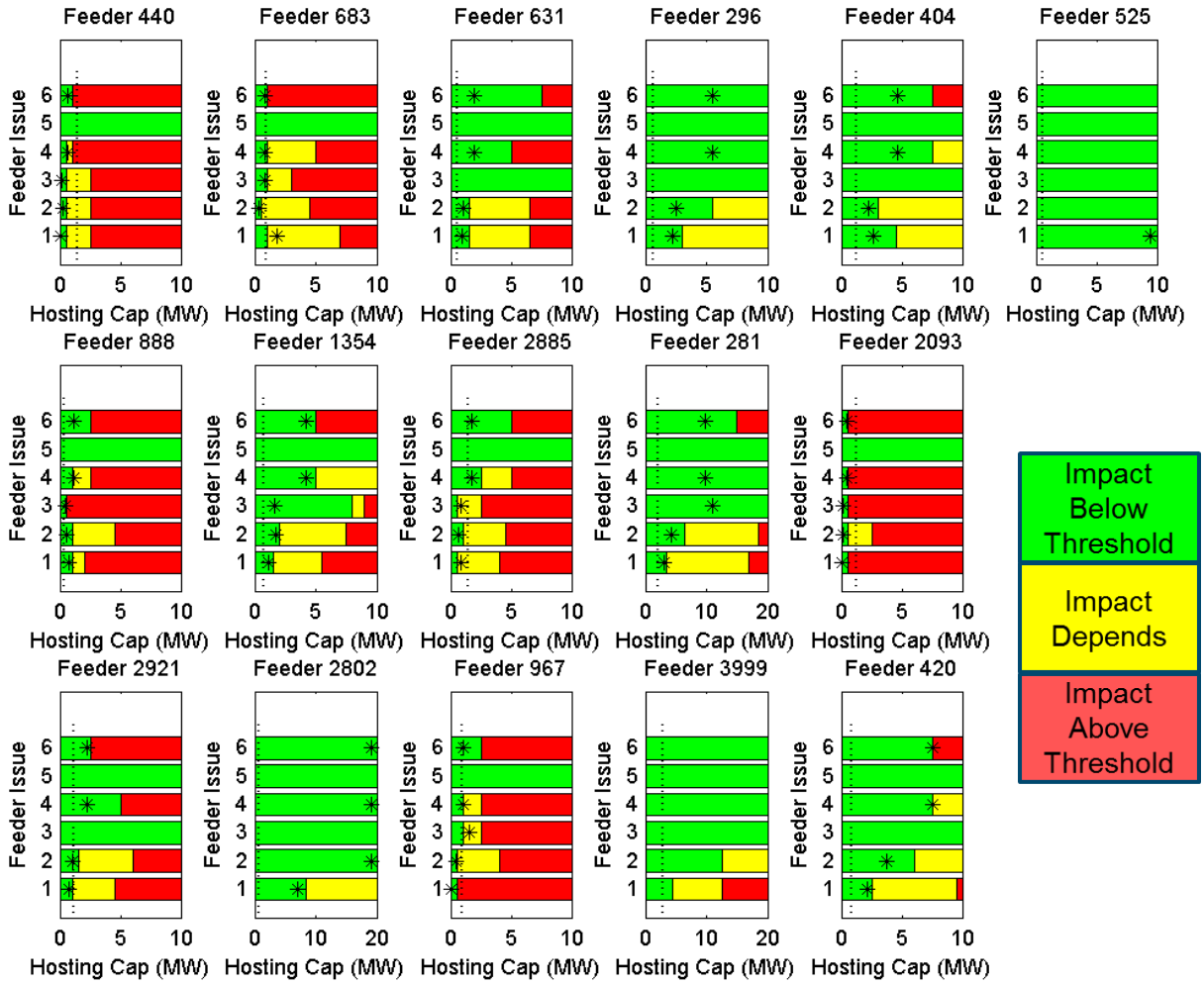

Figure 2-5.
Utility-Scale PV Short-Hand Hosting Capacity

Shorthand Equations

The shorthand equations to estimate a conservative hosting capacity use the variables described in the previous section while the equations are described here. The equations are:

- SR1 – Primary overvoltage
- SR2 – Primary voltage deviation
- SR3 – Regulator voltage deviation
- SR4 – Element fault current
- SR5 – Sympathetic breaker tripping
- SR6 – Breaker reduction of reach

SR1 – Primary Overvoltage

The primary overvoltage shorthand equation determines the amount of aggregate DG that could cause a primary node's voltage to exceed a predefined planning limit (Vpu). Commonly that planning limit is the upper ANSI voltage limit, however, it can be higher or lower depending on the utilities planning criteria. To determine the aggregate DG that can be accommodated without causing adverse impact, the planning limit is compared to the voltage profile/headroom on the feeder. The voltage headroom considered is dependent on if there are or are not line regulators.

