Determining the Effectiveness of Feeder Clustering Techniques for Identifying Hosting Capacity for DER

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Integration of Distributed Energy Resources Program (174)

EPRI Project Manager

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ABSTRACT

The proliferation of renewable generation interconnection requests has led to the need for more effective and efficient distribution system analysis techniques. These analysis techniques should adequately determine the feeder-specific distribution system impacts from distributed energy resources. Traditional methods to perform these studies range from detailed analysis to interconnection screens. Detailed analysis requires feeder models, time, and effort; as a result, it provides the most **effective** method. Interconnection screens do not necessarily require models, time, or effort; as a result, they provide the most **efficient** method.

Modern analysis techniques have begun to bridge the gap between detailed analysis and interconnection screens. One example of such a method is EPRI's Streamlined Hosting Capacity Analysis method. EPRI's method analyzes and processes feeder models to effectively and efficiently determine feeder impacts. However, not all utilities can use such a method—especially if feeder models do not exist. From this situation, a different method was created: it analyzes a small set of feeders and then extrapolates feeder impacts to other "similar" feeders. This method uses clustering techniques to group similar feeders and then choose one that is representative of each entire group. Detailed analysis is performed on the representative feeders and extrapolated to the unanalyzed feeders.

This report summarizes clustering on all feeders across an actual utility distribution system, describes distribution system impacts on all of those feeders, and examines the correlation of clusters and impacts.

Keywords

Clustering
Distribution
Hosting capacity
System-wide

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Chapter 1 – Introduction

Chapter 1 – Introduction

This chapter provides background on the methods to determine the distribution system impacts from Distributed Energy Resources (DER).

Traditional Methods

- Traditional Analysis Methods Aren't Sufficient

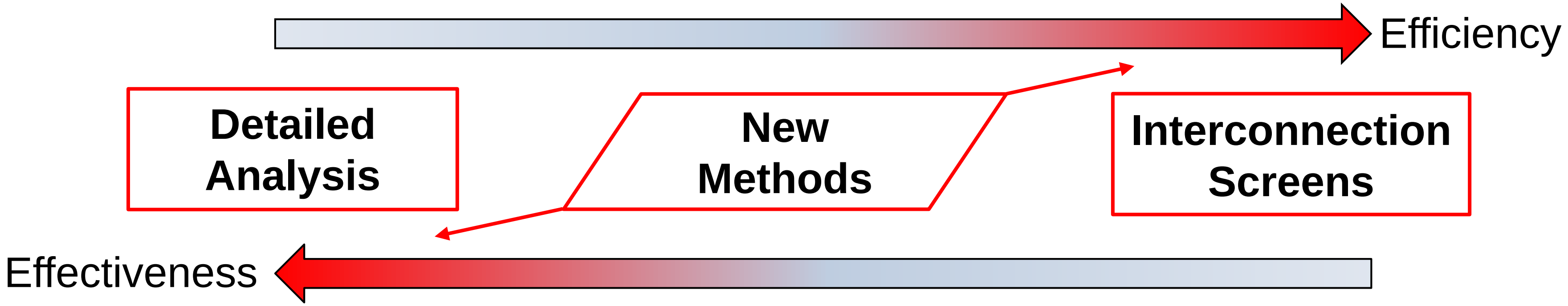
New Analysis Methods

- EPRI's Streamlined Analysis
- Representative Feeders Analysis

Summary

Traditional Methods to Determine Distribution System Impacts

- Distribution system impacts can be determined a number of different ways.
- The most accurate method is based on detailed analysis of valid models but requires a significant amount of analysis time.
- Interconnection screens do not require models and are thus less accurate but require much less analysis time.
- New methods attempt to bridge the gap between Efficiency and Effectiveness.
- ***Detailed Analysis*** – lead by EPRI applying OpenDSS to understand DG and solar in impacts on distribution (last 10 years)…includes hosting capacity
- ***Interconnection Screens*** – such as in FERC SGIP fast-track screening or in CA rule 21 screening procedures, have been around for years…being updated, and EPRI is helping them to improve.

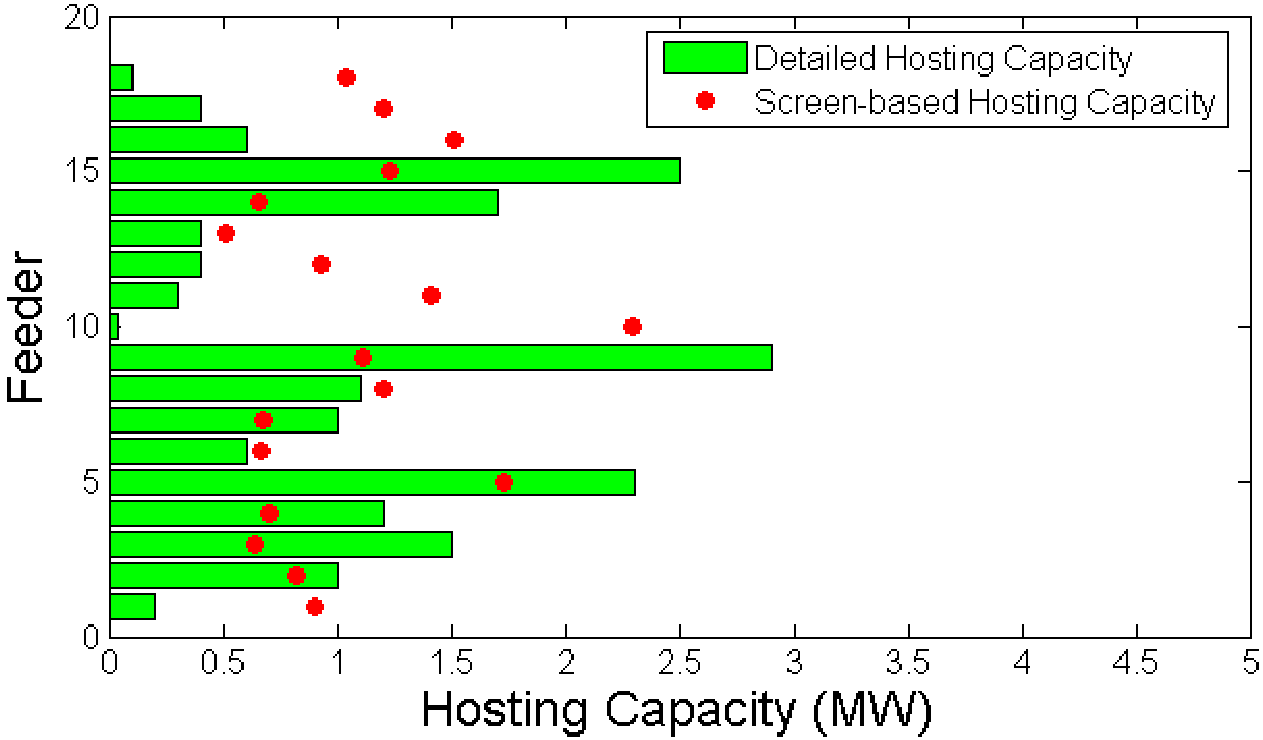


Traditional Analysis Methods Aren't Sufficient

The figure below compares detailed analysis hosting capacity results from 18 feeders* to the results that are a produced from interconnection screens.

Problem with Detailed Analysis
Time required to complete the analysis.

Problem with Interconnection Screens
Results do not match those found with the detailed analysis.



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

New Analysis Methods

There are new analysis methods emerging from the need to evaluate an entire distribution system, large amounts of interconnection requests, and also effectively plan for the future.

- EPRI's Streamlined Analysis*
  - Developed by EPRI using learnings from detailed analysis
  - Effective and time-efficient methods for analyzing many feeders
  - Requires models of all feeders
- Representative Feeder Analysis
  - Detailed analysis conducted on select feeders
  - Results extrapolated to other similar feeders

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

EPRI's Streamlined Analysis

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

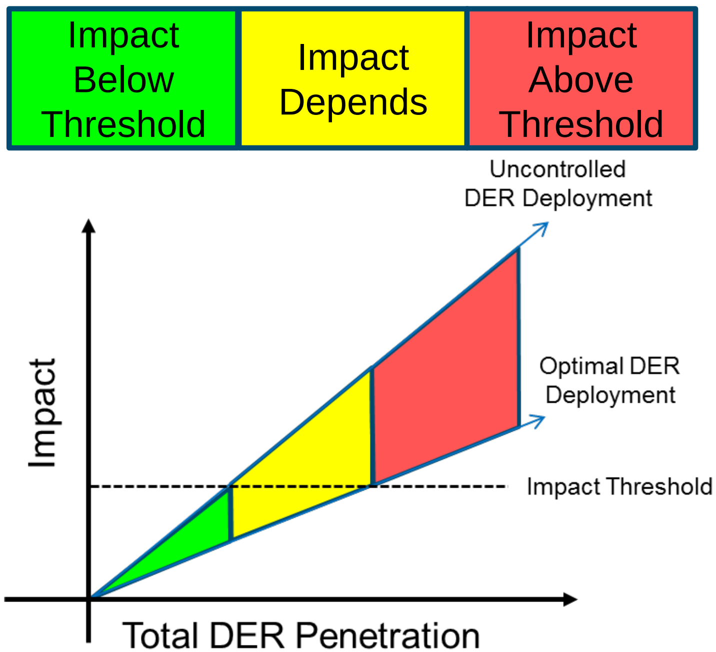
The method, derived from detailed analysis, is performed every feeder model and considers*:

