ELECTRIC POWER RESEARCH INSTITUTE

Advancing Smart Inverter Integration in Utah

Final Report

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Technical Update, February 2019

EPRI Project Manager

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ABSTRACT

With the release of updated interconnection rules for DER (IEEE 1547-2018) and the anticipated availability of smart inverters in the near future, some additional preparation may be necessary for utilities to effectively apply these new capabilities on their distribution networks. EPRI and PacifiCorp have worked together to analyze a portion of the distribution network in the state of Utah to better understand the potential improvement in hosting capacity achievable with smart inverters, recommended settings, and trends in deployment for bulk system support (particularly ride-through of disturbances), and communications technologies. This report depicts the results of that study, conducted during 2018.

Keywords

Smart inverter
Volt-VAR
Hosting capacity
Interconnection rules

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PRIMARY AUDIENCE: PacifiCorp and other stakeholders interested in the potential benefits of smart inverter technology on distribution networks in Utah.

KEY RESEARCH QUESTIONS

- What is the potential PV hosting capacity increase possible by requiring smart inverters in the Rocky Mountain Power service territory?
- How should smart inverters be configured and set for the most effective autonomous operation under varying levels of PV penetration and smart inverter availability?
- Where are smart inverters currently in their adoption of open standards? What are the current gaps in implementation of grid support functions?

RESEARCH OVERVIEW

Advanced (or "smart") inverter technology may increase the hosting capacity of a distribution network at very low cost. The deployment of this technology has been aided by recently revised interconnection standards (IEEE 1547) and certification procedures (UL1741 SA). However, both the technology and its applications are still maturing, and early deployments have shown that careful consideration is needed before the technology can be most effectively deployed.

By combining laboratory testing, computer simulations, and a review of relevant standards, policies, and practices, this project aims to inform the future of smart inverter deployments in Utah and beyond.

KEY FINDINGS

- Some of the distribution feeders studied showed hosting capacity gains by using smart inverters; however, most saw limited improvement due to already being thermally constrained.
- Because improvements in hosting capacity depended greatly on the connection point, the improvements were smaller for distributed systems than central systems because the locations were less finely controlled.
- In addition to hosting capacity, reactive power from inverters can be used to improve distribution losses and substation power factor.
- With the "best" settings, Volt-VAR control performed better than the fixed power factor function; however, with bad settings the performance was worse than all configurations of the fixed power factor function.
- Use of several smart inverter functions (such as Volt-VAR) will require updates to PacifiCorp's *Distributed Energy Resource (DER) Interconnection Policy* (Policy 138).
- IEEE 1547-2018 offers guidance in areas related to DER integration (power quality, protection, ride-through, and communications) that—along with Policy 138—may enhance the overall integration of DER in Utah.
- While IEEE 1547-2018 introduces the requirement that DER have communications capability over an open protocol, utilities have not converged on an approach to interfacing with these devices.

WHY THIS MATTERS

While the technical requirements for smart inverters have been included in international standards, the specific configuration and settings are largely being left up to individual system operators. By understanding the potential impact (positive and negative) of smart inverters, PacifiCorp is able to make more informed recommendations as to the nature and timing of future smart inverter deployment.

HOW TO APPLY RESULTS

The results included in this report are exemplary in nature. They cover a range of distribution circuits and applications and, therefore, may inform general strategy. However, more detailed study of individual circuits may be necessary to understand their limitations as well as the most effective inverter settings.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Multiple workshops and advisory meetings were held with PacifiCorp staff as well as stakeholders.

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PROGRAM: Program 174 – Integration of Distributed Energy Resources

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1 INTRODUCTION

With increased amounts of solar PV generation being installed on the distribution system, there is an opportunity to more effectively integrate this resource with the electric power system in mind. One technology critical to the beneficial integration of PV is the smart inverter. This more advanced inverter not only converts PV energy to grid-compatible AC electricity, but it is also programmed to support the grid when necessary. This support could range from providing ride-through of grid disturbances to reactive power absorption for controlling high voltages on a distribution circuit.

Some of the opportunities for smart inverters to support the grid arise out of natural imitations of the distribution circuit to “host” additional generation. These limitations may be expressed by the metric hosting capacity, which combines several criteria—including voltage, thermal capacity, protection, and reliability and safety—to determine the amount of generation that may be accommodated on a portion of the power system given its current configuration. Hosting capacity is expressed in units of generation power level (that is, MW). By absorbing or injecting reactive power, smart inverters may be able to increase hosting capacity on certain feeders by reducing voltage variations resulting from increased generation (or load).

In addition to hosting capacity, other metrics related to distribution system performance—such as losses or reactive power flow—are affected by DER (along with smart inverters) and are of interest to power system planners and operators. However, while the devices may be ready, the development of usable implementation strategies for utilities has lagged. Previous EPRI research has shown that while the application of smart inverters can be beneficial for accommodating increased levels of PV penetration, the practice is not without its risks. Incorrect settings could produce a sizeable negative impact on voltage levels, variability, and regulating equipment operations.

This project aims to answer several questions:

- What range of potential benefits to PacifiCorp’s network with respect to hosting capacity and system performance may be expected, and how might that vary with reactive power requirements from DER?
- On areas of the distribution system that could benefit from smart inverter support, what are the most beneficial settings to provide voltage regulation limiting (or reducing) losses and improving circuit power factor?
- What changes are needed to existing interconnection policies and practices to enable smart inverters for PV and other DER?
- How are other utilities implementing smart inverter functionality, particularly in related areas such as ride-through of system disturbances and communication to distributed systems?

2

HOSTING CAPACITY AND SMART INVERTERS

EPRI studied 14 of PacifiCorp's feeders to understand the potential impact of smart inverters on the feeders' hosting capacity. EPRI simulated each feeder with DER operating at power factors between 0.90 (absorbing) and 1.0 and found the worst-case hosting capacity for each operating condition.

EPRI performed two types of simulations of DER deployments to determine hosting capacity, illustrated in Figure 2-1. The first—centralized DER—is based on adding DER at a centralized location; this is useful for understanding DER impact when it is installed as a large, single interconnection. The second—distributed DER—is based on adding DER distributed around a single location, which is useful for understanding the DER impact of smaller installations at multiple connection points.

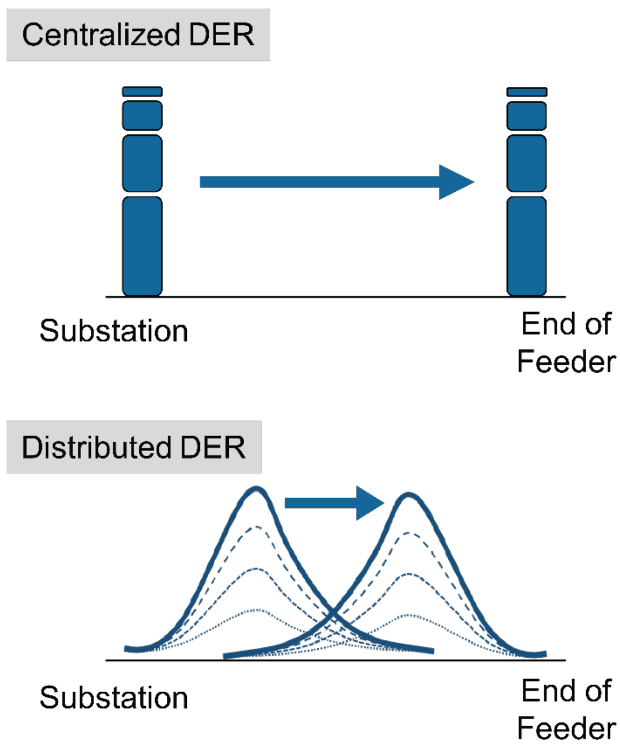

Figure 2-1
Methods of simulating DER interconnection for hosting capacity studies

Both types of simulations were performed on a collection of 14 feeders, identified by the project team. The circuit selection criteria was intended to develop a set of feeders reflecting a range of system conditions, including:

- Total DER penetration in relation to daytime loading
- Ongoing issues caused by DER (with and without smart inverters)
- Multiple customer classes (residential, commercial, and industrial)

- Types of equipment on the distribution circuit—voltage regulators, capacitor banks, etc.
- Levels of universal solar and private solar generation technologies

The selected circuits are partially described in the table below (Table 2-1):

Table 2-1
Summary of studied feeders and characteristics

Feeder	# of Generators	Regulators on Feeder	Reclosers on Feeder	Notes
BGT17	57	0	0	High kW DER penetration
BNG11	256	0	0	Highest # DER, newer suburban
BRT11	1	0	0	Rural high penetration growth
COA11	11	1	2	Rural northern Utah
ENV12	14	0	1	Voltage issues due to solar
IVN13	123	0	0	High DER, rural with a regulator
LPK15	141	0	0	High DER, some commercial
MCL15	94	0	0	Older suburban
OLY13	74	1	1	Regulator and recloser
SAR17	161	0	1	Highest # DER with recloser
TAR11	1	0	1	Rural/irrigation planned
TOQ31	14	0	3	Multiple reclosers, rural southern Utah
WCD28	3	2	3	Multiple reclosers and regulators
WRN11	69	0	0	Rural/suburban/northern Utah

As an example, Figure 2-2 shows a feeder map of SAR17 for each power factor case with centralized DER. The color of each segment is based on the mean hosting capacity of the two nodes it is between. The four maps reveal that operating DER at a lower-than-unity power factor adds hosting capacity to most nodes, particularly at the substation and spreading down the feeder.

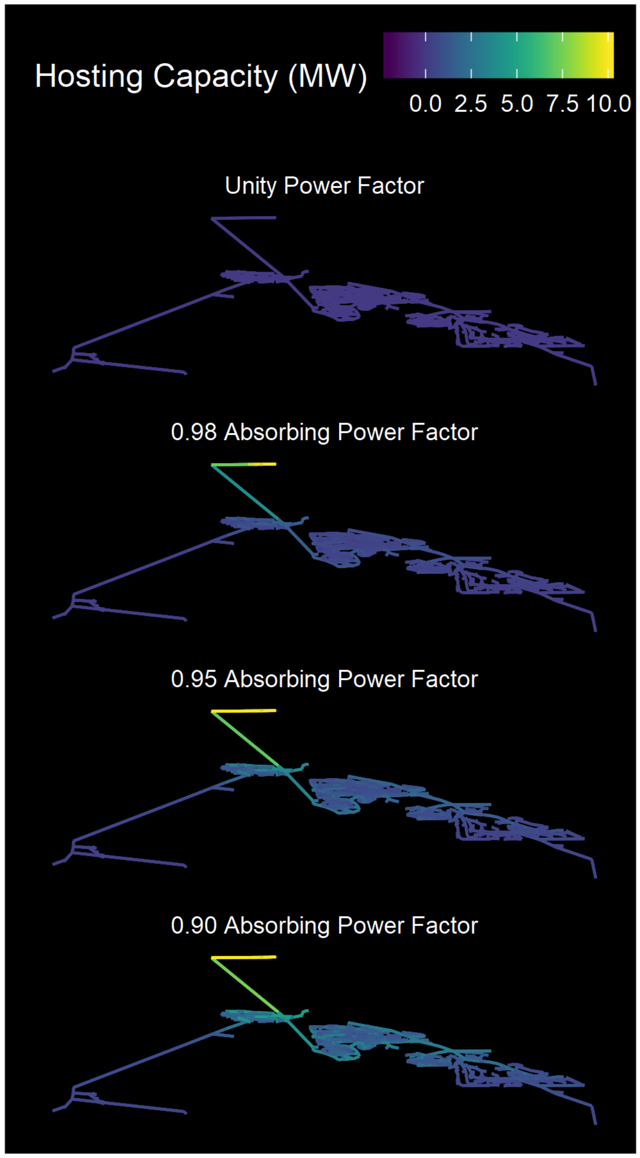

Figure 2-2
Hosting capacity of SAR17 at various power factors

Figure 2-3 shows the same map, but the segments are colored according to the constraining factor (such as voltage, thermal, or fault current rise) as opposed to the hosting capacity. The unity case's constraining factor at all nodes is primary overvoltage—but as reactive power absorption increases because of lower power factors, other constraining factors determine the hosting capacity. For example, several segments begin to have thermal constraints instead of overvoltage.