Primary voltage headroom (in percent) when line regulators are not present:

$$PrimaryHeadroom = PlanningLimit - max\left[\left(\sum_{i=1}^{k} max[V_a, V_b, V_c]_i/k\right)_{PeakLoad}, \left(\sum_{i=1}^{k} max[V_a, V_b, V_c]_i/k\right)_{OffpeakLoad}\right] \cdot 100$$

Primary voltage headroom (in percent) when line regulators are present:

$$PrimaryHeadroom = PlanningLimit - max\left[\left(max\left[max[V_a, V_b, V_c]_{i=1}^{k}\right]\right)_{PeakLoad}, \left(max\left[max[V_a, V_b, V_c]_{i=1}^{k}\right]\right)_{OffpeakLoad}\right] \cdot 100$$

where k is the number of primary nodes. Voltages are in per unit.

The potential voltage deviation caused by the aggregate DER is:

$$VDev = \frac{MaxR}{FeederkVLL^2} \cdot 100$$

The primary overvoltage aggregate hosting capacity in MW is

$$SR1 = \frac{PrimaryHeadroom}{VDev}$$

Notes:

- To calculate voltage headroom, line-line or line-neutral voltage should be used based on feeder design.
- Aggregate DG closer in than MaxR would increase feeder hosting capacity. When line regulators exist and a single node voltage is considered, the resistance to that single node should replace MaxR to provide a more accurate yet still conservative hosting capacity.
- When multiple regulators are present, SR1 can be calculated separately for each regulator. The minimum of all results would be the conservative hosting capacity.
- If voltage profiles are not known, the LTC/regulator setpoints could be used to estimate the voltage profile. If line drop compensation exists, SR1 would require more thorough knowledge of voltage across the feeder.
- Distributed generation is assumed to be able to make a 100% sudden change in output. Reduction in output swing would linearly scale SR1 result.

SR2 – Primary Voltage Deviation

The primary voltage deviation shorthand hosting capacity calculation utilizes the same voltage deviation formula as previously shown. The voltage deviation is compared to a predefined utility threshold (in percent) to determine the aggregate DG feeder hosting capacity in MW.

$$VDev = \frac{MaxR}{FeederkVLL^2} \cdot 100$$

$$SR2 = \frac{VoltageDeviationThreshold}{VDev}$$

Notes:

- Aggregate DG closer in than MaxR would increaser feeder hosting capacity.
- Distributed generation is assumed to be able to make a 100% sudden change in output. Reduction in output swing would linearly scale SR2 result.

SR3 – Regulator Voltage Deviation

The regulator voltage deviation hosting capacity prediction is only applicable if there is an LTC or regulator on the feeder. If there is line drop compensation, the impact from power output swings will impact the LTC/regulator based on the settings of the device. With line drop compensation, the voltage that device is regulating changes based upon

$$\mathrm{RthatRegSees} = \mathrm{RtoReg} + \frac{\mathrm{LDC_Rsetting}}{\mathrm{NCT}} \cdot \mathrm{NPT}$$

The voltage deviation at the regulating device becomes:

$$RegVDev = \frac{RthatRegSees \cdot 1000}{FeederkVLL \cdot NPT \cdot sqrt(3)}$$

The simplified hosting capacity value for SR3 in MW becomes:

$$SR3 = \frac{Bandwidth}{2 \cdot RegVDev}$$

Notes:

- If the aggregate DG is upstream from the regulator the hosting capacity would increase.
- Applies to each LTC/regulator on the feeder.
- Distributed generation is assumed to be able to make a 100% sudden change in output. Reduction in output swing would linearly scale SR3 result.

SR4 – Element Fault Current

The element fault current hosting capacity estimation is based on the fault current produced by the DG. The detailed analysis has been conducted based on two times nominal current but because of the nature of distributed generation, only a fraction is additive at the protection elements. If a lower/higher fault current level is considered, the hosting capacity would change. Similarly, the threshold used to determine impact is dependent on the utility perspective. The following equation calculates the aggregate DG hosting capacity in MW.

$$SR4 = PercentIncreaseThreshold \cdot \frac{FeederkVLL^2}{MaxZ} \cdot \frac{2}{FaultIpv}$$

Notes:

- If the DG interconnect transformers are grounded Wye-Delta, significantly higher impact and lower hosting capacity would occur due to zero sequence ground fault current contribution.
- The impedance MaxZ is used for the analysis to provide a conservative result, however, the adverse impact typically occurs upstream at a lower impedance where DG both upstream and downstream can feed faults while system fault current is relatively unaffected.