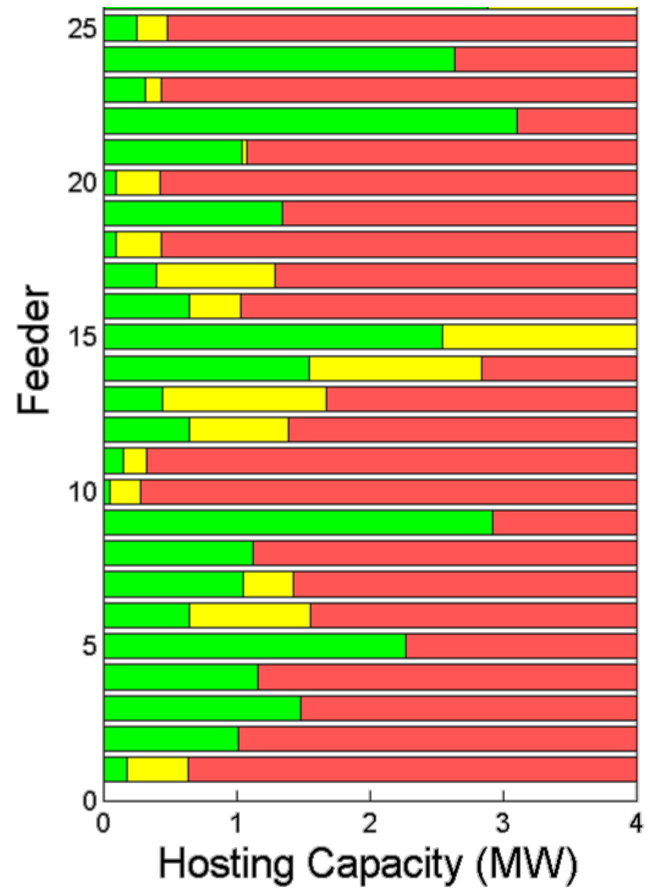
- DER technology and impacts
- DER size and location
- Feeder design and operation

Voltage

Protection coordination

Thermal capacity





DER Technology and Impacts

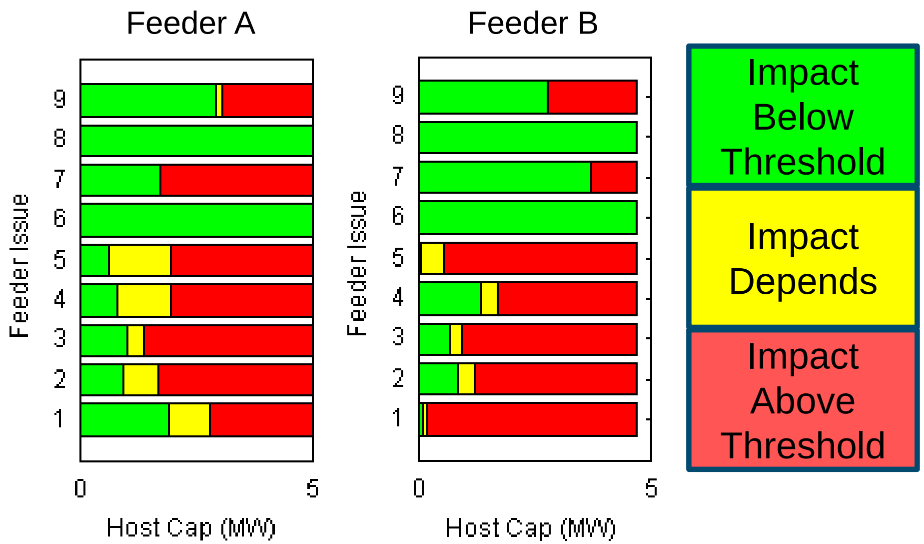
DER Size and Location

Feeder Design and Operation

Representative Feeder Analysis

Method

- All feeders are grouped into clusters
- Detailed analysis is then performed on select feeders within each cluster
- Results from select feeders are then extrapolated to remainder of distribution system



Initial Concern with Representative Feeder Method:
Feeder A and Feeder B have been analyzed with detailed analysis. Although both have the several common characteristics such as voltage class, peak load, and feeder length, they have different DER impacts and Hosting Capacity. The issues evaluated are both voltage and protection based impacts.

Research Question:

How effective do the select feeders analyzed actual represent the remainder of the distribution system? How well do the results map to other “similar” feeders?

Case Study to Examine the Representative Feeder Analysis

- **Actual Distribution System Analyzed in this Report**
- Tennessee Valley Authority (TVA) distributor Electric Power Board of Chattanooga (EPB)
  - Approximately 100 substations
  - Approximately 300 feeders
  - Voltage class
    - ~60% are 12 kV
    - ~40% are 4 kV
  - Peak load of all feeders
    - Maximum: 15.3 MW
    - Average: 4.2 MW
  - Approximately 8% have line regulators

Summary

- Traditional methods to analyze DER impacts to a feeder have limitations
- New methods have been developed to improve the DER impact assessment
- The Representative Feeder Method potentially has limitations with regards to how well impacts can be equated across similar feeders

Chapter 2

- Illustrates how similar feeders are grouped and how the Representative Feeder is chosen

Chapter 3

- Illustrates the DER impact across all feeders

Chapter 4

- Compares the DER impact across the representative feeder and all similar feeders

Chapter 5

- Provides conclusions drawn from the report

Chapter 2 – Clustering

Chapter 2 – Clustering

This chapter describes the process of clustering feeders into groups and identifying a representative feeder from each of those groups*. Two sets of characteristics that describe the same set of feeders are used in the clustering.

Clustering Feeders

- Topological Characteristics
- Electrical Characteristics

Selecting Representative Feeders

Summary

**Clustering Methods and Feeder Selection for PV System Impact Analysis.* Palo Alto, CA: 2014. 3002002562.

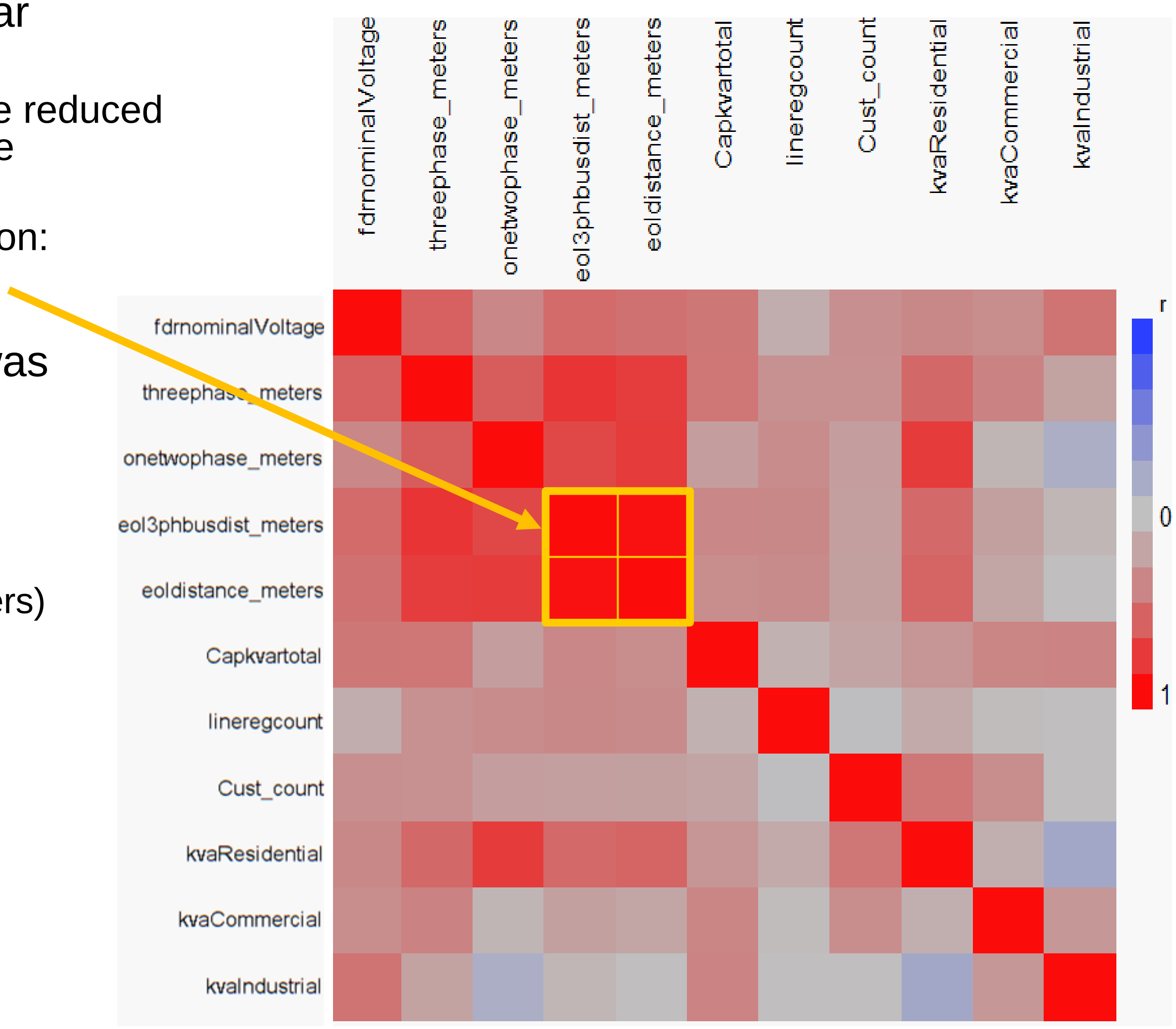
Clustering Feeders Based on Topological Characteristics

Topological feeder characteristics are used to cluster feeders into similar groups. There are an infinite number of characteristics, but some of the commonly referred characteristics are those shown in the following table.