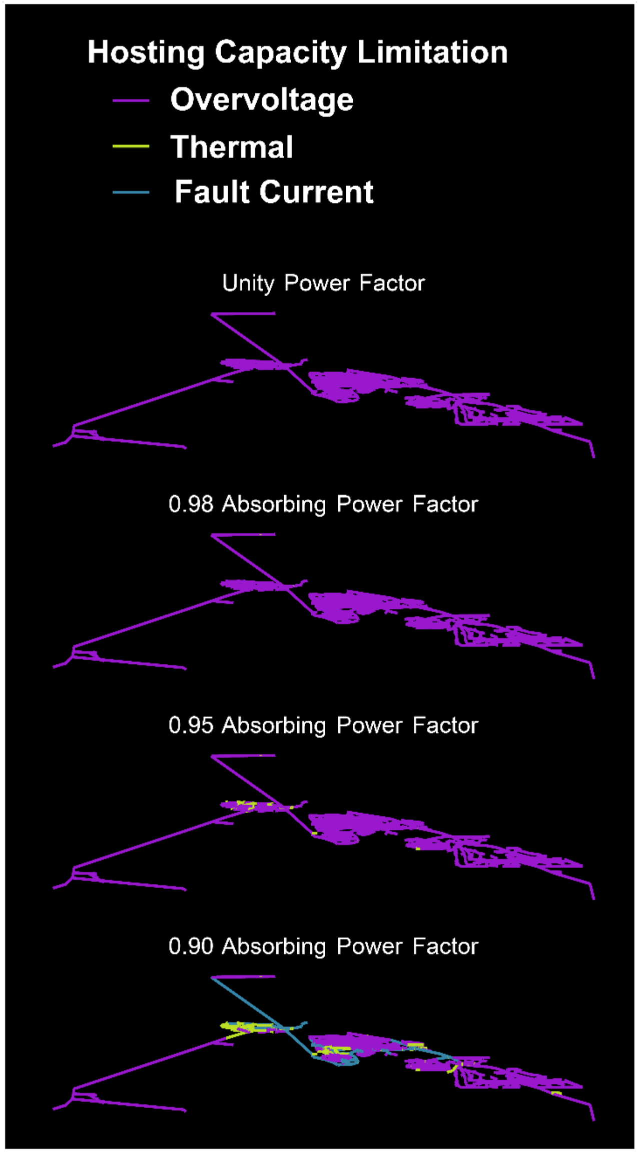

Figure 2-3
Constraining factor of hosting capacity on SAR17 at various power factors

While some feeders have their hosting capacity improved by smart inverters, this is not true for all feeders. Figure 2-4 shows a feeder map of hosting capacity at various power factors, such as the one shown in Figure 2-3. Unlike the map of SAR17, IVN13 shows less improvement at most nodes regardless of the power factor case.

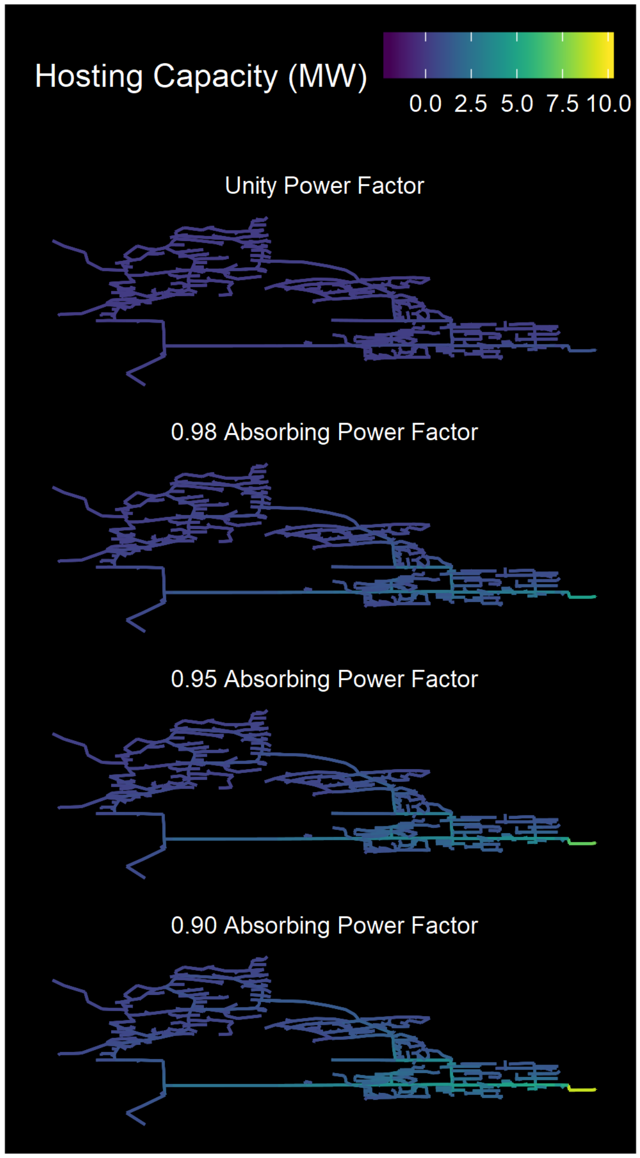

Figure 2-4
Hosting capacity of IVN13 at various power factors

To understand why this feeder IVN13 does not show a similar improvement to SAR17, EPRI looked at the constraining factor at each node, shown in Figure 2-5. The constraining factor changes from overvoltage to thermal as the power factor decreases, particularly at the nodes closest to the substation. As the power factor decreases, the thermally limited nodes increase in number away from the substation. The smart inverters improve the hosting capacity somewhat, but they cannot solve thermal constraints.

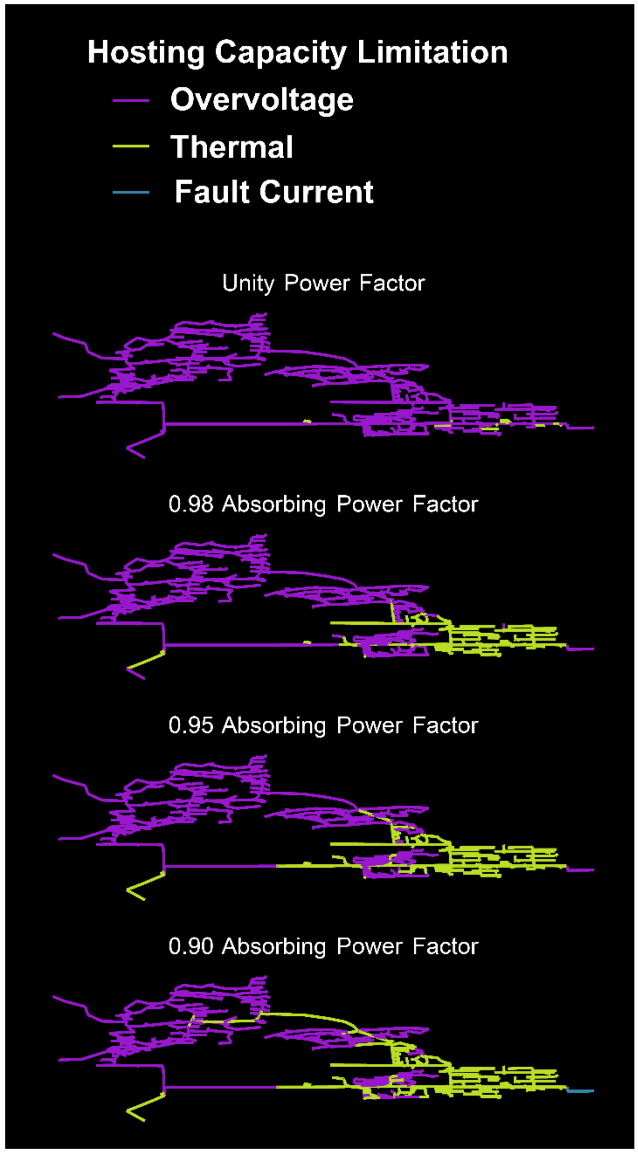

Figure 2-5
Constraining factor of hosting capacity on IVN13 at various power factors

To better understand this, EPRI studied the improvement of individual nodes from different power factors (see Figure 2-6). There are two main takeaways from looking at the hosting capacity in this way:

- Nodes near the substation (with the lowest impedance looking toward the source) have much larger improvements in hosting capacity than nodes farther away.
- Nodes whose constraint is thermal, not voltage related, cannot have their hosting capacity improved through smart inverters.

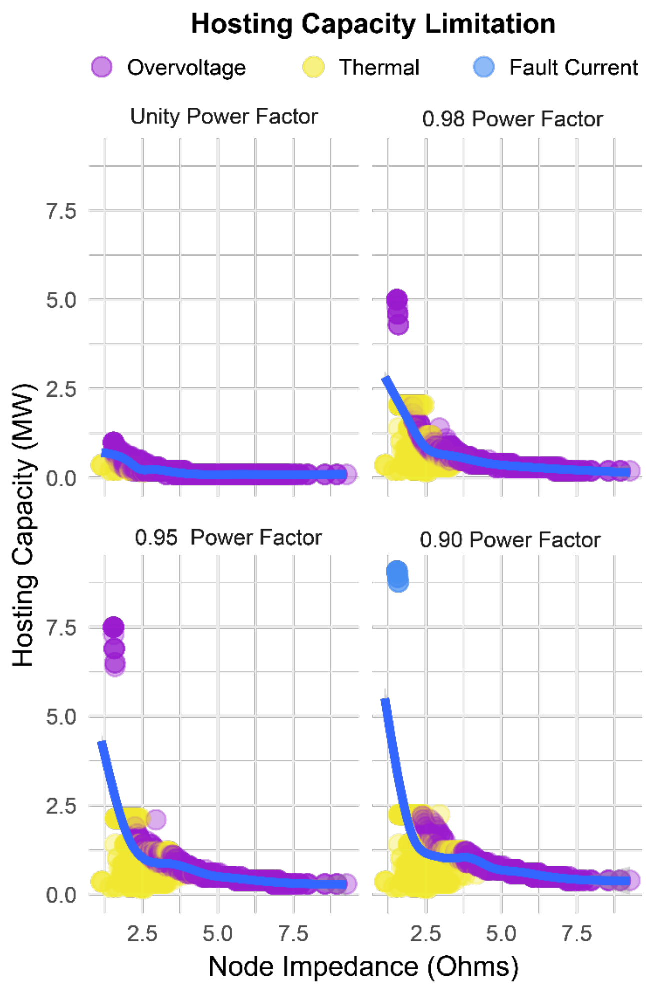

Figure 2-6
IVN13 hosting capacity by node impedance

Results from analysis of the feeders for distributed PV tell the same story. Of the 14 feeders analyzed, only four (MCL15, OLY13, SAR17, and IVN13) showed improvement in hosting capacity from distributed small-scale smart inverters (see Figure 2-9). The rest saw no improvement, mostly because of non-voltage-related hosting capacity constraints (that is, the feeders were thermally constrained).