SR5 – Sympathetic Breaker Tripping

The shorthand equation for sympathetic breaker tripping is dependent on the threshold and fault current from the distributed generation. The calculation only pertains when the interconnect transformer can contribute to zero sequence faults. The shorthand MW hosting capacity prediction is calculated as:

$$SR5 = SympatheticTrippingThreshold \cdot \frac{FeederkVLL}{1000 \cdot sqrt(3)} \cdot \frac{2}{FaultIpv}$$

Notes:

- DG on all phases can feed ground current at the breaker.
- Hosting capacity can be higher if DG is beyond the line regulator, step-down, or service transformer that blocks ground currents.
- If the DG interconnect transformers are grounded Wye-Delta, significantly higher impact and lower hosting capacity would occur due to high zero sequence ground fault current contribution.

SR6 – Breaker Reduction of Reach

The shorthand calculation of breaker reduction of reach is identical to SR4 except the threshold is different. The following equation determines the SR6 hosting capacity in MW.

$$SR6 = BreakerSensitivityThreshold \cdot \frac{FeederkVLL^2}{MaxZ} \cdot \frac{2}{FaultIpv}$$

Notes:

- If the DG interconnect transformers are grounded Wye-Delta, significantly higher impact and lower hosting capacity would occur due to high zero sequence ground fault current contribution.
- Using MaxZ assumes the feeder does not extend much further. Longer single-phase drops would reduce the hosting capacity, while DG further out on the feeder than MaxZ would increase hosting capacity.

Revised Screen

The suggestions to improve the Initial Review and Supplemental Review screens in CA Rule 21 are shown in Figure 2-6. These suggestions target the methods to analyze the impact of aggregate generation and specifically provide "Alternatives to the 15% Rule." The improvements are based on the technical analysis and include:

- Add Initial Review screen that addresses if the feeder has line regulators
- Modify the Initial Review to always address aggregate generation
- Add Supplement Review equations as guidelines to address the impacts of aggregate generation