Feeder Topology	Nominal Voltage
	Total 3-Ph Meters
	Total 1&2 Ph Meters
	End of Line 3-Ph Bus Distance (meters)
	End of Line Distance (meters)
Voltage Control	Capacitors (total kvar)
	Line Regulators (#)
Customer Data	Customer Count
	kVA Residential
	kVA Commercial
	kVA Industrial

Selecting Variables for Clustering

- Correlations between variables are examined to identify similar characteristics
  - Similar characteristics are reduced to one variable to improve clustering analysis
  - Example of high correlation: *eol3phbusdist_meters* and *eoldistance_meters*
- Final clustering solution was obtained using these final variables:
  - Nominal Voltage
  - Total 3-Ph Meters
  - End of Line Distance (meters)
  - Capacitors (total kvar)
  - Line Regulators (#)
  - Customer Count
  - kVA Residential
  - kVA Commercial
  - kVA Industrial



Ten Distinct Topology-Based Feeder Clusters

Cluster	Voltage	3-Ph meters	End of Line Distance (meters)	Capacitors (total kvar)	Regs	Customer count	KVA Res	KVA Comm	KVA Ind	Feeder Count
1	12470	4045.1	1821.55447	428.742857	0	635.6	91.12	137.85	5397.6	35
2	4160	2734.1	1508.94284	201.666667	0	1669.4222	1033	113.04	129.95	90
3	12470	11814	6145.49331	1867.24138	0	6332.8276	5974	360.55	1263.6	29
4	12470	10574	3817.25417	4975	0	2511	588.3	989.56	10358	6
5	12470	4096.8	2423.922	6750	0	147.5	54.34	146.25	5254.9	2
6	12470	9595.6	4180.85691	1230.55556	0.019	5147.6296	2329	508.98	2533.8	54
7	12470	5358.4	3325.673	1200	0	163	0	4385.1	4229.7	1
8	12470	9938.1	3773.42409	1309.09091	0	21825.545	3952	903.06	2748.3	11
9	12470	15164	12176.0903	1140	0.6	4861.4	3826	336.77	1142	10
10	12470	17461	8582.3285	1912.5	3	3583.25	4143	425.17	2893.6	4

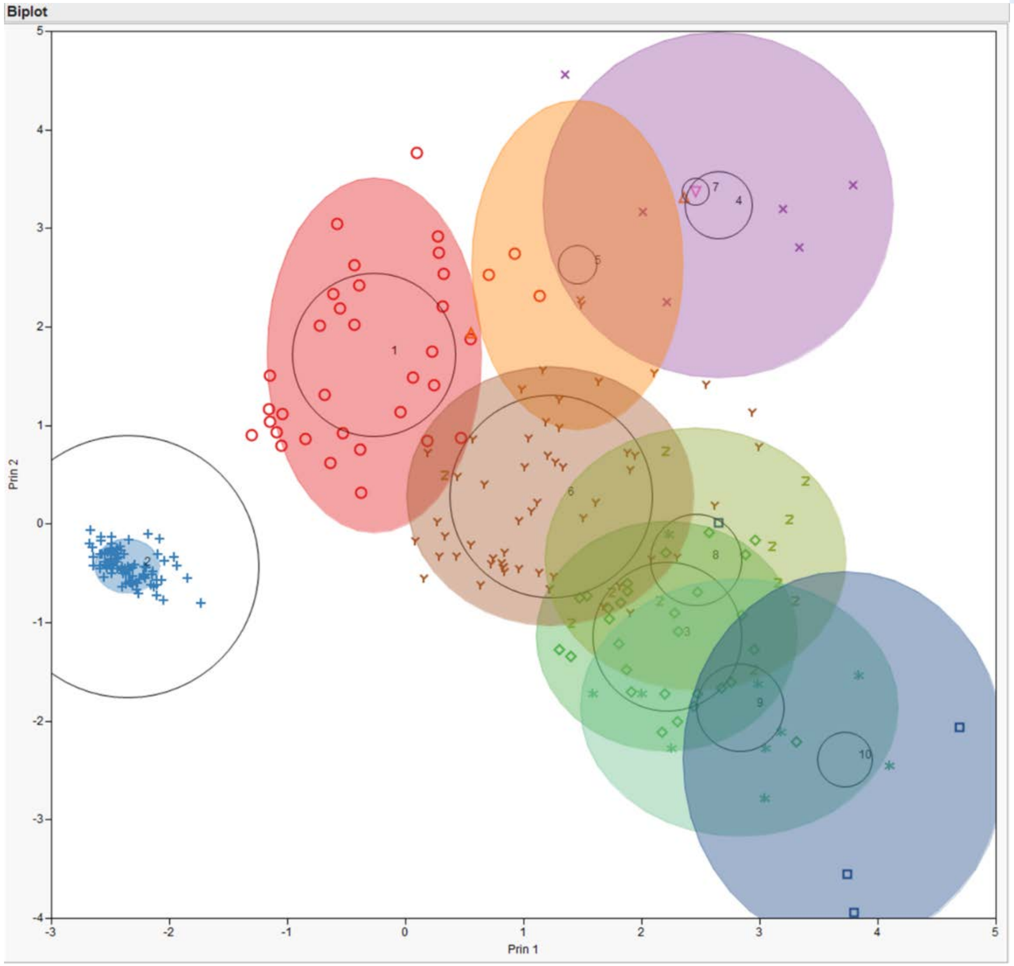
Values shown are the average of all feeders within each cluster

Cluster	Characteristics
1	12470, short 3-ph meters, short EOL distance, 0 regulators, low customer count, high kVA industrial
2	4160, 0 regulators, shortest 3-ph meters, shortest EOL distance
3	12470, long 3-ph meters, medium EOL distance, 0 regulators, highest kVA residential
4	12470, long 3-ph meters, short EOL distance, 0 regulators, high kvar, highest KVA industrial
5	12470, short 3-ph meters, short EOL distance, 0 regulators, highest total kvar, 6750 kvar, low customer count
6	12470, medium 3-ph meters, medium EOL distance, 0 regulators (except for 1 feeder with 1)
7	12470, short 3-ph meters, short EOL distance, 0 regulators, 1200 kvar, highest KVA commercial
8	12470, medium 3-ph meters, medium EOL distance, 0 regulators, highest customer count, medium length
9	12470, long 3-ph meters, highest EOL distance meters, 0&1 regulators
10	12470, longest 3-ph, long EOL distance, 2,3 and 4 regulators

Biplot Illustrating Feeders in Each Cluster

- Some clusters represent a tighter range of feeders
  - Light blue Cluster 2
- Some clusters represent a wider range of feeders
  - Red Cluster 1

Graphical representation of the feeder in the 10 clusters



Clustering Feeders Based on Electrical Characteristics

- A second approach is taken where electrical feeder characteristics are used to cluster feeders into similar groups.
- Prior detailed analysis has identified key feeder electrical characteristics that have considerable influence on DER impacts (shown below)

Feeder Topology	Nominal Voltage
Voltage Control	Line Regulators (#)
	Load Weighted Average R
Calculated Values	Feeder Max R

Load Weighted Average R: Resistance where the load is centered on the feeder

Feeder Max R: Resistance to the end of the feeder

Ten Distinct Electrical-Based Feeder Clusters

Cluster	Voltage	LoadWeightedAvgR	FeederMaxR	Regs	Feeder Count
1	12470	2.3583775	7.207995942	1	4
2	12470	0.407413157	1.011578608	0	72
3	12470	1.097251754	3.133015385	0	65
4	12470	0.865108	3.382	4	1
5	12470	1.78351	19.39154906	2	1
6	12470	1.019187	2.299	1	3
7	4160	0.467095467	1.179766667	0	90
8	12470	2.42828	6.477	3	1
9	12470	4.88258	13.295	3	1
10	12470	1.77676	9.107	0	4

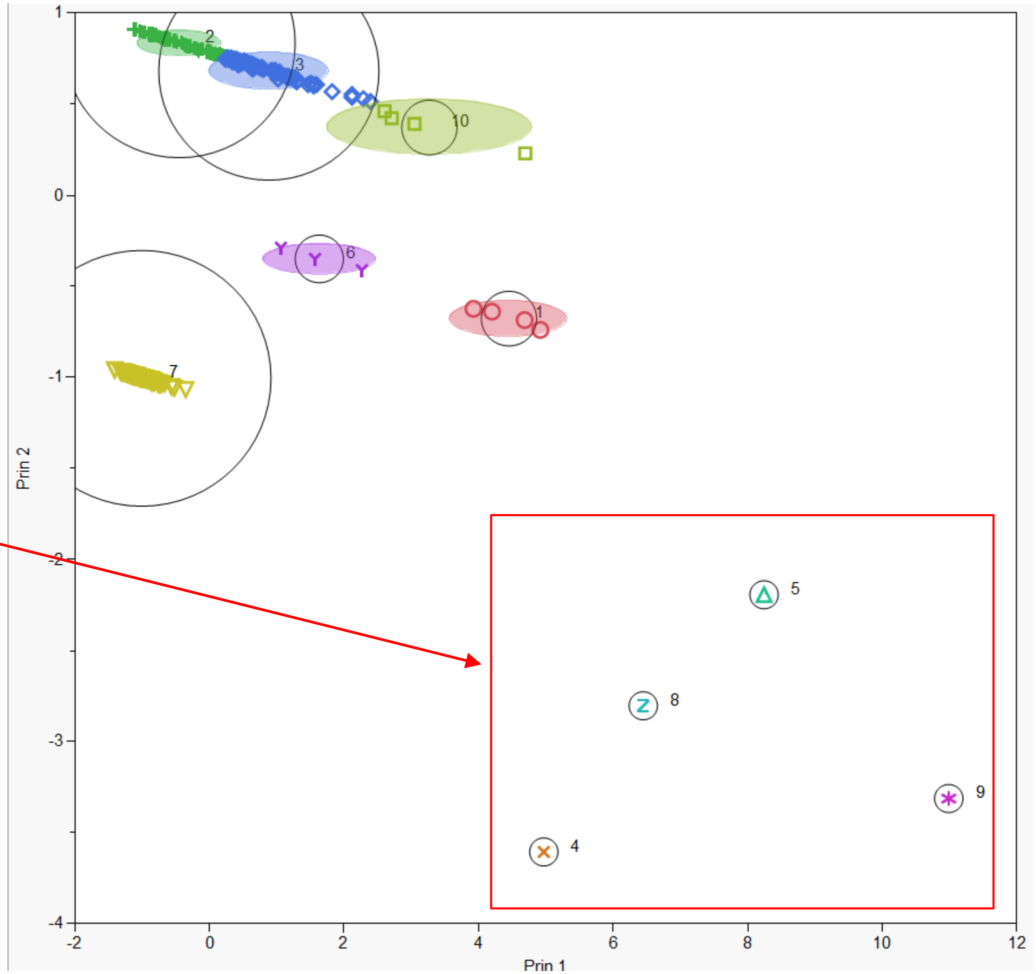
Values are the average of all feeders within each cluster