The results are dependent upon assumptions about the deployment of smart inverters. For the analysis in this report, three sensitivities were included:

- No retrofit case (Figure 2-7) – existing PV systems are not retrofitted with smart inverters. Results show limited improvement in hosting capacity. This scenario highlights the difficulties for smart inverters to address pre-existing voltage conditions caused by DER.
- Full retrofit case (Figure 2-8) – all PV systems (current and future) are equipped with smart inverters. Results show the largest improvement in hosting capacity with smart inverters.
- Retrofit-only case (Figure 2-9) – only the existing PV systems are retrofitted with smart inverters. Results show moderate improvement in hosting capacity, depending on the initial install base of PV systems.

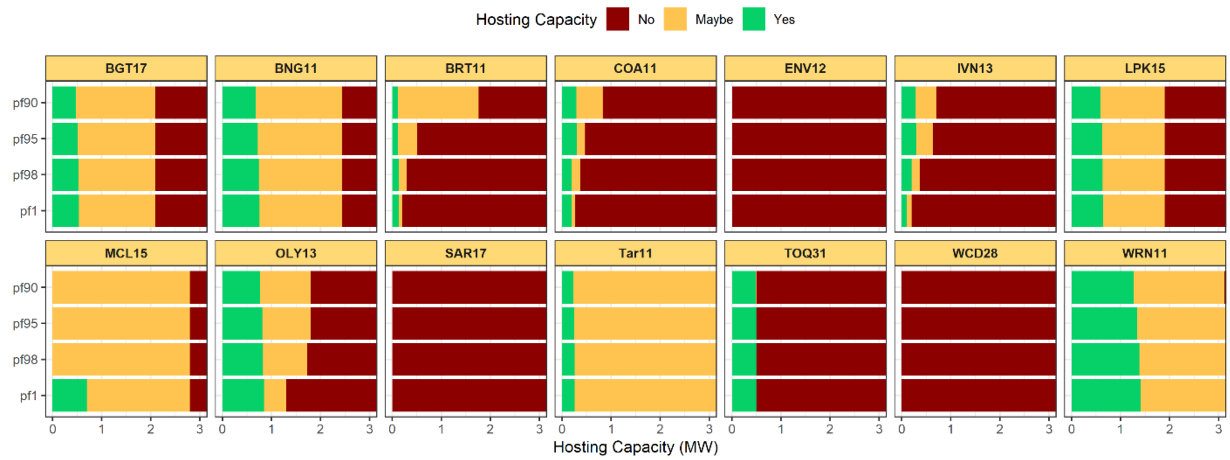

Figure 2-7
Hosting capacity of 14 feeders (no retrofit)

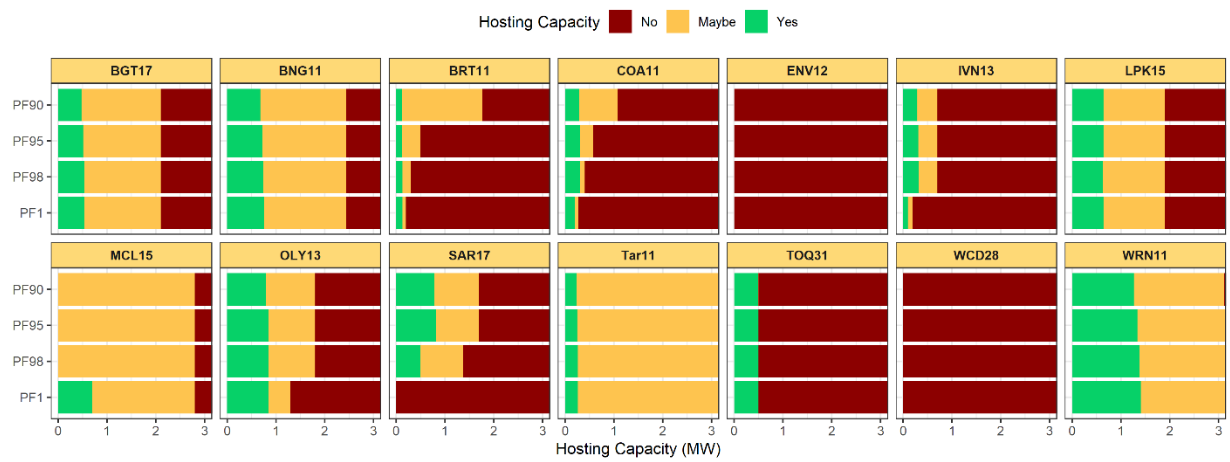

Figure 2-8
Hosting capacity of 14 feeders (full retrofit)

The appendices (A, B, and C) of this report document the detailed hosting capacity results (maps) for each of the retrofit cases.

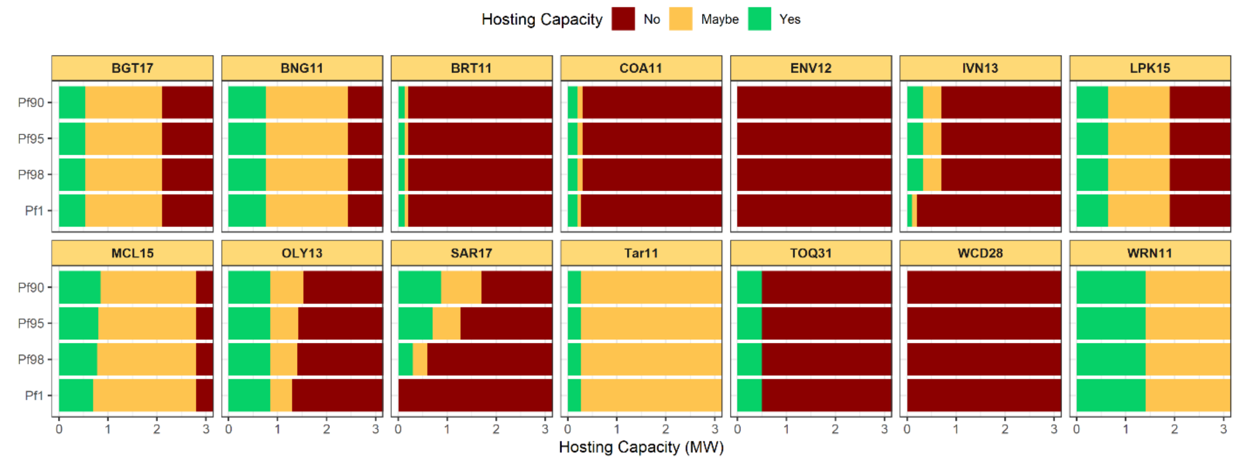

Figure 2-9
Hosting capacity of 14 feeders (retrofit-only)

Some key takeaways about the influence of retrofitting:

- If the feeder already has a pre-existing voltage issue due to installed DER (such as SAR17 or WCD28) it is unlikely that the hosting capacity can be improved by merely incorporating smart inverters into newly added DER systems.
- For most feeders however, especially those with a relatively small number of installed DER systems, the influence of retrofitting existing systems was relatively minor.

3
SMART INVERTER SETTINGS

Though many of the circuits in the hosting capacity analysis showed minimal improvement with smart inverters, a few showed moderate improvement (including SAR17 and OLY13). Smart inverters may affect two other aspects of distribution system performance: delivery losses and distribution circuit (or substation) power factor. While it is possible that smart inverters may simultaneously improve all three metrics, poorly chosen reactive power settings could negatively impact one or more them.

If reactive power support from smart inverters is desired, two primary options are available: running the inverter output at a fixed power factor or employing Volt-VAR control. Deploying fixed power factor requires specifying only the desired magnitude and direction (that is, 0.97 absorbing). However, Volt-VAR control requires selecting several parameters—including maximum and minimum outputs, slope, setpoint, and deadband (if applicable) (see Figure 3-1).

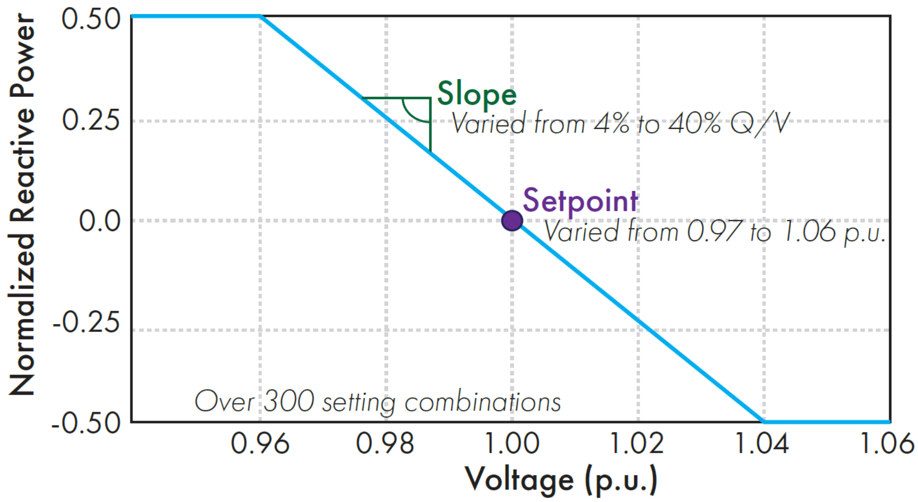

Figure 3-1
Key parameters of analyzed Volt-VAR curves

While the previous analysis was a "snapshot" of the circuit hosting capacity and inverter reactive power output, understanding the full impact of smart inverters requires consideration of an entire day's operation, with a variety of solar and load combinations. For this analysis, the team considered two daily load profiles (minimum and peak load days) and three solar day types (clear, overcast, and variable). Combinations of these solar and load profiles resulted in six characteristic "days," analyzed under each combination of either fixed power factor or Volt-VAR to produce over 2000 individual simulations. Throughout each simulation, the total losses and reactive power flow were tracked for later analysis.

Given a solar/load combination along with an objective (such as improving circuit power factor), the results may be plotted in a way similar to Figure 3-2 or Figure 3-3. Figure 3-2, for instance, shows that the best Volt-VAR curves for optimizing substation power factor on a clear day with high loading have a setpoint of roughly 0.99 p.u. and a slope of roughly 16% reactive power per volt. Conversely, optimizing for losses on a similar day (Figure 3-3) results in a setpoint of approximately 1.02 p.u. and a slope of 26% reactive power/volt.