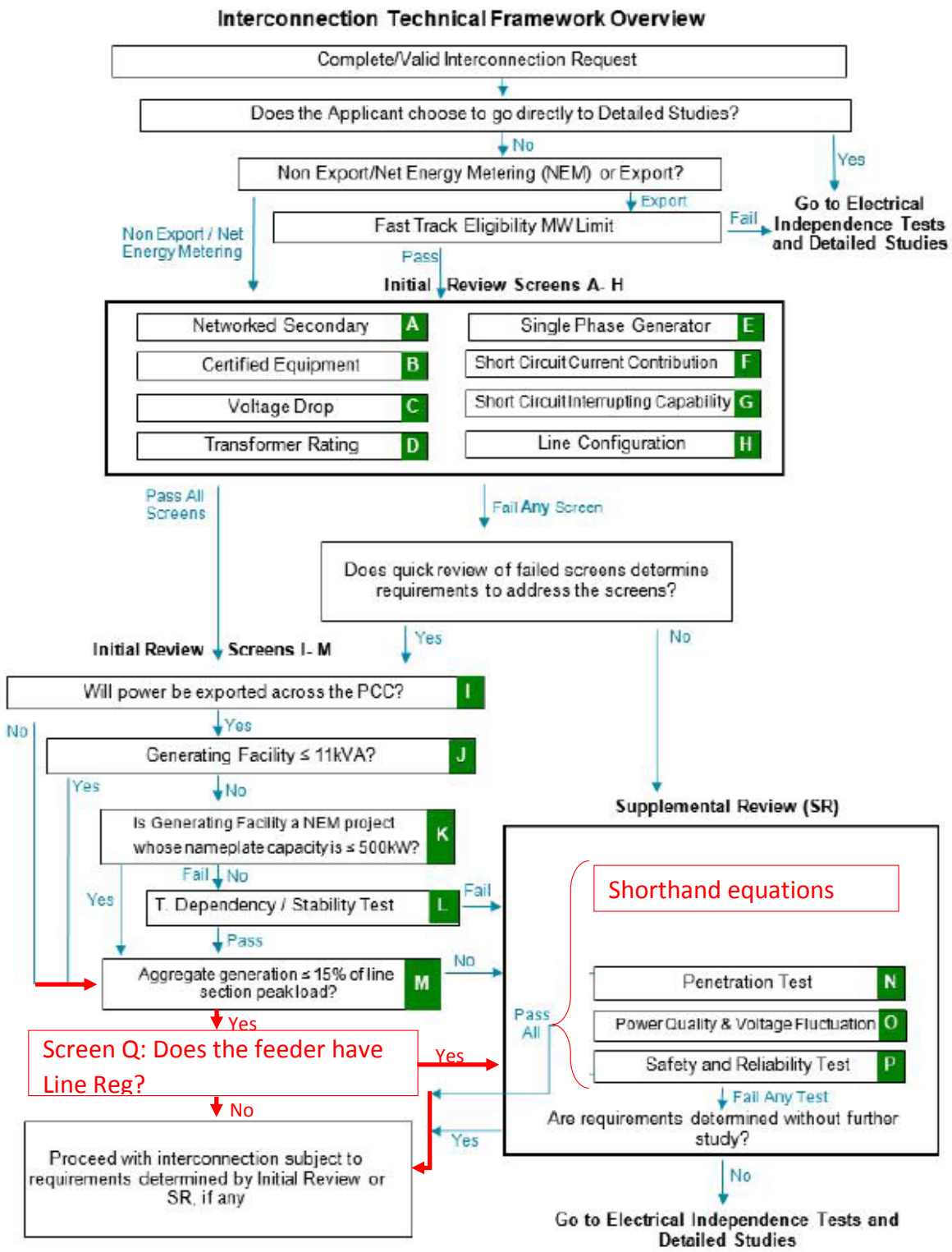

Figure 2-6.
Suggested Modifications to CA Rule 21

3 VALIDATION

The proposed modifications to CA Rule 21 are validated based on their application to the project's six validation feeders. These modifications include changes to the Initial Review process as well as the Supplemental Review process. The goal of the validation is to determine if the modified screening process more accurately identifies aggregate PV system impacts than the current Rule 21 framework. More effective screening allows 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.

Methodology

A control group of feeders (referred to as the validation feeders) are used to determine whether the proposed modifications successfully screen PV interconnection requests. The control set included six feeders – two from each utility. These six validation feeders are developed in the same way as the other 16 study feeders and have been selected during the feeder clustering portion of this project[12]. These six feeders represent three medium voltage (MV) classes and included a good mix of general feeder types. Development of the validation feeders include the following general process:

- Develop OpenDSS model of the feeders from utility supplied feeder models
- Validate the operation and loading of the modeled feeders using the available utility Supervisory Control and Data Acquisition (SCADA) data
- Remove existing PV on the feeders from the model and adjust the loading of the feeders to compensate for any load masking in the utility SCADA data
- Determine the appropriate loading levels required for detailed analysis using EPRI's Distributed PV (DPV) PV impact analysis tool

The PV hosting capacity for these six validation feeders is determined using EPRI's DPV analysis tool in an identical manner to how the sixteen study feeders had been analyzed[13]. Validation for the proposed modified PV interconnection screening process is then divided in two parts and described below in terms of the validation of Initial Review process modifications and Supplemental Review process modifications.

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

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

Initial Review

The proposed changes to the Initial Review process include the addition of Screen Q (Does the feeder have a line regulator?) and the rerouting of the decision tree for existing Screens I and J (Will power be exported across the PCC? and Generating facility < 11 kVA?, respectively) to make sure that existing Screen M (Aggregate generation < 15% of the line section peak load?) is not bypassed. The implementation of the Initial Review validation reduces to the following:

- If the feeder contains a line regulator, no PV is deployed under the Initial Review process, thus the validation of Screen Q is actually part the Supplemental Review validation.
- Otherwise, allow PV deployment up to an aggregate generation of 15% of the peak feeder load and make sure issues do not arise at lower penetration levels.

Validation of the proposed Initial Review modifications consists of identifying the validation feeders that have a line regulator and, for feeders that don't contain a line regulator, checking that PV deployments up to 15% of the peak load do not cause adverse impact (hosting capacity greater than 15% of peak load). For utility-scale, representative of large centralized systems, PV deployment analysis Screen K (Is Generating facility a NEM project whose nameplate capacity is < 500 kW?) did not affect validation of the modified Initial Review process because all large-scale systems analyzed in the detailed analysis are 500 kW in nameplate capacity. Also, for both residential/commercial rooftop PV and centralized utility-scale PV, Screen L (Dependency/Stability Test) is not considered during validation because such tests are utility and location specific and often do not factor into the majority of PV interconnection requests.

Supplemental Review

The modified screening procedures in the Supplemental Review process have been augmented by six shorthand equations that directly calculate the PV hosting capacity of a particular feeder with a minimal amount of required feeder characteristic data. The validation of the modified Supplemental Review process included the following steps:

- Calculate SR1 through SR6 using the equations in the previous section. All thresholds applied in the shorthand equations are the same as those used in the detailed analysis.
- Compare the PV hosting capacity calculated for the six shorthand equations to the minimum hosting capacity determined from detailed analysis
- Compare the PV hosting capacity calculated for the six shorthand equations with 15% peak load

Shorthand equation SR1 and SR2 require the calculation of the maximum voltage deviation potentially experienced on the feeder due to PV. This calculation requires the maximum feeder resistance. This resistance is determined by sorting all the primary three-phase nodes of the feeder and selecting the highest resistance value observed. SR1 also requires the feeder's voltage headroom as an input. The specific method for calculating the voltage headroom is dependent on if the feeder does/does not have a voltage regulator and/or a load tap changing transformer. For validation these voltage headroom calculations are completed using feeder data derived from the detailed analysis cases with no PV installed on the feeders (i.e. base case analysis).