Nominal Voltage	LoadWeightedAvgR	MaxR	Regulators	Count	Description
12470	2.3583775	7.208	1	4	12470, 1 reg, high LWAvgR, med MaxR
12470	0.407413157	1.0116	0	72	12470, 0 regs, lowest LWAvgR, lowest Max R
12470	1.097251754	3.133	0	65	12470, 0 regs, high med LWAvgR, high med Max R
12470	0.865108	3.382	4	1	12470, 4 regs, low LWAvgR, med high MaxR
12470	1.78351	19.392	2	1	12470, 2 regs, lowo LWAvgR, highest MaxR
12470	1.019187	2.299	1	3	12470, 1 reg, high LWAvgR, med Max R
4160	0.467095467	1.1798	0	90	4160, 0 regulators, low LWAvgR, low MaxR
12470	2.42828	6.477	3	1	12470, 3 regs, high LWAvgR, high MaxR
12470	4.88258	13.295	3	1	12470, 3 regs, highest LWAvgR, high MaxR
12470	1.77676	9.107	0	4	12470, 0 regs, high LWAvgR, high Max R

Biplot Illustrating Feeders in Clusters

- Some clusters represent a tighter range of feeders
  - Yellow Cluster 7
- Some clusters represent a wider range of feeders
  - Blue Cluster 3
- Four clusters (4,5,8,9) contain one feeder each due to outlying characteristics described in previous slide
- Less variables in the clustering algorithm makes clusters appear linear in the plot

Graphical representation of the feeders in the 10 clusters



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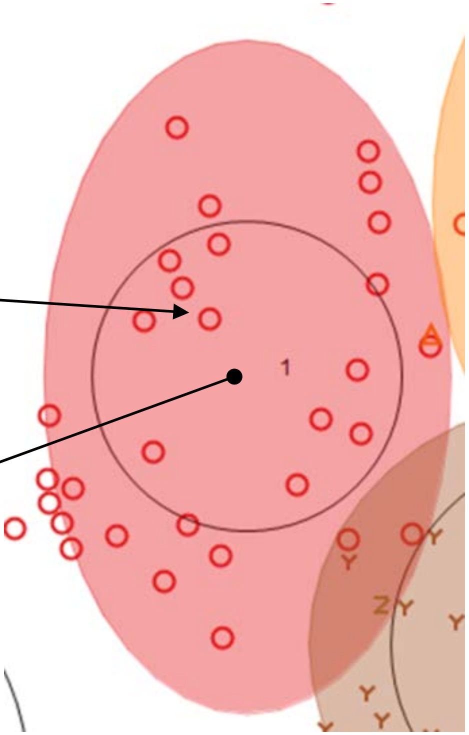
Identifying Representative Feeders

With the Representative Feeder Method, the impact of DER on the representative feeder is assumed to be similar to all other feeders in the cluster. The representative feeder is identified to compare those DER impacts.

- The representative feeder of a cluster is the one that is most similar to all others
- The representative feeder is chosen by the shortest distance to the center of the cluster

Representative Feeder for Topology-Based Cluster 1

Topology-Based Cluster 1 Center



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Summary

- Two methods are used to cluster (group) feeders with similar characteristics
  - Topology Characteristic clustering is inherent to the feeder design
  - Electrical Characteristic clustering is inherent to the electrical properties of the feeder
- Both methods identify 10 clusters of feeders
- A representative feeder is chosen from each cluster
- The clusters of feeders and their representative feeders will be used to examine the effectiveness of clustering to determine DER impacts

Chapter 3 – Distribution System Impacts

Chapter 3 – Distribution System Impacts

This chapter describes the potential DER impacts to an entire distribution system. Each feeder is analyzed independently using EPRI's Streamlined Analysis Method for determining hosting capacity.

DER Impact Analysis

- Issues considered
- Node and feeder-level hosting capacity

Results

- Illustration of system-wide hosting capacity
- Distribution of hosting capacity
- Range in hosting capacity among clusters

Summary

DER Impact Analysis

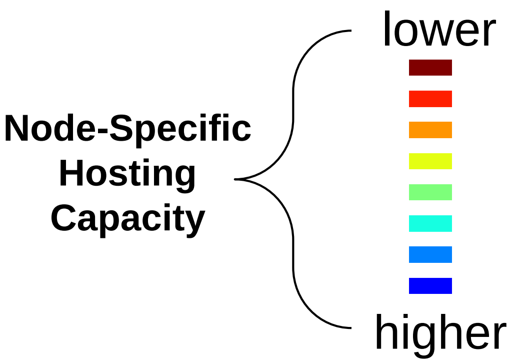
A subset of EPRI's Streamlined Analysis criteria is used for this DER Impact Analysis. The tables below indicate the criteria considered. Feeder level (aggregate) hosting capacity values for each combination are then determined for comparison to the feeder clusters.

DER
Utility-Scale Centralized/Localized

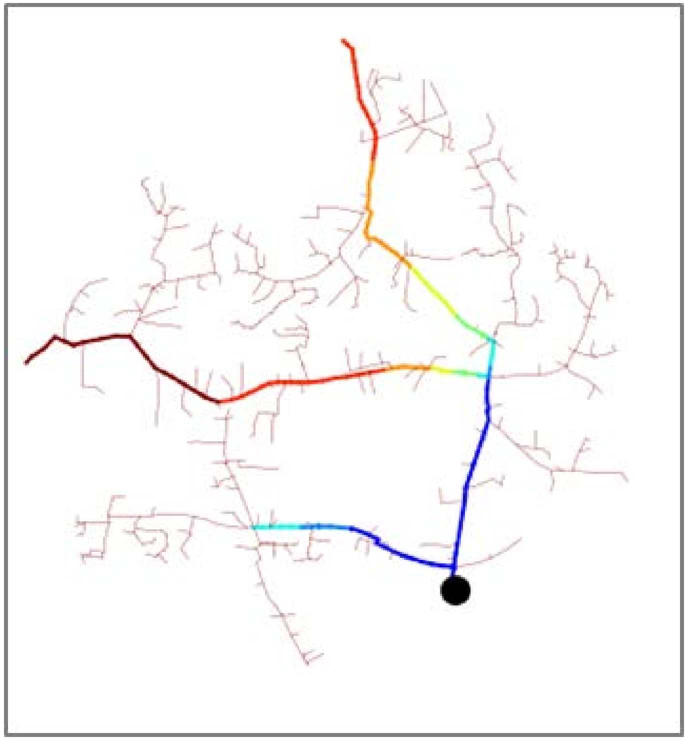
Issue	Criteria	Threshold
Voltage	Overvoltage	≥ 1.05 Vpu
Thermal	Element Loading	≥ 100% normal rating

Condition for Feeder-Level Hosting Capacity
Best Location (corresponds to maximum hosting capacity)
Worst Location (corresponds to minimum hosting capacity)

Understanding the Localized Utility-Scale Hosting Capacity Results
Node Level

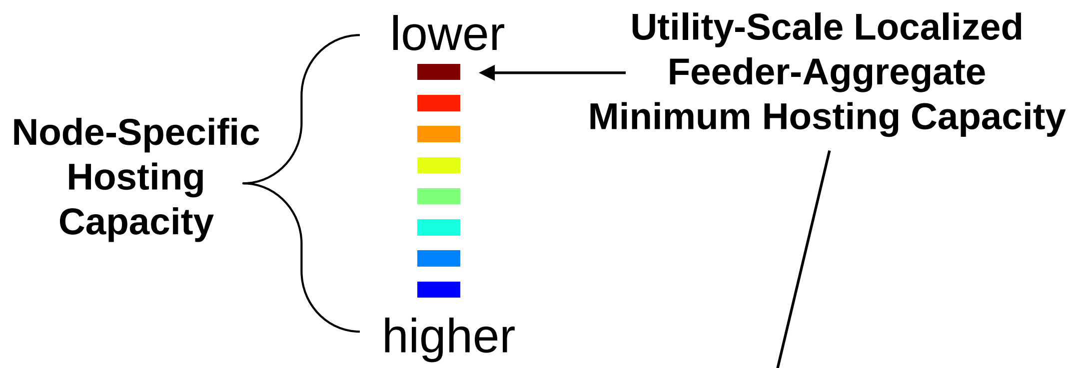


- Node-Specific Hosting Capacity
  - Determined for each three-phase node, zero for single- and two-phase nodes
  - Based on DER only at that node
  - If no violation occurs by the maximum analyzed penetration, the hosting capacity is set to the maximum penetration analyzed (10 MW for voltage issue)