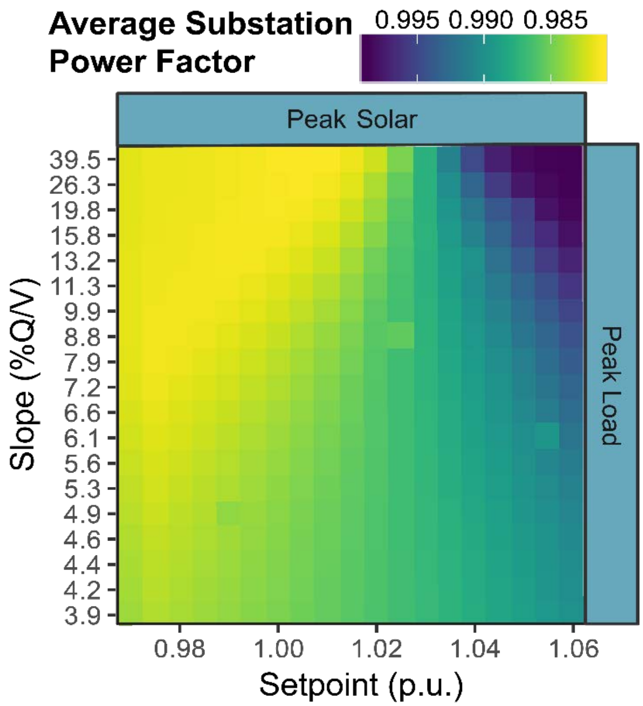

Figure 3-2
Average substation power factor under clear and heavy load conditions on SAR17 varying Volt-VAR slope and setpoint

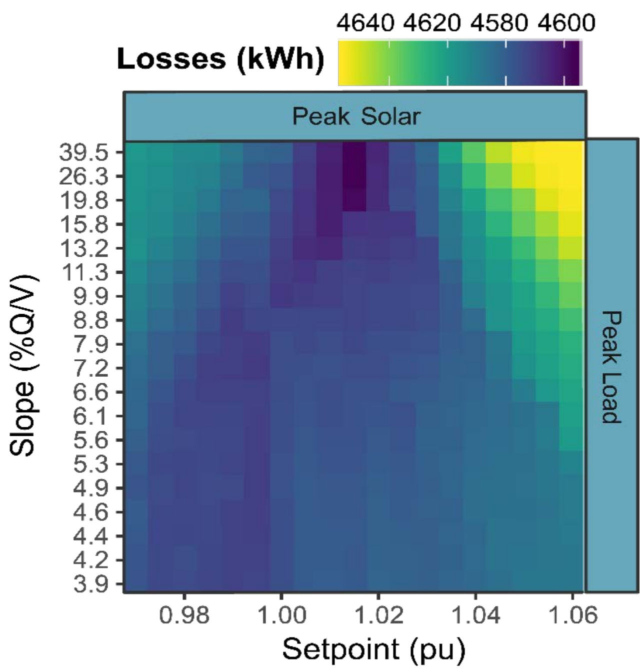

Figure 3-3
Delivery losses under clear and heavy load conditions on SAR17 varying Volt-VAR slope and setpoint

Figure 3-4 and Figure 3-5 show the best settings for each solar/load day for the loss reduction and power factor improvement objectives. These results show that the best settings vary substantially and are more strongly influenced by load level rather than solar output. This indicates that the same setting could be left in place from day to day (that is, regardless of weather conditions); however, there would be some additional value in changing settings seasonally (with load level).

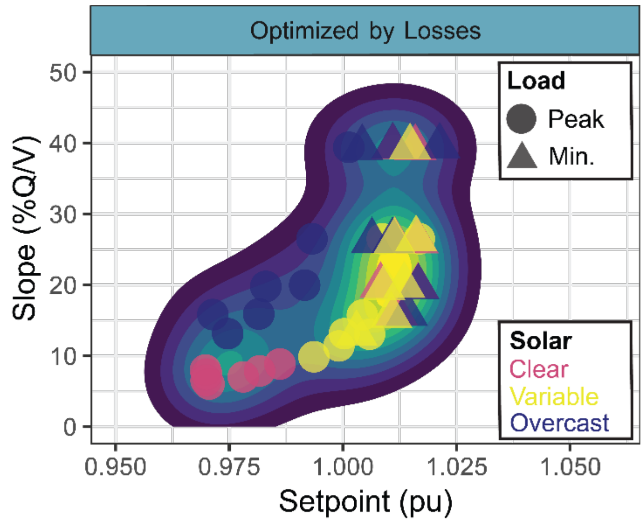

Figure 3-4
"Best" Volt-VAR settings for inverters to reduce delivery losses on SAR17, varying Volt-VAR slope and setpoint

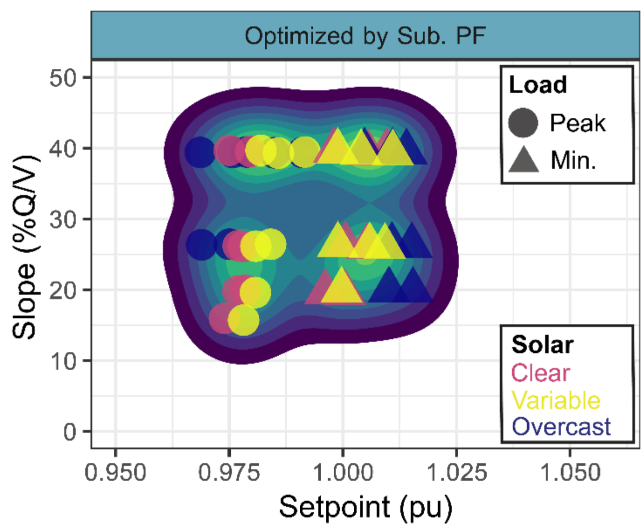

Figure 3-5
"Best" Volt-VAR settings for inverters to improve power factor on SAR17, varying Volt-VAR slope and setpoint

Figure 3-6 and Figure 3-7 show the results of a similar analysis on OLY13. On this feeder, there is much less distinction between the "best" settings for different solar or load combinations as well as performance objective (either loss reduction or substation power factor). A good Volt-

VAR setting could be selected at roughly 0.98 p.u. voltage and a slope of roughly 30% reactive power per unit voltage change. This setting could be left in place continually.

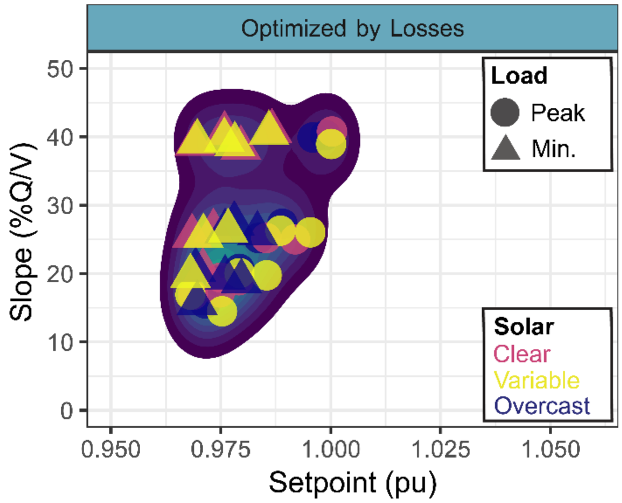

Figure 3-6
"Best" Volt-VAR settings for inverters to reduce delivery losses on OLY13, varying Volt-VAR slope and setpoint

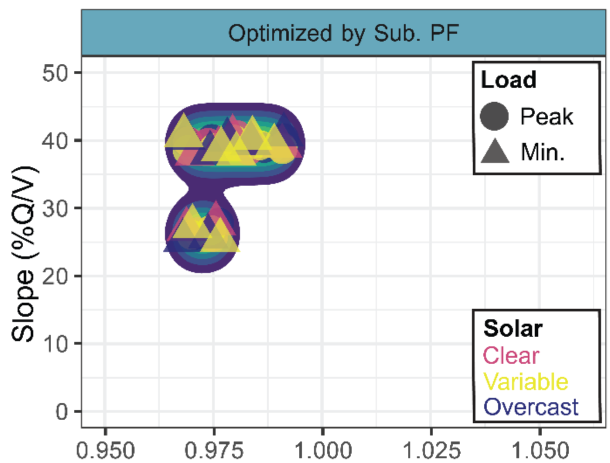

Figure 3-7
"Best" Volt-VAR settings for inverters to reduce delivery losses on OLY13, varying Volt-VAR slope and setpoint

Figure 3-8 compares relative losses with various power factor and Volt-VAR control settings on a clear day with minimum (left) and peak (right) conditions. With a "good" Volt-VAR curve (white marker), the losses are improved roughly 0.5% under either condition. Although fixed power factor settings offer a slight improvement in the minimum load case, they make the losses worse under the peak load conditions. However, the "worst" Volt-VAR setting makes the losses consistently worse than the base case (no power factor control) by approximately 2.0% in the minimum load case and 1.2% in the peak load case.

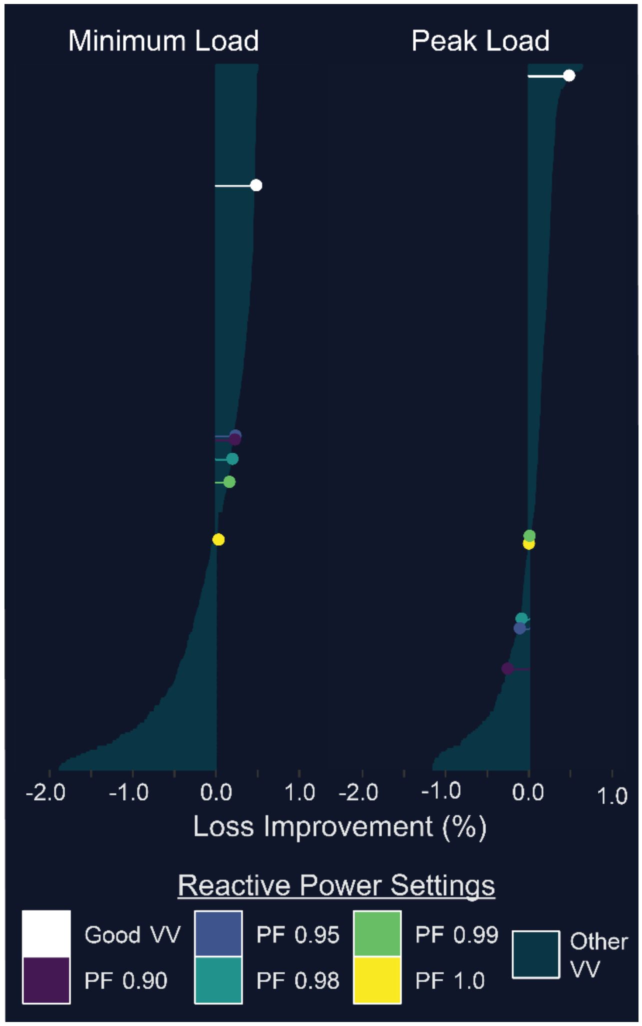

Figure 3-8
Loss reduction from using Volt-VAR and fixed power factor control on SAR17, relative to a base case of unity power factor (gold dot)

Figure 3-9 is a comparison of the losses using the same Volt-VAR curves under differing weather conditions. The selected Volt-VAR curve consistently improved losses under each weather condition: overcast, variable, and sunny (or clear).