The shorthand equation SR3 requires an input for the resistance to line regulators and any line drop compensation settings. This information is gathered from the feeder models.

The shorthand equation SR4, SR5 and SR6 estimate PV hosting capacity for protection related issues. SR4 and SR6 use a maximum circuit impedance to calculate PV hosting capacity. This impedance is determined in an identical manner as the maximum resistance used in SR1 and SR2. Additionally, SR4 and SR5 require an estimation of the total fault current expected from interconnected PV systems. For validation purposes the assumed fault current contribution by PV systems is 2.0 per unit (pu) current, similar to the detailed analysis.

Validation Result

Figure 3-1 shows some characteristics of six validation feeders, including voltage class, peak load, total number of line regulators and total number of LTCs. Validation feeders 514 and 1140 have both line voltage regulators and LTCs, and feeders 679 and 142 have LTCs only. The existence of LTCs is indicated because SR3 can be applied if a feeder doesn't have a line regulator but has an LTC.

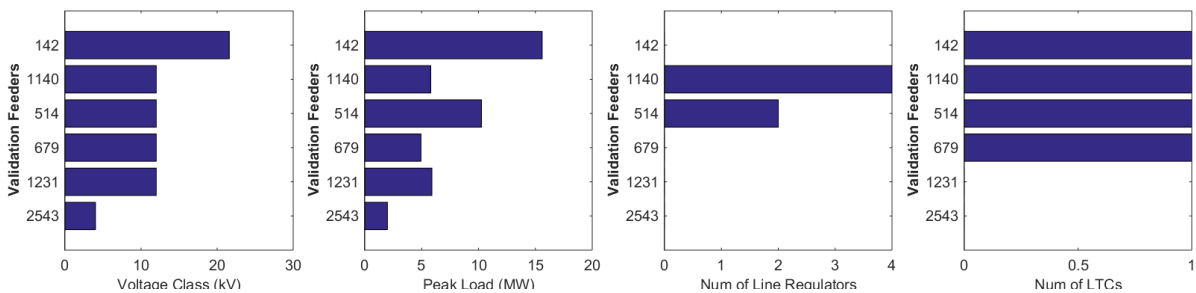

Figure 3-1.
Characteristics of the Six Validation Feeders

Initial Review

Figure 3-2 and Figure 3-3 show the detailed hosting capacity of the validation feeders for residential/commercial and utility scale PV, respectively. The green regions indicate aggregate penetration where adverse impact does not occur. The yellow regions indicate that issues may occur when the aggregate feeder penetration is within that range. The dashed line is added to denote 15% of peak load.

For residential/commercial rooftop PV, all validation feeders that have no line regulator could host more than 15% of peak load without adverse impact. Feeders 1231 and 679 do not have any violations for the six metrics even at the highest analyzed penetration (rooftop hosting capacity only analyzed up to maximum feeder load), so those feeders can host more PV than the figure illustrates with respect to those issues.

For utility-scale PV, adverse impact is shown to be well above the 15% load screen for feeders without line regulators. Therefore, the Supplemental Review would better determine the true hosting capacity for those feeders. However, feeder 142 does have a detailed hosting capacity for SR-1 slightly below 15% peak load. This shows that load is not the best indication of hosting capacity and cannot always define the best conservative hosting capacities.

Feeders 514 and 1140 both have line regulators. For both residential/commercial rooftop PV and utility-scale PV, there are adverse impacts when the aggregate penetration is lower than 15% peak load. Thus, it is validated that the existence of line voltage regulators indicates a high likelihood of adverse impact.