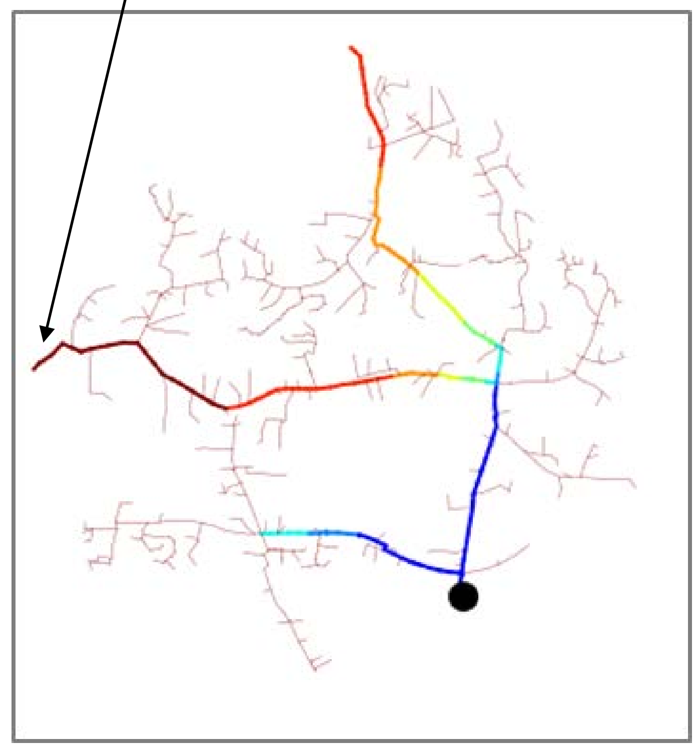


Understanding the Localized Utility-Scale Hosting Capacity Results

Node and Feeder Level



- The Feeder-Aggregate <u>Minimum</u> Hosting Capacity
  - The lowest node-based hosting capacity of the feeder
  - Effectively the worst location for DER



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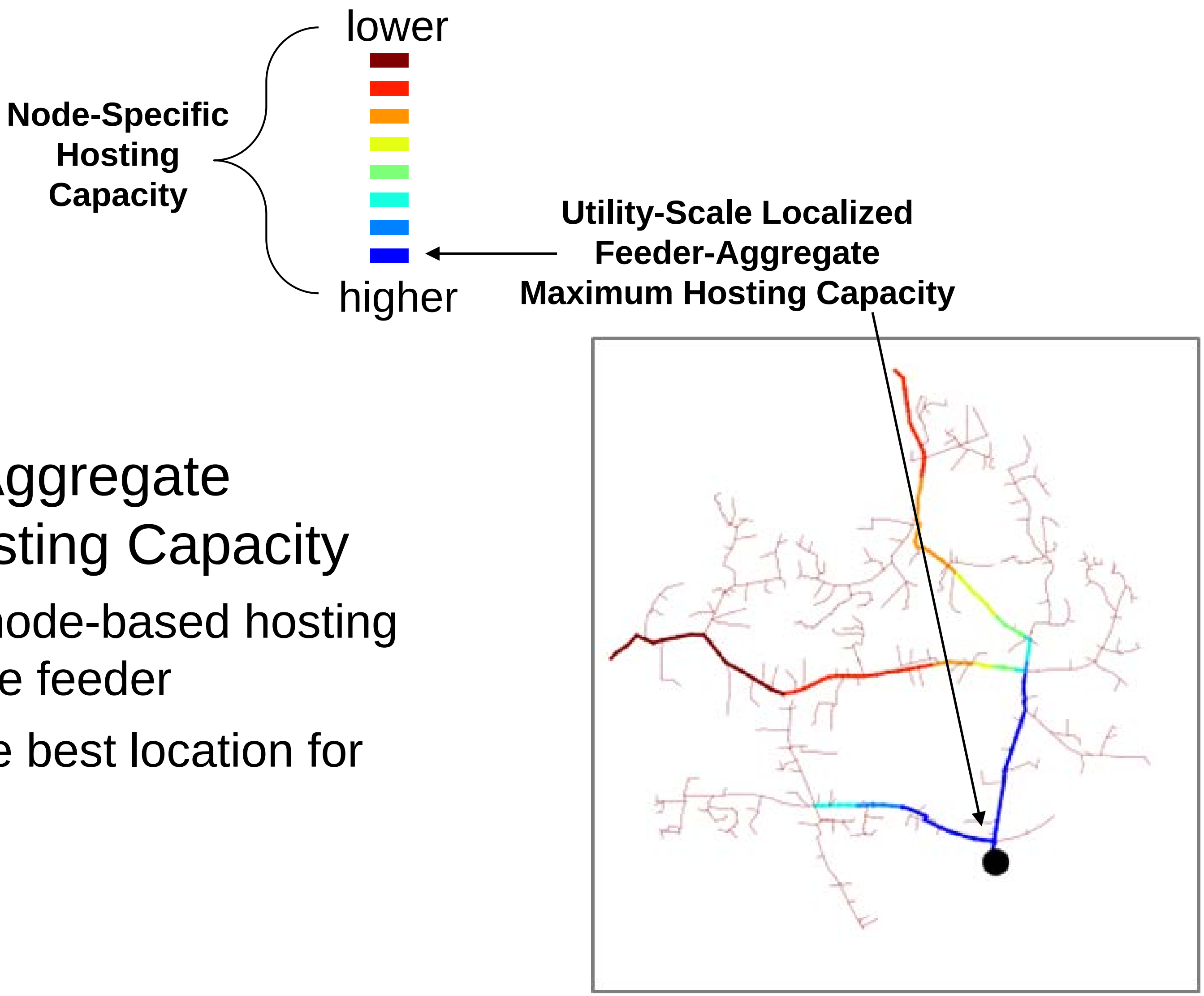
Understanding the Localized Utility-Scale Hosting Capacity Results

Node and Feeder Level



- The Feeder-Aggregate Maximum Hosting Capacity
  - The highest node-based hosting capacity of the feeder
  - Effectively the best location for DER

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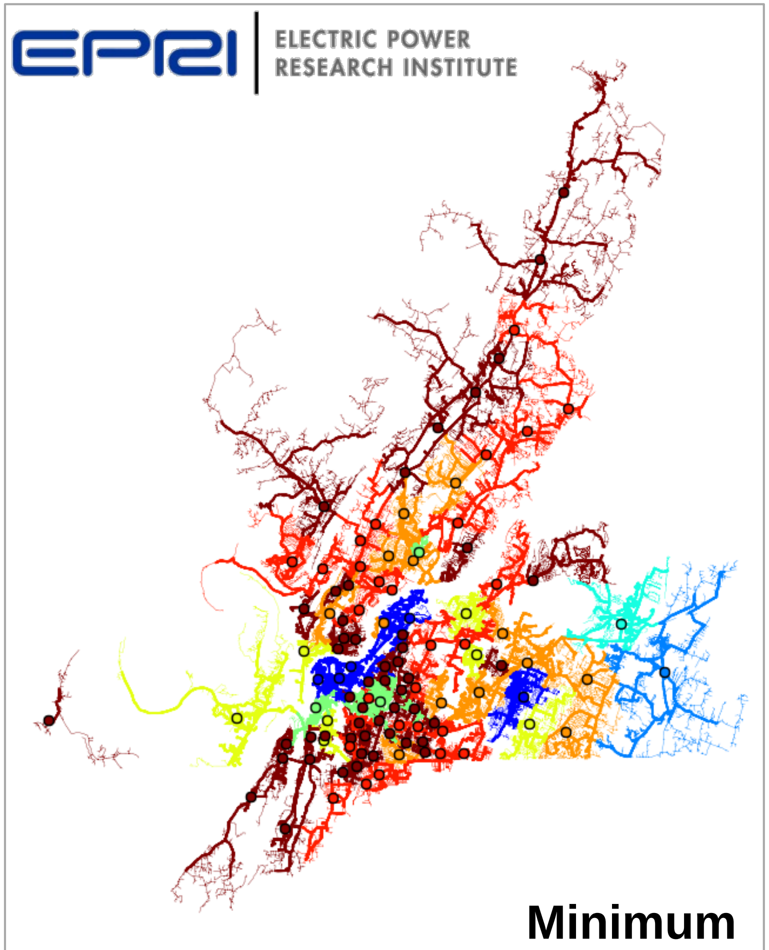
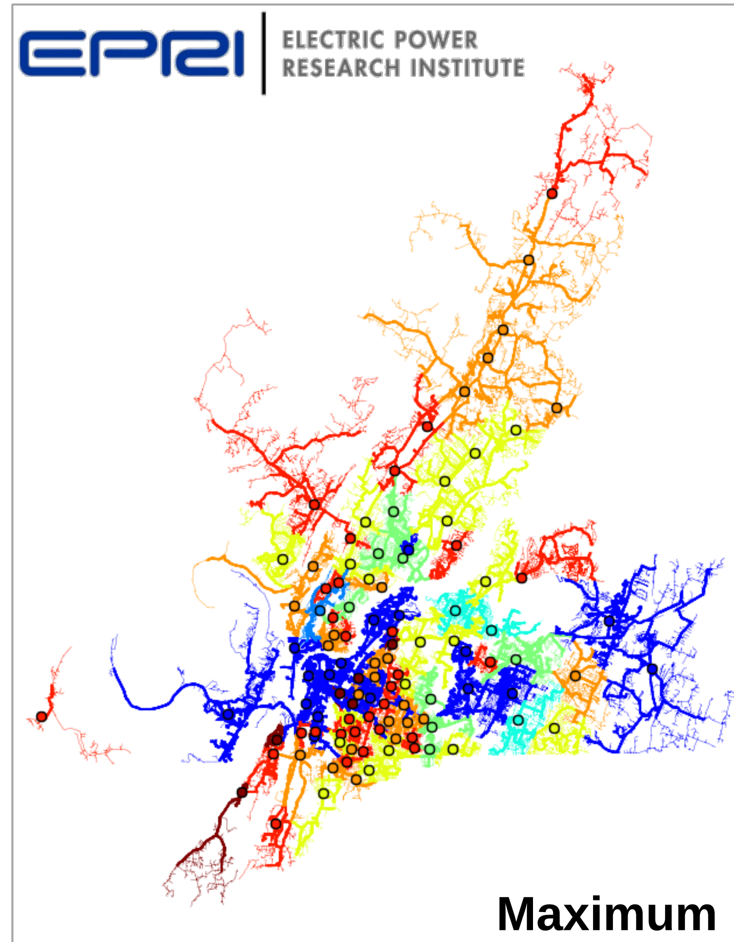
Analysis of Complete System

Figures below illustrate the Substation Hosting Capacities which are the sum of Feeder-Aggregate Hosting Capacity of all feeders served off of each substation.