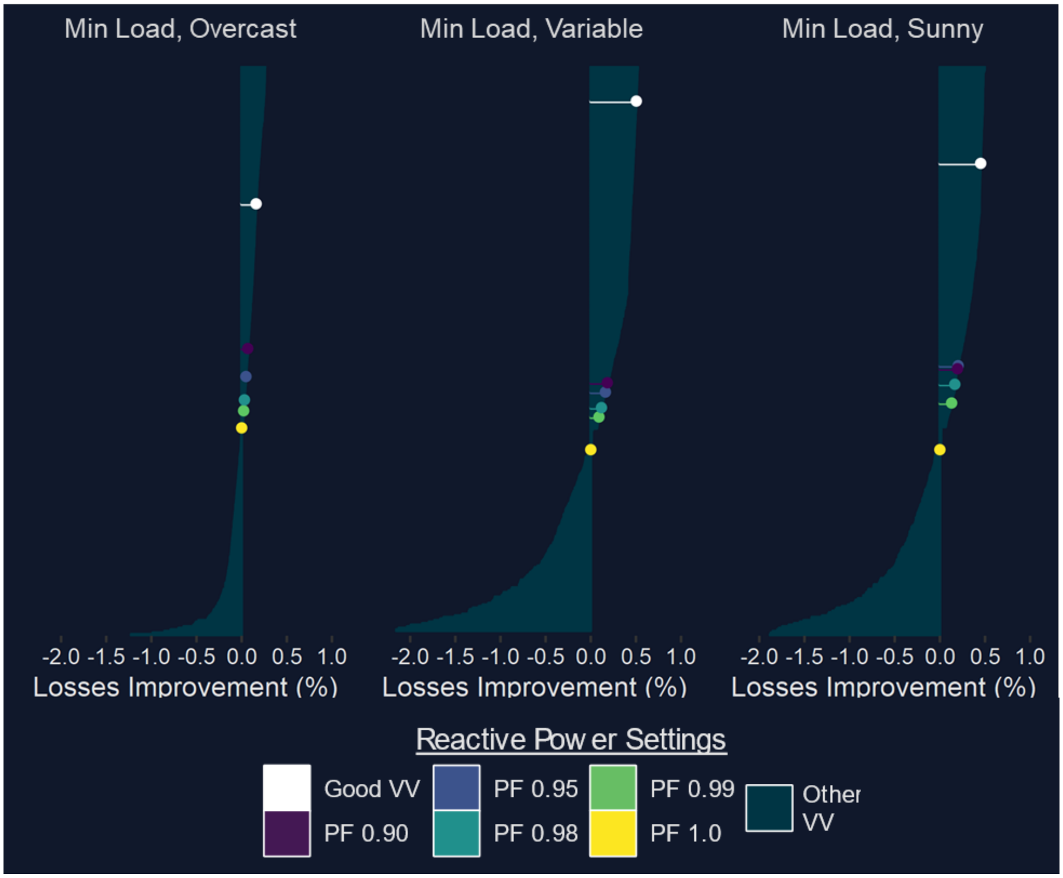

Figure 3-9
Loss reduction comparison with minimum load on SAR17, under different weather conditions

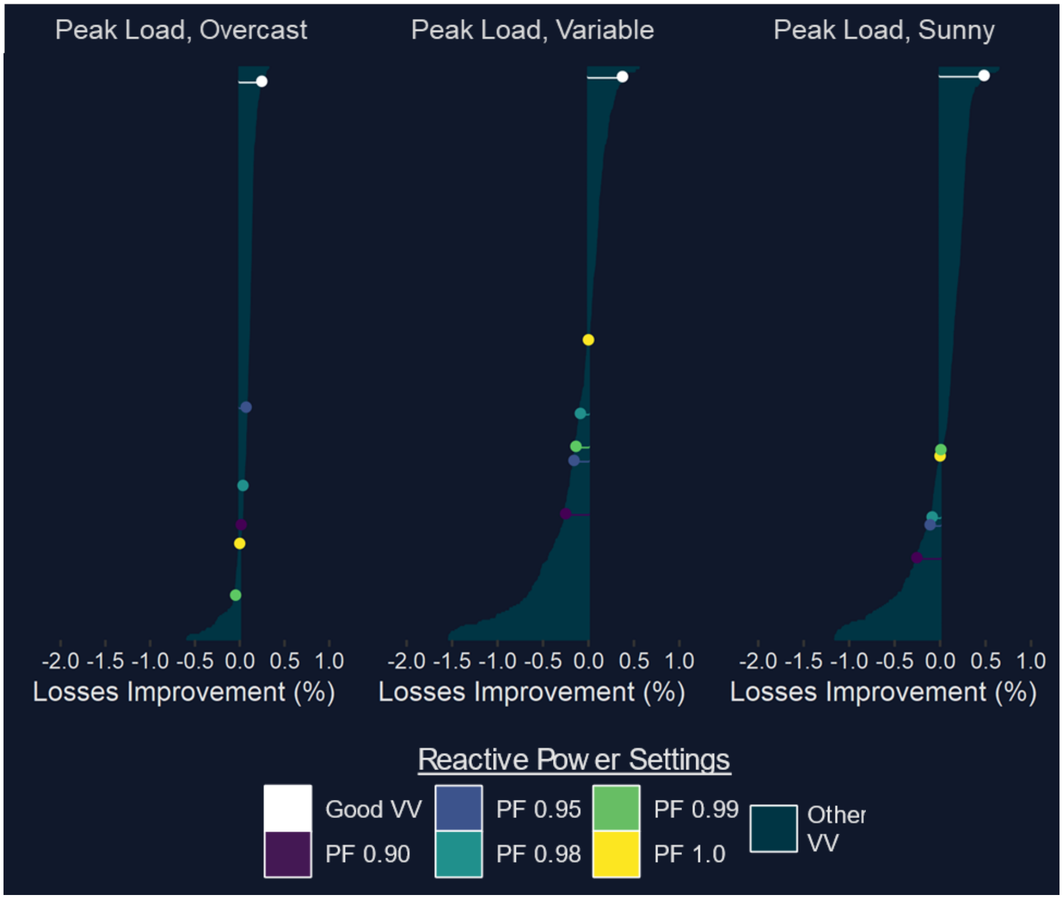

Figure 3-10
Loss reduction comparison with peak load on SAR17, under different weather conditions

Similarly, Figure 3-11 shows the average substation power factor with various Volt-VAR and fixed power factor settings. The "good" Volt-VAR curve consistently improves feeder power factor under all conditions over the base case; however, a poor selection of a Volt-VAR curve can have a significantly negative impact on power factor.

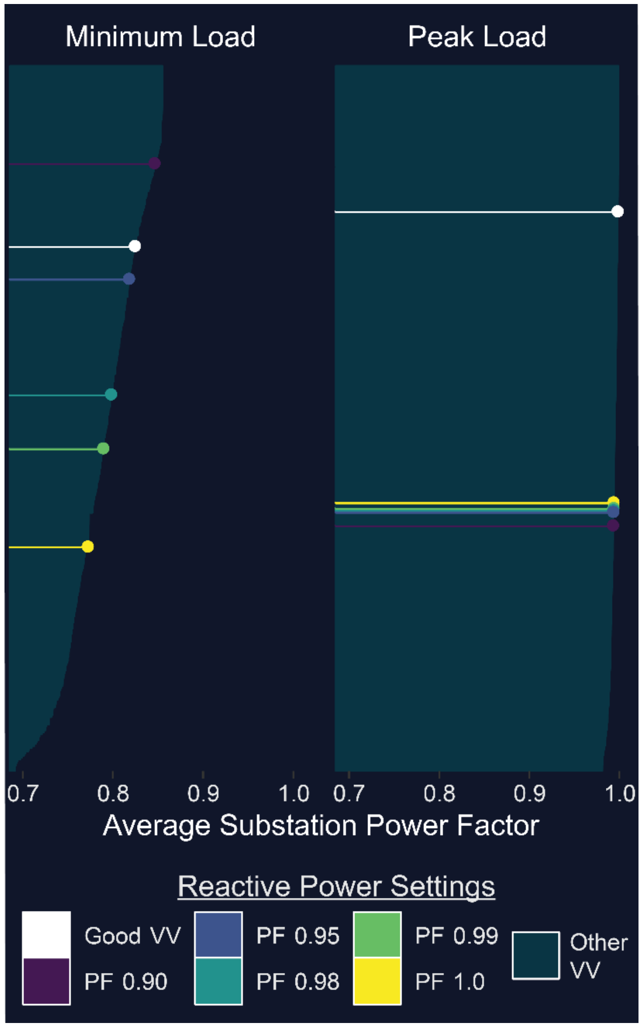

Figure 3-11
Average substation power factor using Volt-VAR and fixed power factor control for PV inverters on SAR17, relative to a base case of unity power factor (gold dot)

A comparison of the impact of Volt-VAR control on substation power factor under different weather conditions is shown in Figure 3-12. Volt-VAR is a general improvement over fixed power factor, with the exception of a clear day, where the 0.9 power factor case is a slight improvement over the selected Volt-VAR curve.

During peak load periods, the impact of inverter Volt-VAR (or reactive power control in general) had a minimal impact on substation power factor on this circuit during the study period.

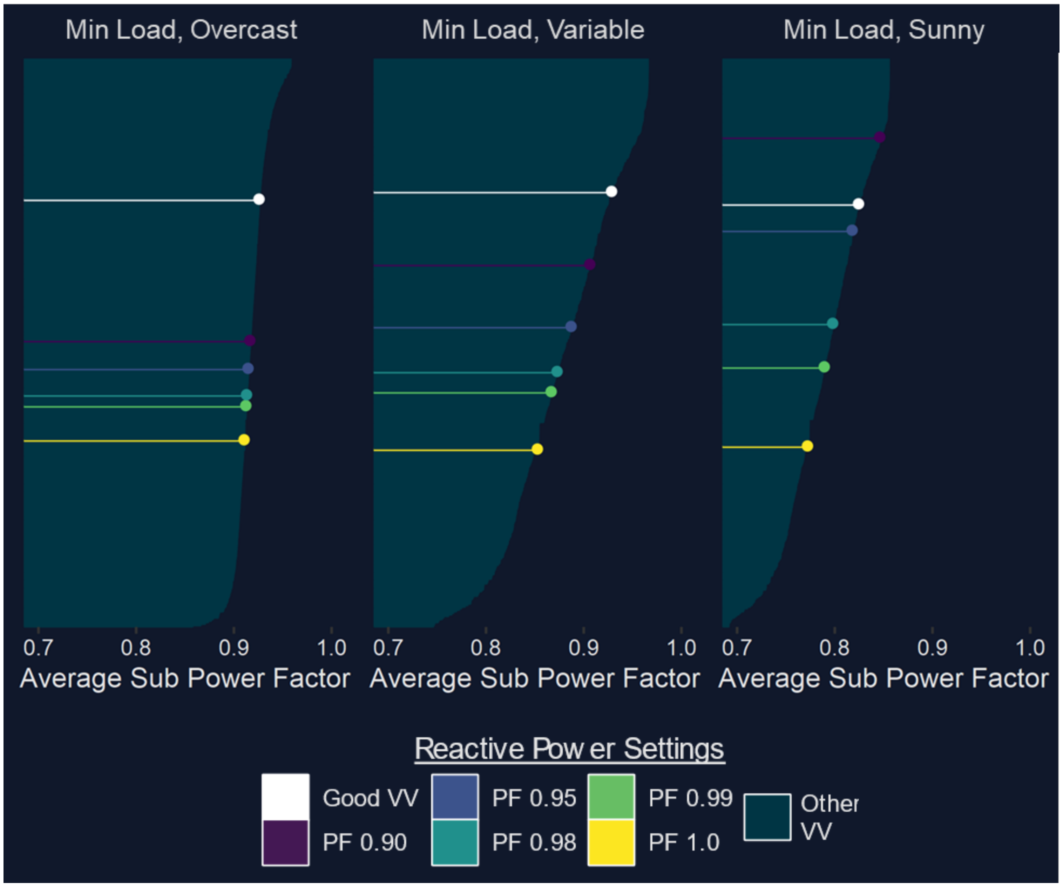

Figure 3-12
Average substation power factor comparison with minimum load on SAR17