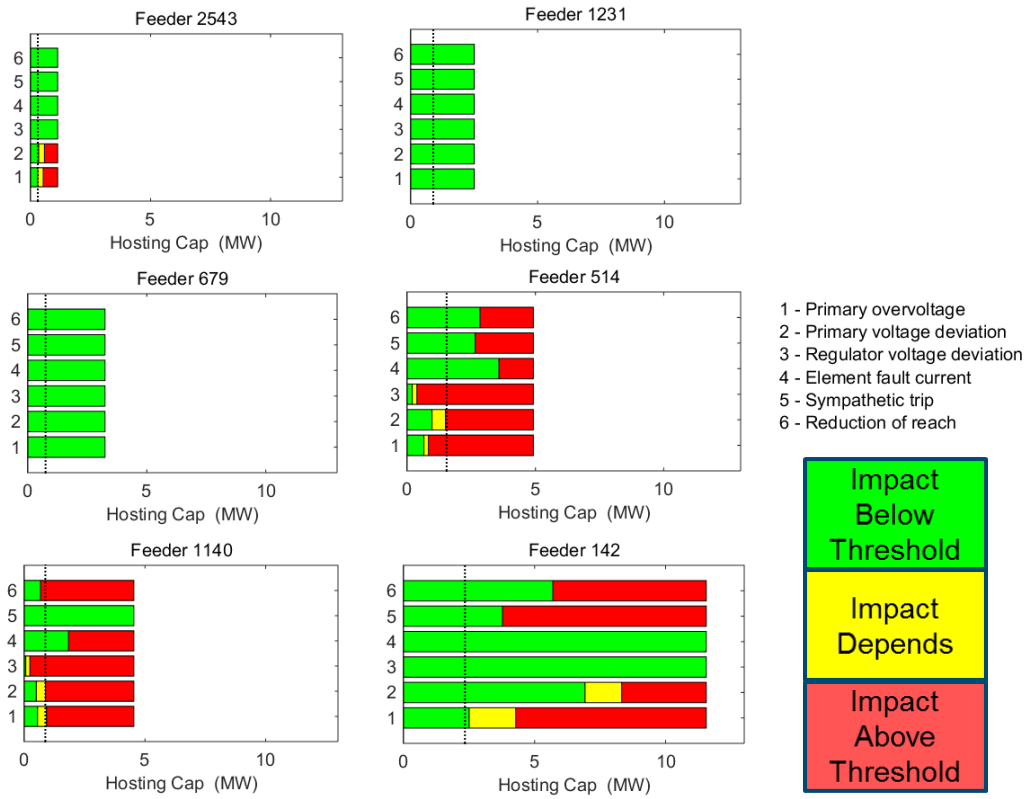

Figure 3-2.
Residential/Commercial Rooftop PV Detailed Hosting Capacity (Dashed lines indicate 15% of peak load)

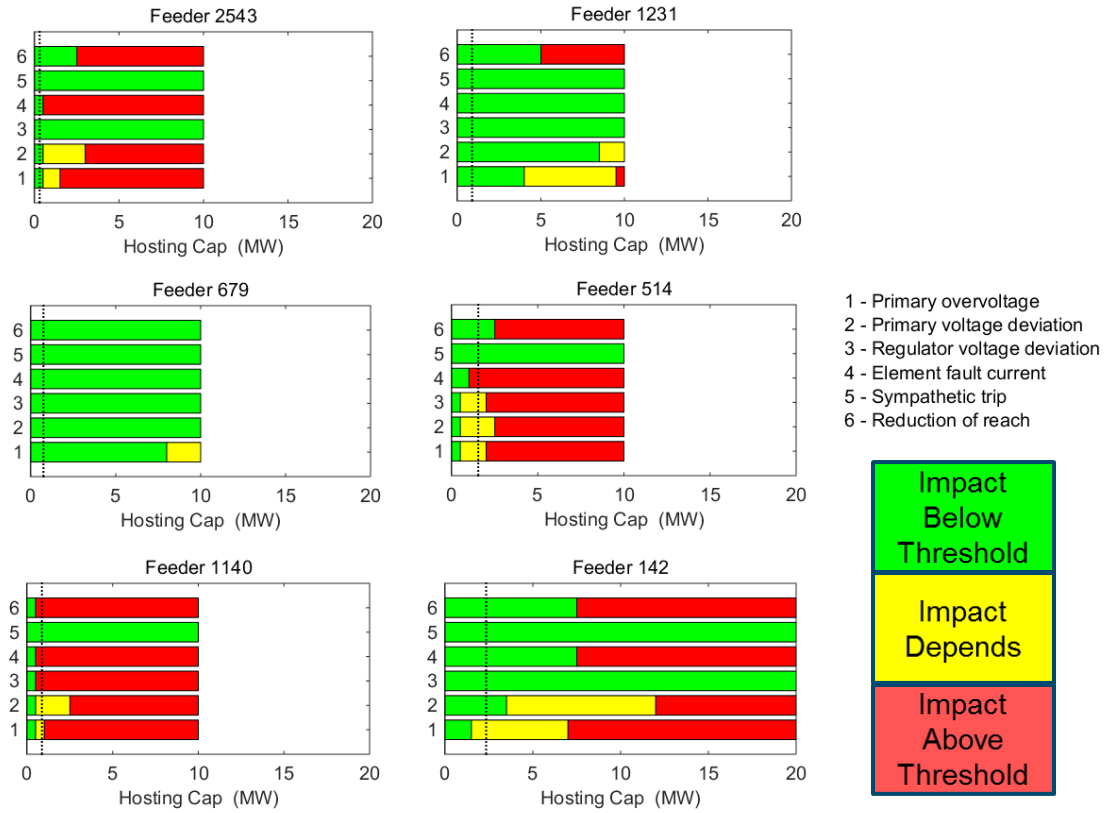

Figure 3-3.
Utility-Scale Centralized PV Detailed Hosting Capacity (Dashed lines indicate 15% of peak load)