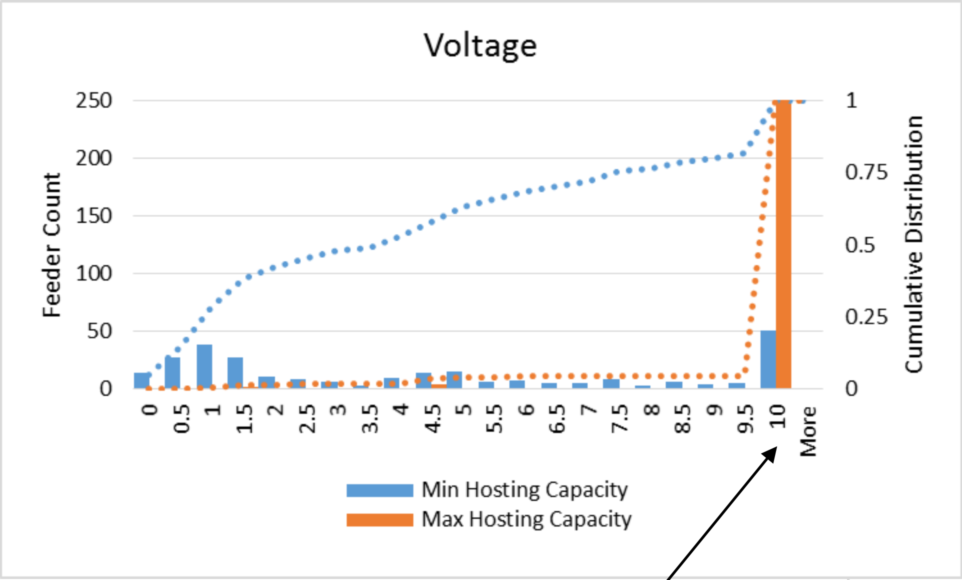


Substation Hosting Capacity

- < 2.5 MW
- 2.5-5.0 MW
- 5.0-7.5 MW
- 7.5-10.0 MW
- 10.0-12.5 MW
- 12.5-15.0 MW
- 15.0-17.5 MW
- > 17.5 MW



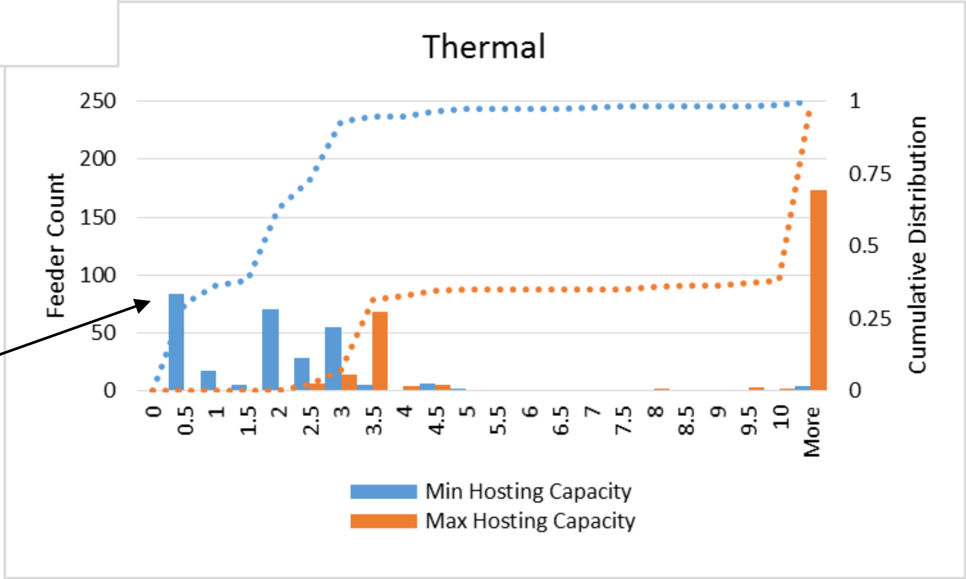
Distribution of Feeder Hosting Capacity Values



The localized utility-scale scenario considers that the PV is not distributed and only can exist at three-phase locations. These max/min hosting capacities are extreme because the best/worst locations are considered.

Nearly all feeders have a voltage-based maximum hosting capacity of 10 MW

Minimum Hosting Capacity is lower among feeders for thermal issues



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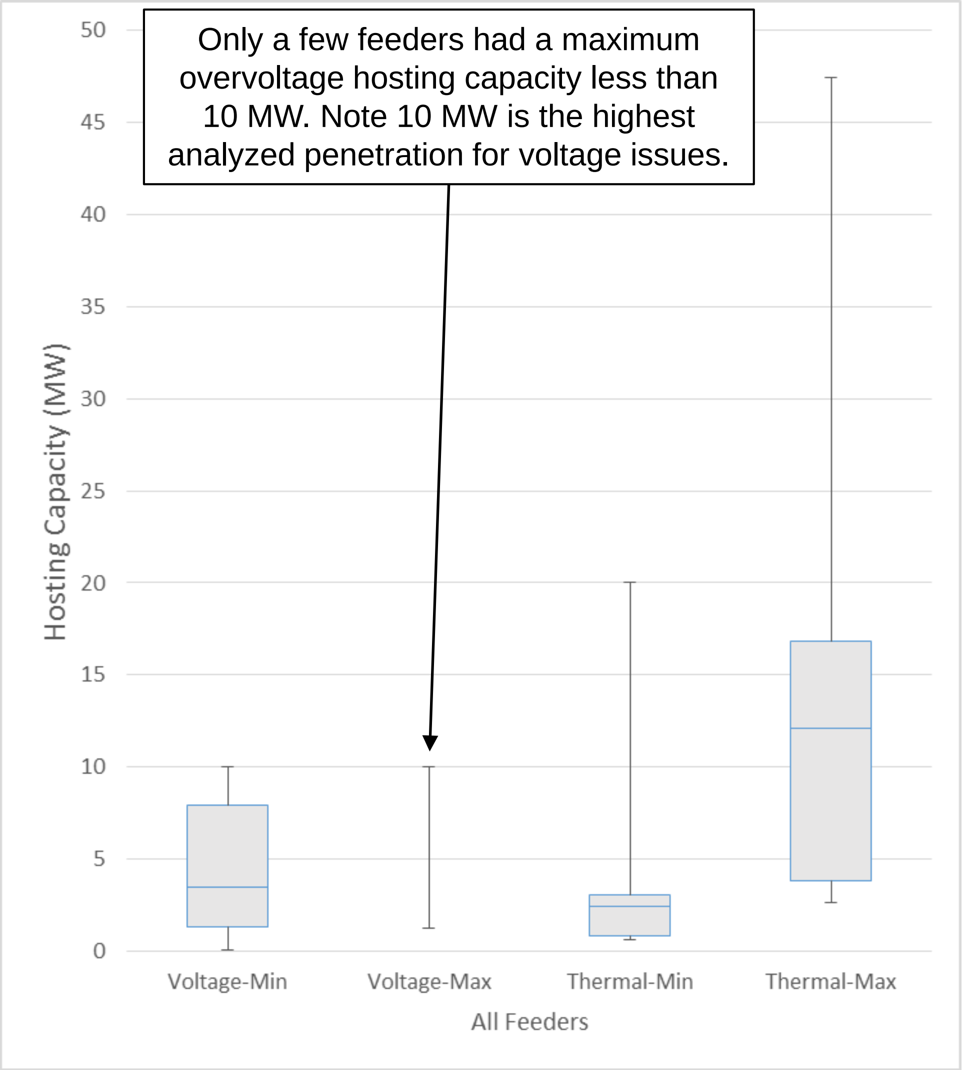
Range in Hosting Capacities

A large set of distribution feeders are going to have a wide range of hosting capacities. Ideally, grouping feeders by clusters will reduce this range.

- All feeders are considered in the figure to the right
- All combinations of issues/conditions shown
  - Voltage-Min: Primary Overvoltage - Minimum Hosting Capacity
  - Voltage-Max: Primary Overvoltage - Maximum Hosting Capacity
  - Thermal-Min: Overload - Minimum Hosting Capacity
  - Thermal-Max: Overload - Maximum Hosting Capacity
- Box-and-whisker plot
  - The center horizontal line represents the median hosting capacity of all feeders
  - The box indicates one quartile above/below the median
  - The error bars indicate the absolute highest and lowest hosting capacity value



Summary

- EPRI's Streamlined Analysis is used to determine hosting capacity of each feeder in the distribution planning area
- Results indicate a wide range in hosting capacity across the set of feeders
- Next section: The hosting capacity results will be compared to the clustered groups of feeders and the representative feeder from each cluster

Chapter 4 – Hosting Capacity and Clustering

Chapter 4 – Hosting Capacity and Clustering

This chapter discusses the effectiveness of using clustering and representative feeders to describe the DER hosting capacity of similar feeders.