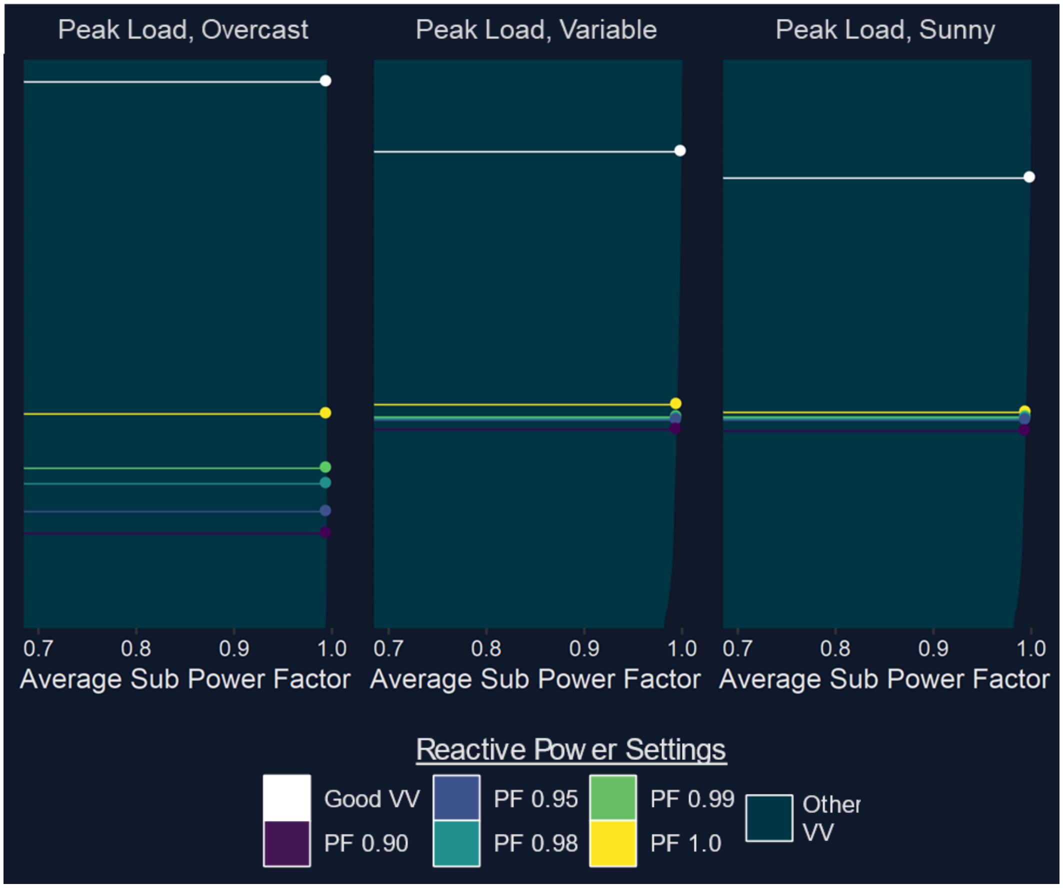

Figure 3-13
Average substation power factor comparison with peak load on SAR17

4
INTERCONNECTION POLICIES

Policy 138 is PacifiCorp's official DER interconnection policy, covering both inverter-based and rotating generators. According to the document, it includes "technical requirements for establishing and maintaining (generator) interconnections…." As such, the document references (and in some cases replicates) material from existing interconnection standards and testing guidelines, such as IEEE 1547 and UL 1741, as well as PacifiCorp's own engineering guides. The policy applies to any distribution-connected generator, regardless of MVA rating.

Because IEEE 1547 has undergone its largest revision to date, it is prudent to review Policy 138 with respect to the items that have changed significantly in the IEEE standard: voltage regulation, ride-through, power quality, and communication. Rather than a line-by-line review of the document, the following sections will highlight key changes and the clauses in Policy 138 (or elsewhere) that may need to be modified for alignment with recent revisions of IEEE 1547. Some content may require further discussion (such as ride-through settings) at PacifiCorp before finalizing content.

Voltage Regulation

With the 2018 revision,[1] the IEEE 1547 working group completely reversed one of the strictest positions in the 2003 edition of their standard. Instead of forbidding DER from providing voltage regulation, the 2018 standard requires the capability of voltage regulation functions such as Volt-Watt and Volt-VAR. Language that referred to this provision may need to be loosened (such as Section 1.6.3.1 in Policy 138) if these new functions are to be used to support PacifiCorp's distribution network. Some explanation of the functions required may be helpful in Policy 138.[2]

While it may be premature to recommend that these functions be enabled by default in Policy 138, the document should allow the ability to revisit settings or enable these functions later. In the meantime, the maximum capabilities required (Category A or B in the IEEE standard) should be specified by PacifiCorp.

Voltage and Frequency Ride-Through

Similar to voltage regulation, IEEE 1547-2018 relaxes a previously strict limitation of DER to remain connected and provide support to the grid during disturbances. This limitation was likewise reflected in Policy 138 (Section 1.6.3.2). While the language here is still applicable even under the new standard, the default limitations have been expanded—allowing the inverter to remain connected for longer periods. In addition, DER are now required to remain connected during shorter (or less severe) disturbances. The exact length of this requirement, or ride-through period, should be determined by PacifiCorp and included for reference.

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[1] *Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, IEEE Standard 1547-2018, 2018.

[2] Though fixed power factor was not excluded as "voltage regulation" in the previous IEEE 1547-2003 standard, it is unclear whether it falls under the current wording of this section and needs to be expressly referred to here.

IEEE 1547-2018 has provided several example categories that align with ride-through requirements from the North American Electric Reliability Corporation (NERC) (Category II) and California's Rule 21 (Category III). Tables 6.3.1 and 6.3.2 in Policy 138 should be updated to reflect the new ride-through and updated disconnect requirements.

Power Quality

Though power quality is ultimately the responsibility of the utility, proper DER behavior can help ensure that this is maintained for other customers. Four key areas affect DER:

- **Harmonics**: injection of power at frequencies other than the system frequency (60 Hz) can cause customer equipment to misbehave or cause excessive heating in nearby power system components. Requirements of harmonic current injection are consistent between the PacifiCorp Engineering Handbook 1C.4.1, *Harmonic Distortion*, and IEEE 1547-2018. The latter, however, did change its vocabulary from a rating of *total demand distortion (TDD)* to *total rated distortion (TRD)* for clarity.
- **Flicker**: repetitive changes in grid voltage (slower than 60 Hz) that are visible in customer lighting, typically caused by fluctuating generation and load. In 2003, IEEE 1547 did not have specific requirements for flicker. The 2018 revision adds generator and facility requirements that are stricter than PacifiCorp allows in Policy 138 (in reference to PacifiCorp Engineering Handbook 1C.5.1, *Voltage Fluctuation and Flicker*) for individual generators.
- **Rapid voltage change (RVC)**: transient (that is, not repetitive) changes in grid voltage. These may upset customer loads (causing them to trip offline) or interfere with utility regulating equipment and are typically caused by sudden events, such as frequently energizing transformers. This is a new requirement added in 2018. RVCs should be limited to no greater than 3% when measured at the medium-voltage level (or 5% at the low-voltage level).
- **Temporary overvoltage**: sudden increase in voltage (particularly phase-neutral) caused by a generator becoming *islanded*—separated from the rest of the local power system—and either a line-ground fault (called *ground-fault overvoltage* [GFO]) or a rapid load disconnection (called *load-rejection overvoltage* [LRO]). IEEE 1547-2018 adds guidance limiting the contribution of DER during transient conditions resulting from events such as faults and open phases. These limits will likely be enforced as a "type" test done at the factory.

5
UTILITY PRACTICES FOR INVERTER RIDE-THROUGH AND COMMUNICATIONS

Utility Practices for Communications with DER

The latest IEEE 1547 revision referenced three open communication protocols: SunSpec Modbus, IEEE 1815 (DNP3), and IEEE 2030.5 (SEP2.0). DER are required to support at least one of these protocols in addition to any other protocols they support. These connections are required to be available at the interface to either the individual DER or the combined plant.

- **SunSpec Modbus**: a simple protocol with origins in industrial control. Modbus is implemented by almost all inverter manufacturers and is often used at least for local control. The protocol itself, though transportable over TCP/IP, is not securable at the protocol level and requires security at another level (such as a VPN). Though it is used extensively by device manufacturers and aggregators, utility use has been limited to mostly pilot projects (examples include Arizona Public Service's Solar Partner Program and Salt River Project's Advanced Inverter Pilot).
- **DNP3**: another industrial control protocol often used by utilities in their supervisory control and data acquisition (SCADA) networks. Typically only available in larger, centralized PV plants, this protocol is often preferred for applications in which the DER are being directly integrated into the utility network. Secure authentication is now available in DNP3-SA; however, implementation of this is recent and limited.
- **SEP2.0**: an XML-based protocol with origins in home area networking (Zigbee). SEP2.0 is not normally supported by inverters and may require some form of adapter. The largest market for SEP2.0 is California, where it is being proposed primarily for utility-to-aggregator communications for DER. The protocol borrows many elements from modern internet protocols (such as certificate-based security) and is well-suited to those applications. However, the bandwidth required may overwhelm other, more dedicated communication paths such as advanced metering infrastructure (AMI). Use of the protocol is expected to continue to expand with the implementation of California's Phase III Smart Inverter functions.

Utility Practices for Inverter Ride-Through

Prior to IEEE 1547-2018, the State of California and Hawaiian Electric had already implemented inverter ride-through as part of their interconnection rules (Rule 21 and Rule 14H, respectively). Both implementations were led by stakeholder working groups: the Smart Inverter Working Group (SIWG) in California and the Reliability Standards Working Group (RSWG) at Hawaiian Electric.