Supplemental Review

The maximum resistance to the furthest three phase primary node is a key parameter to compute shorthand equation voltage-based hosting capacity. Figure 3-4 shows the maximum resistance of the six validation feeders. The maximum resistances of feeders 2543, 1231, 679 and 142 are all lower than 5 ohms, but the resistances of 1140 and 514 are much higher. Figure 3-5 gives the primary voltage headroom on each feeder. The primary headroom of feeders without line regulators (2543, 1231, 679 and 142) is around 0.017 Vpu, while the headroom of feeders with line regulators (1140 and 514) is much lower.

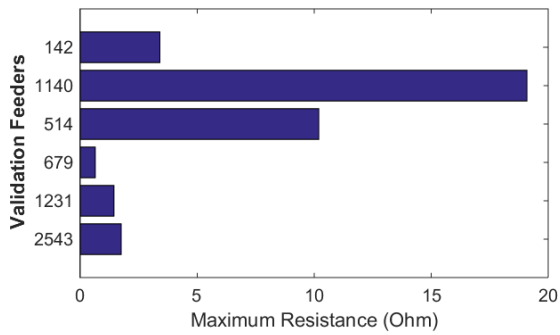

Figure 3-4.
Maximum Resistance to Last Three-phase Primary Node on Validation Feeders

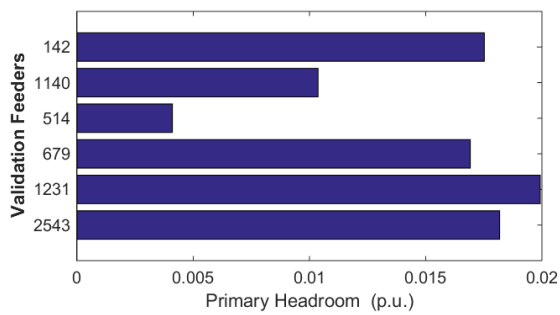

Figure 3-5.
Primary Voltage Headroom of Validation Feeders

Supplemental Review shorthand equations are applied to the six validation feeders to approximate the hosting capacities, and the solutions are then shown on the detailed analysis results. Figure 3-6 and Figure 3-7 give the shorthand hosting capacity of residential/commercial rooftop and utility-scale PV, respectively. The asterisk in each bar is the hosting capacity prediction computed using the Supplemental Review shorthand equations. If the asterisk is not shown on the plot, the shorthand hosting capacity is greater than the range shown in the plot.