Hosting Capacity and Topology-Based Clustering

- Hosting capacity comparison to representative feeder
- Hosting capacity comparison to entire cluster of feeders

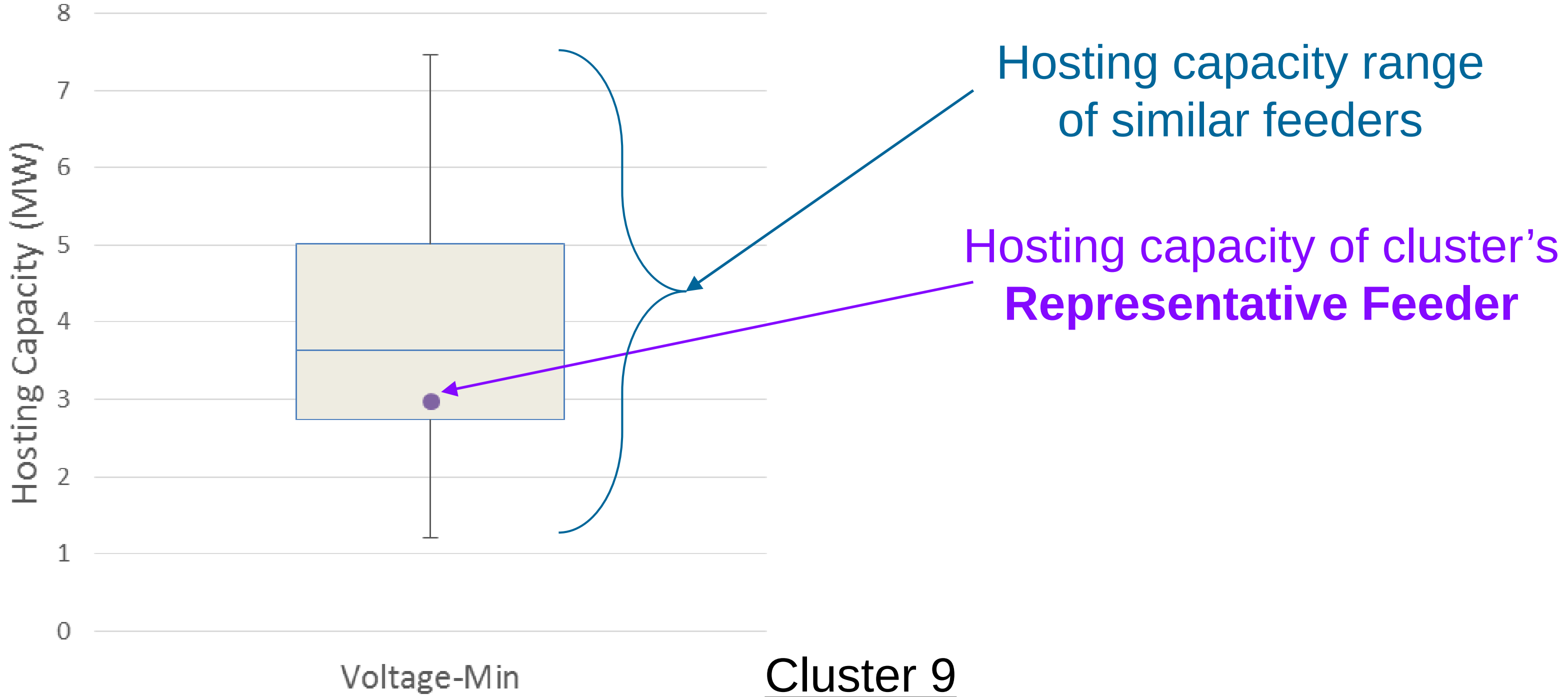
Hosting Capacity and Clusters Based on Different Characteristics

- Topology- and electrical-based characteristics
- Comparison of overall clustering effectiveness

Summary

Hosting Capacity and Topology Clustering

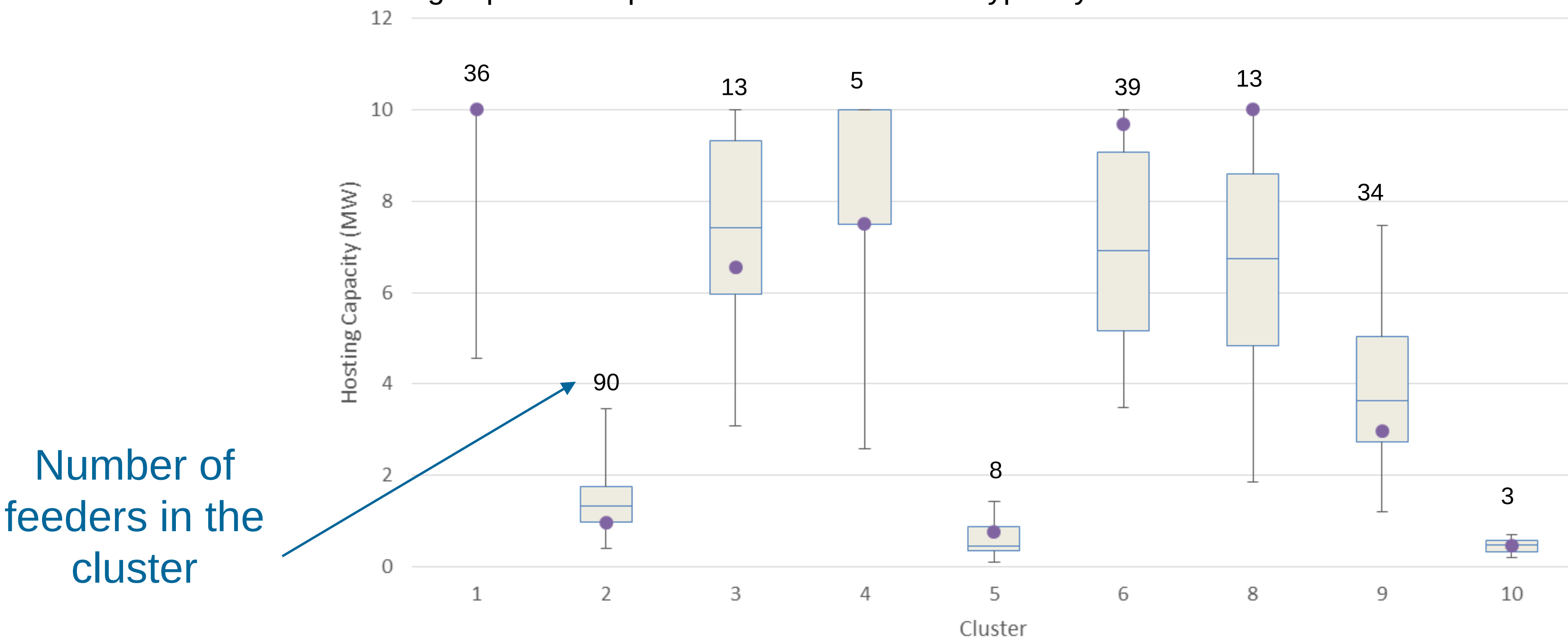
- Hosting capacity values comparing
  - Voltage issue
  - Worst case condition (minimum hosting capacity)
  - One clustered group of similar feeders and the representative feeder
- Results
  - Hosting capacity range in the cluster varies considerably
  - Hosting capacity of representative feeder is not the median of the cluster



Cluster 9

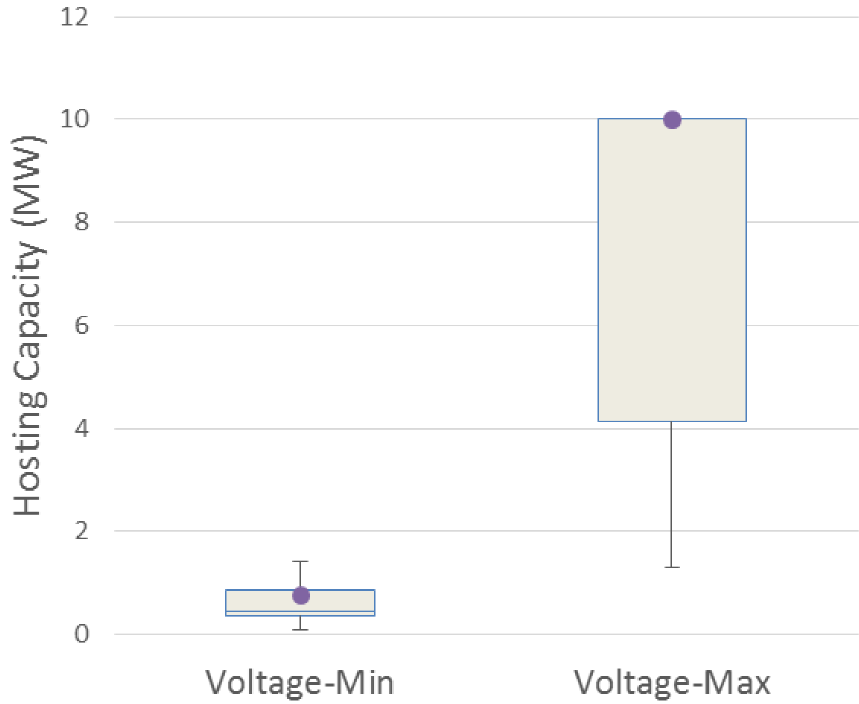
Hosting Capacity and Topology Clustering