- **California**: ride-through of both voltage and frequency events is required of inverters installed after September 2017.[3] Frequency ride-through requirements are like those of IEEE 1547-2018; voltage ride-through requirements are most like those of Category III.[4]
- **Hawaii**: ride-through capability is required of systems installed after January 2016.[5] Frequency ride-through and trip settings are wider than those of IEEE 1547-2018 to better coordinate with the realities of an island grid. Ride-through is required indefinitely if the frequency is between 57 Hz and 63 Hz.[6] DER are permitted to trip if the frequency drops below 56 Hz. Voltage ride-through requirements are like those of California, except that ride-through is not required below 50% of nominal voltage.

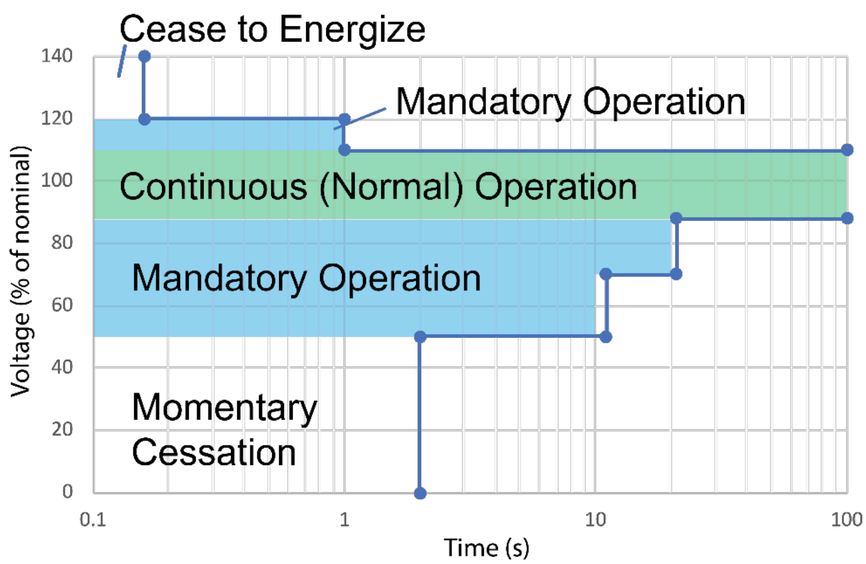

Figure 5-1
Hawaiian Electric Rule 14H voltage ride-through requirements

Since the approval of IEEE 1547-2018, the following system operators have begun efforts to implement ride-through for DER in their territories:

- **ISO New England**: now requires inverter manufacturers to certify IEEE 1547 ride-through requirements (Category II, shown in Figure 5-2) through the UL 1741 SA process.[7]

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[3] http://www.cpuc.ca.gov/General.aspx?id=4154

[4] https://www.pge.com/tariffs/tm2/pdf/ELEC_RULES_21.pdf.

[5] https://www.hawaiielectriclight.com/documents/products_and_services/customer_renewable_programs/advanced_inverters_oct_2016.pdf.

[6] https://www.hawaiianelectric.com/Documents/clean_energy_hawaii/producing_clean_energy/attachment1_trovandfvrt_public_nov2015update2.pdf

[7] https://www.iso-ne.com/static-assets/documents/2018/02/a2_implementation_of_revised_ieee_standard_1547_iso_source_document.pdf.

- **PJM Interconnection**: recently began stakeholder processes. The current proposal being discussed recommends Category II performance with slight modification.[8]
- **Xcel Energy (Minnesota)**: finishing a year-long stakeholder process and beginning smaller breakout sessions; also leaning toward a Category II implementation.
- **Midcontinent ISO**: just beginning stakeholder process.

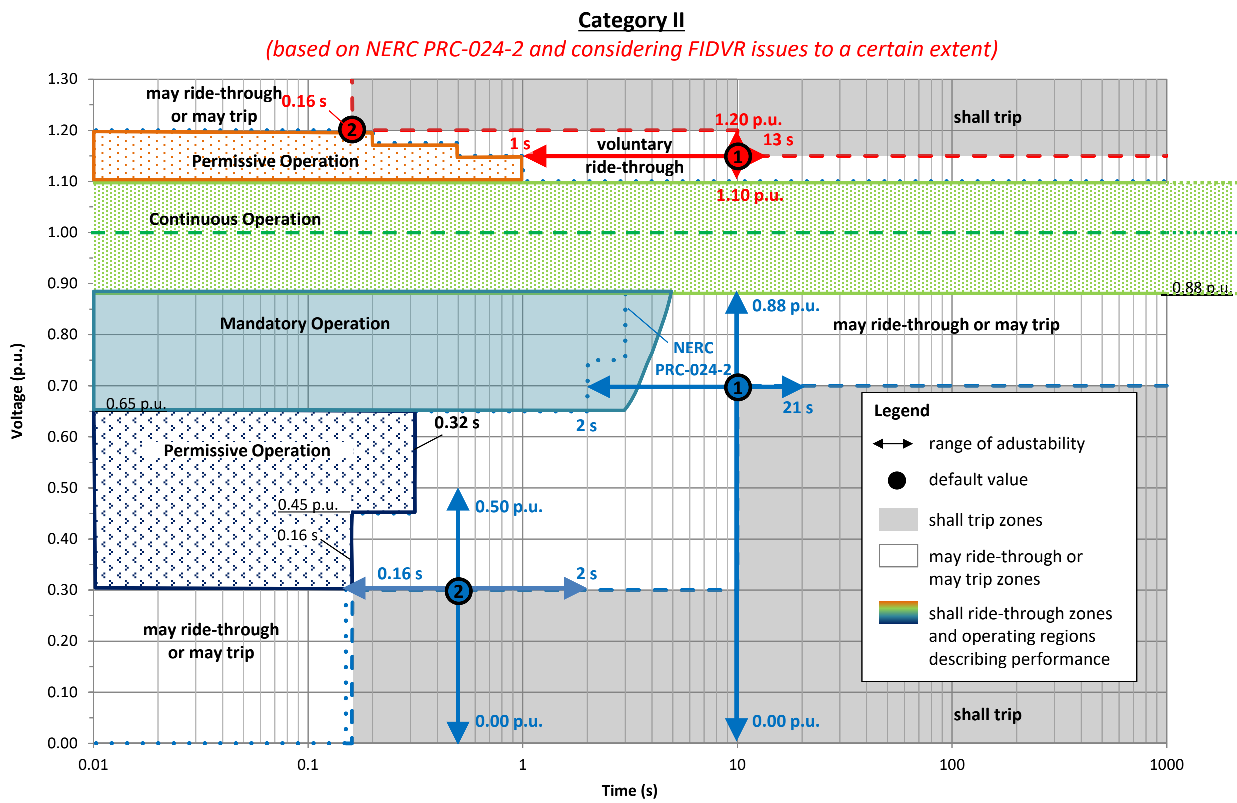
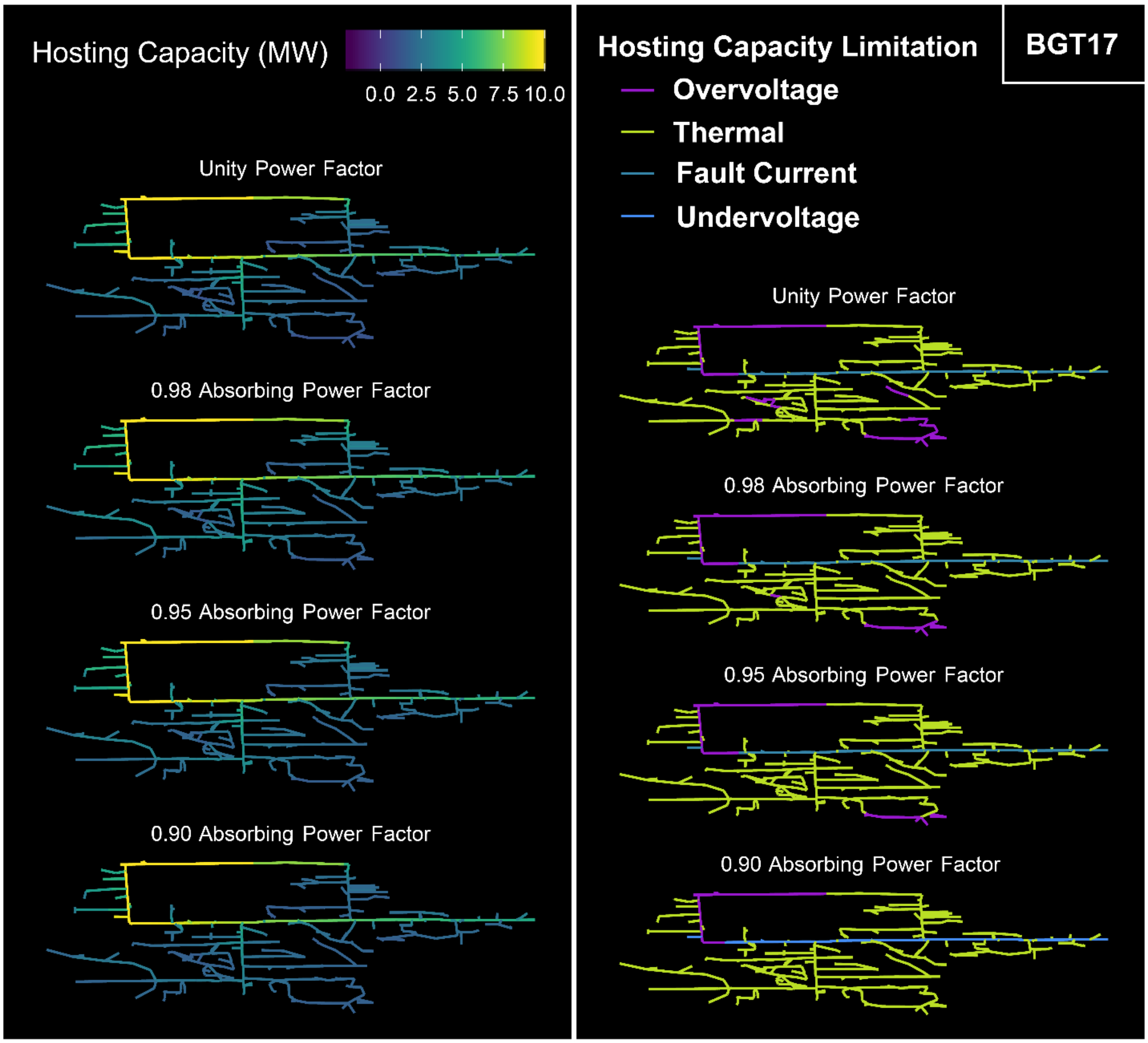
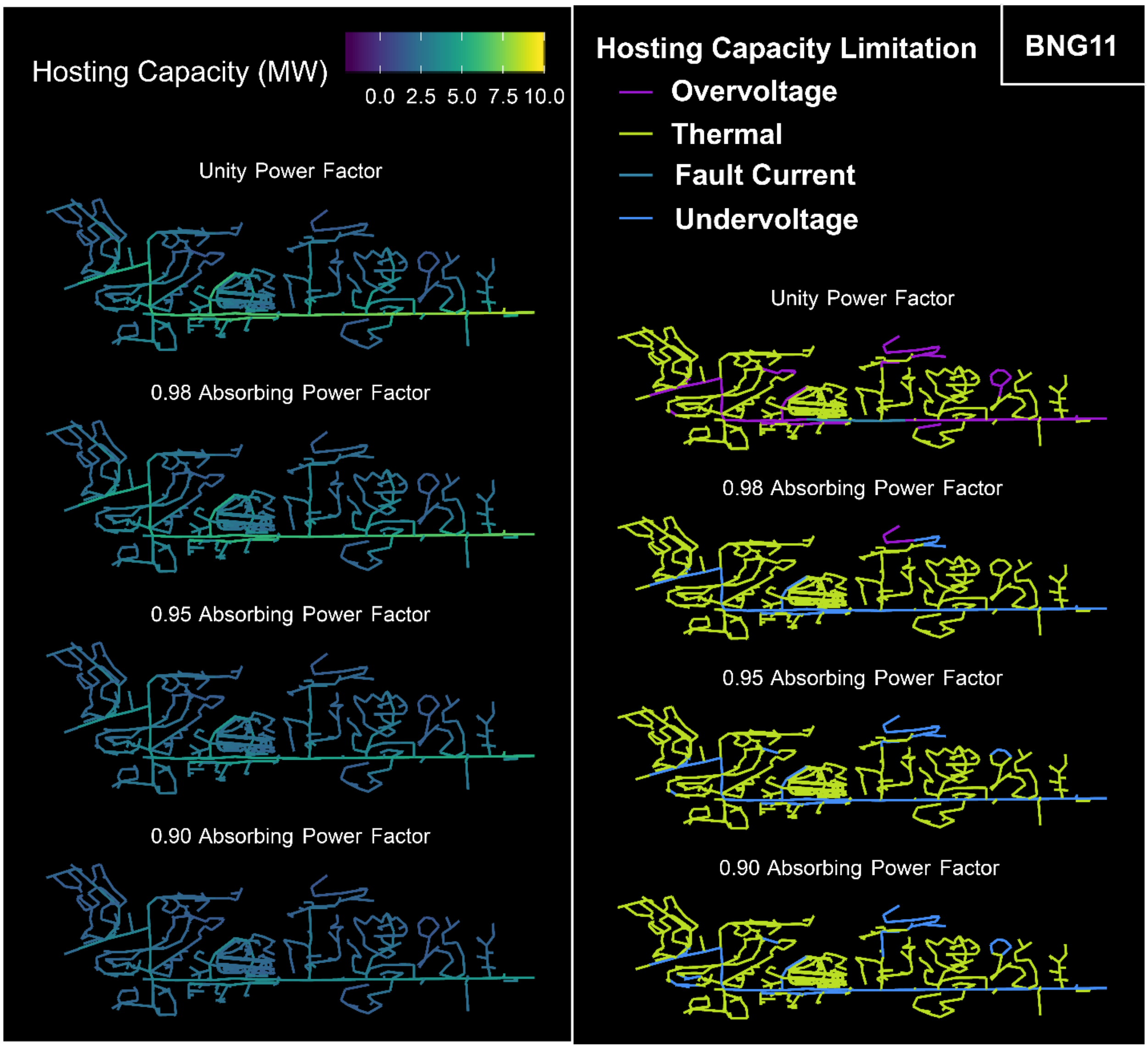