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

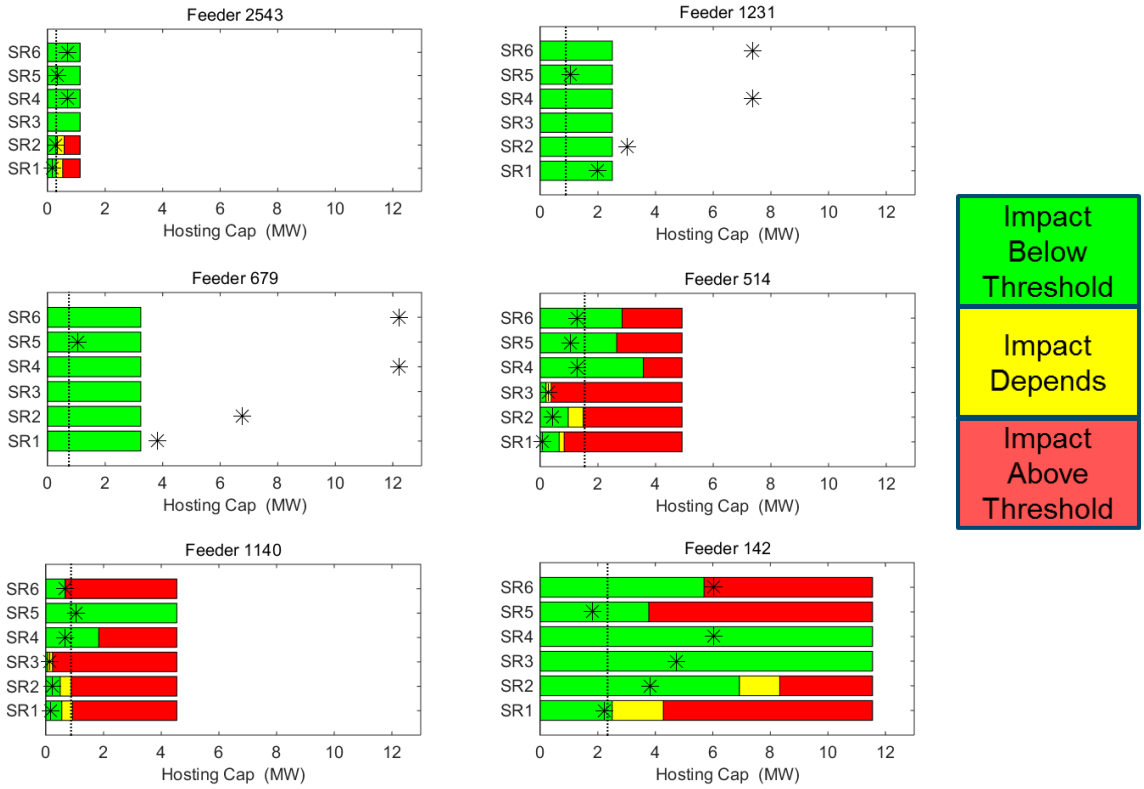

Figure 3-6.
Residential/Commercial Rooftop PV Hosting Capacity (Dashed lines indicate 15% of breaker peak load)

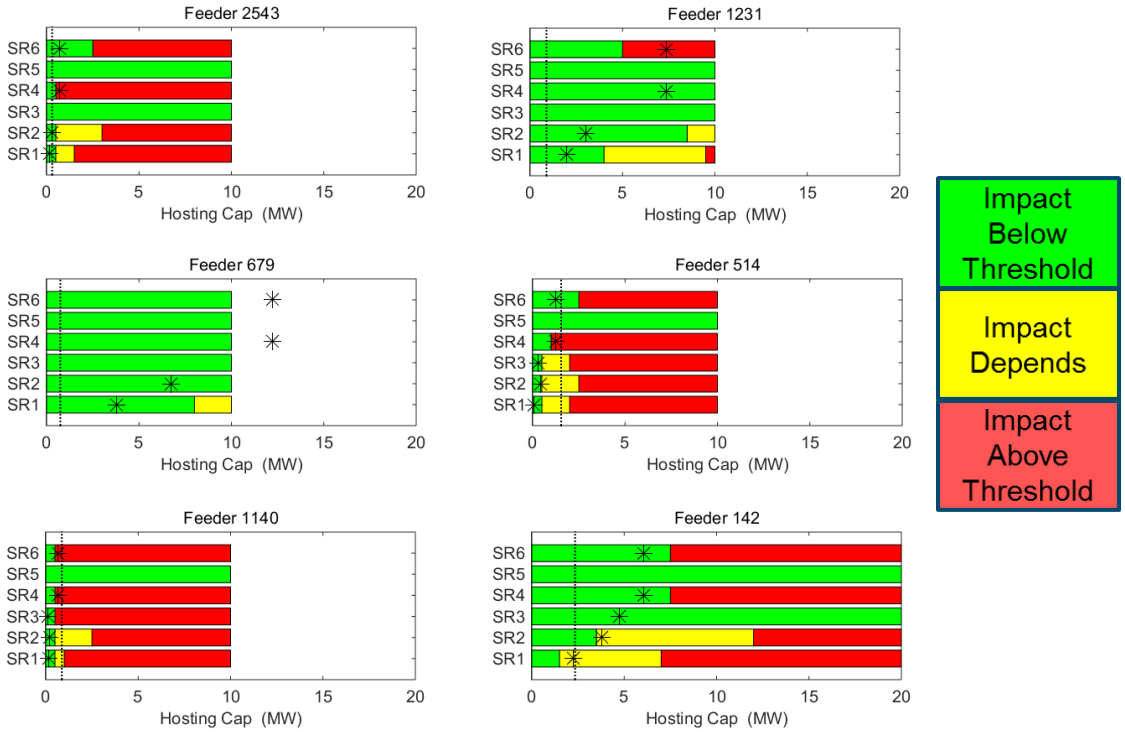

Figure 3-7.
Utility-Scale PV Hosting Capacity (Dashed lines indicate 15% of breaker peak load)

4 CONCLUSION

The detailed feeder impact analysis performed in the previous project task determined 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. These findings have allowed for the development of improved screens in CA Rule 21.

The "Alternatives to the 15% Rule" address the impacts from aggregate distributed generation and are not dependent on load level alone. The improvements are based on the detailed technical analysis and include:

- 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 guidelines to address the impacts of aggregate generation for issues not solely dependent on load

These improvements are based on the detailed analysis of 16 study feeders that span a wide range in characteristics. The modified screens are 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 can be better screened for the issues analyzed.