- Hosting capacity values comparing
  - Voltage issue
  - Worst case condition (minimum hosting capacity)
  - All clustered groups of similar feeders and their representative feeder
- Results
  - Hosting capacity range in each cluster varies considerably
  - Hosting Capacity of Representative Feeder can be either **higher or lower** than the median value of the cluster
  - Clusters in which hosting capacities represent the entire cluster typically contain few feeders



Hosting Capacity and Topology Clustering

- Hosting capacity values comparing
  – Voltage issue
  – Best and worst case condition (maximum and minimum hosting capacity)
  – One clustered group of similar feeders and the representative feeder
- Results
  – Some clusters have good representation of minimum hosting capacity
  – Some are not well represented for maximum hosting capacity

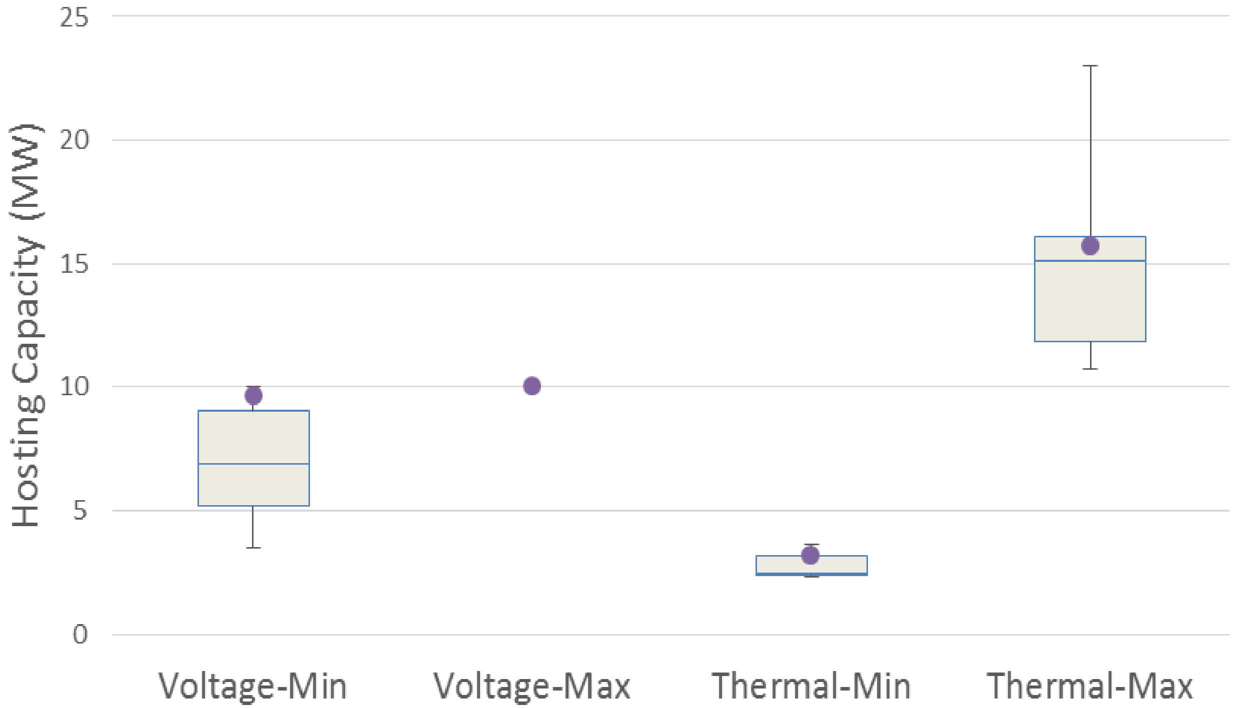


Cluster 5

Hosting Capacity and Topology Clustering

Multiple issues, minimum and maximum hosting capacity, one cluster

- Hosting capacity values comparing
  - Voltage and thermal issues
  - Best- and worst-case conditions (maximum and minimum hosting capacity)
  - One clustered group of similar feeders and the representative feeder
- Results
  - Minimum thermal and maximum overvoltage match fairly well
  - Maximum thermal and minimum overvoltage hosting capacity do not
  - All maximum voltage hosting capacities in the cluster are 10 MW



Cluster 6

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Overall Clustering Effectiveness

The previous results portray that the hosting capacities within a topology-based cluster of feeders are not that similar to each other or the representative feeder.

This next section examines the correlation between hosting capacity and clusters based on a different sets of characteristics.

- Clustering based upon
  - Topology characteristics
  - Electrical characteristics
- The overall effectiveness of clustering is compared using two different approaches:

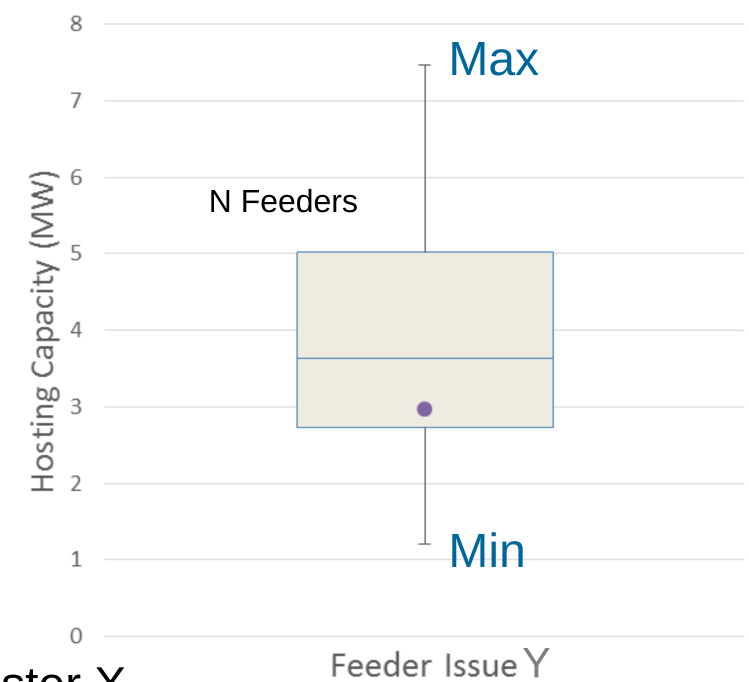
  1) How well clustering creates groups of feeders with similar hosting capacity

  2) How well the representative feeder represents the median hosting capacity of the cluster

Overall Effectiveness Comparison Approach #1

The overall effectiveness of using clusters to identify hosting capacity is calculated by the error between Min and Max hosting capacity values (see figure).

- Error calculated for
  - 10 topology-based clusters and 10 electrical-based clusters
  - Overvoltage and Thermal issues
  - Minimum and Maximum Hosting Capacities
- Total error is summed for topology- and electrical-based clusters



Cluster X

Variables

- Cluster X
- Feeders in Cluster: N
- Feeder Issue/Condition: Y
- Total of feeders in all clusters: Ntotal

$$f(X,N,Y) = \underbrace{(Max - Min)}_{\text{MW error per cluster}} * \underbrace{N/_{Ntotal}}_{\text{Weighting puts more emphasis on error for a cluster with a lot of feeders}}$$

MW error per cluster

Weighting puts more emphasis on error for a cluster with a lot of feeders

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Overall Effectiveness Comparison Approach #2

The overall effectiveness of using clusters to identify hosting capacity is calculated by the error between feeder hosting capacity and the Representative Feeder hosting capacity values (see equations below).

- Error calculated for
  - 10 topology-based clusters and 10 electrical-based clusters
  - Overvoltage and Thermal issues
  - Minimum and Maximum Hosting Capacities
- Total error is summed for topology- and electrical-based clusters

<u>Variables</u>

- Cluster X
- Feeders in cluster: N
- Feeder Issue/Condition: Y
- Feeder: k
- Representative Feeder: R
- Total of feeders in all clusters: Ntotal

$$g(X,N,Y) = \sum_{k=1}^{N} ABS(YR - Yk)$$

$$f(X,N,Y) = \underbrace{g(X,N,Y)}_{\text{MW error per cluster}} * \underbrace{N/_{Ntotal}}_{\text{Weighting puts more emphasis on error for a cluster with a lot of feeders}}$$

MW error per cluster

Weighting puts more emphasis on error for a cluster with a lot of feeders

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Overall Clustering Effectiveness

- Topology-based clusters previously shown as **ineffective** to portray hosting capacity
- Both approaches show electrical-based clustering is **not** more effective to group feeders with similar hosting capacity
- Clusters based on topology data **works better** than electrical data
  - More characteristics needed to differentiate feeders in the clustering analysis
  - Results in previous box and whisker plots would look worse for electrical-based clustering than that shown for topology-based clustering

	Approach #1		Approach #2	
	Topology	Electrical	Topology	Electrical
Overvoltage (min)	4.89	5.10	47.7	66.9
Overvoltage (max)	0.36	2.11	0.8	2.2
Thermal (min)	4.51	7.50	30.3	46.6
Thermal (max)	11.73	20.24	87.8	341.1

**Error should not be compared between the different approaches. Units are MW error per cluster. Smaller numbers in the table mean better consistency in hosting capacity values within a cluster*

Summary

- Feeders within a cluster can have a wide range in hosting capacity
- Hosting capacity for a cluster is typically tighter for clusters with less feeders
- Similarity of hosting capacity values within a cluster may be better for one issue than another
- The hosting capacity of the representative feeder is seldom the median of the cluster
- Topology-based clustering shows overall better results
  - Due in part to the inability to cluster with a small characteristic dataset. More characteristics are needed to better differentiate feeders.

Chapter 5 – Conclusions

Chapter 5 – Conclusions

- The hosting capacity for each feeder within a cluster can vary considerably
- Clustering on different sets of characteristics (even those known to be more influential – electrical characteristics) are found to be ineffective
- The representative feeder method **should not** be used to extrapolate hosting capacity to other feeders within the cluster

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