Figure 5-2
IEEE 1547-2018 Category II voltage ride-through requirements

[8] https://www.pjm.com/-/media/committees-groups/stakeholder-meetings/ride-through-workshop/2018-der-ride-through-strawman-proposal.ashx?la=en.

A
HOSTING CAPACITY - DETAILED RESULTS (NO RETROFIT)

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Thermal
Fault Current
Undervoltage
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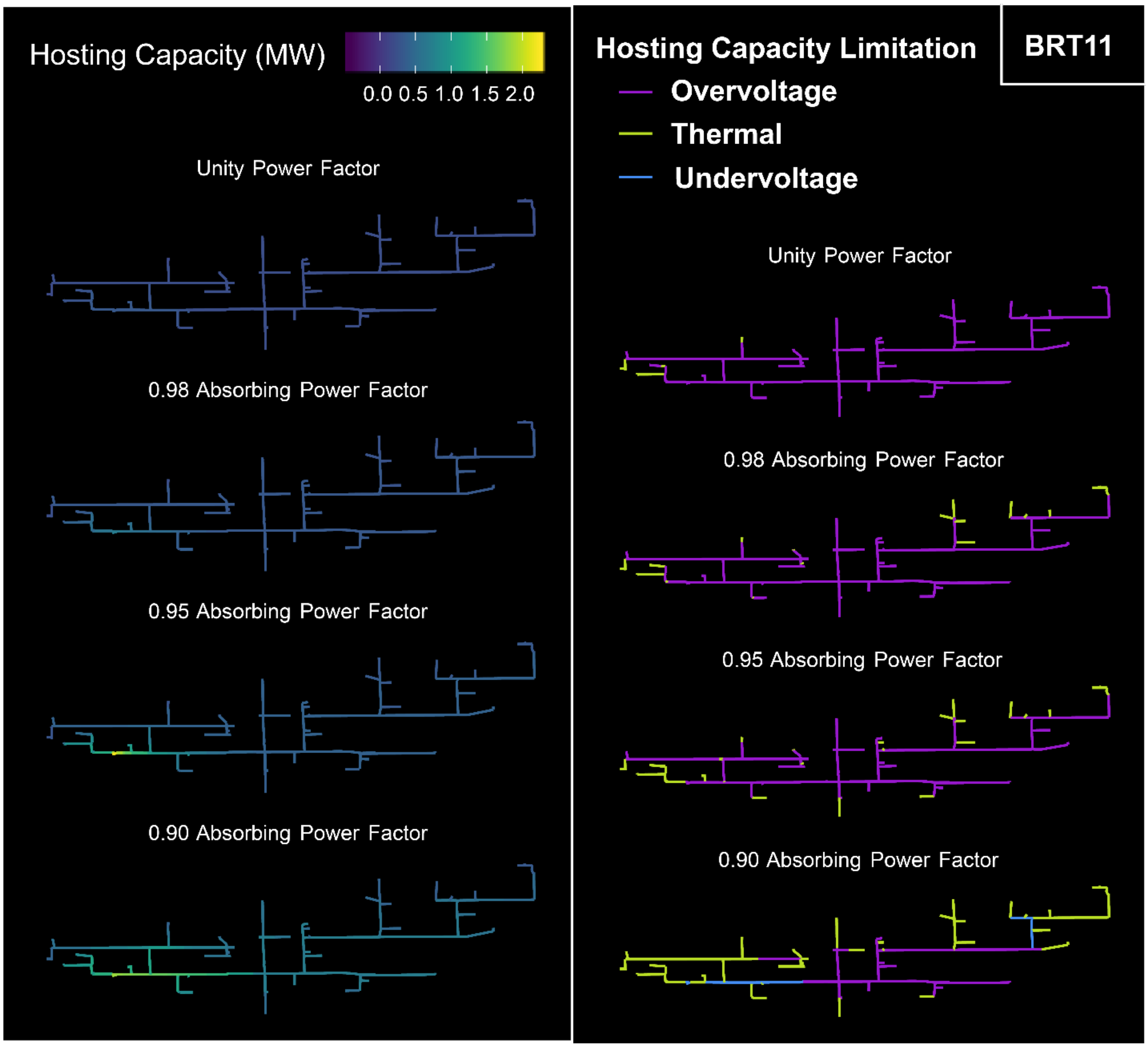
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Thermal
Undervoltage
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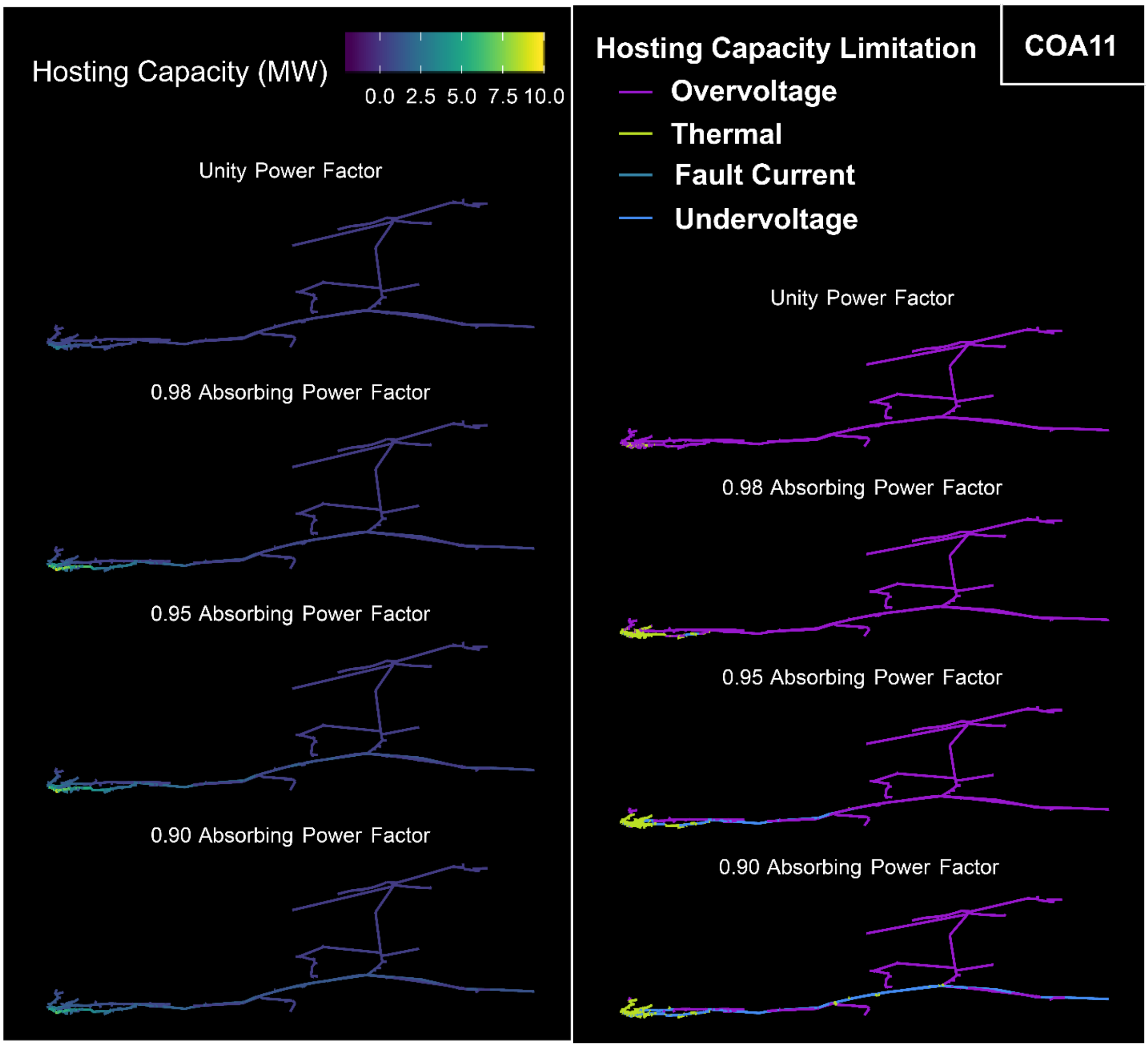
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Thermal
Fault Current
Undervoltage
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Unity Power Factor
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Hosting Capacity (MW)
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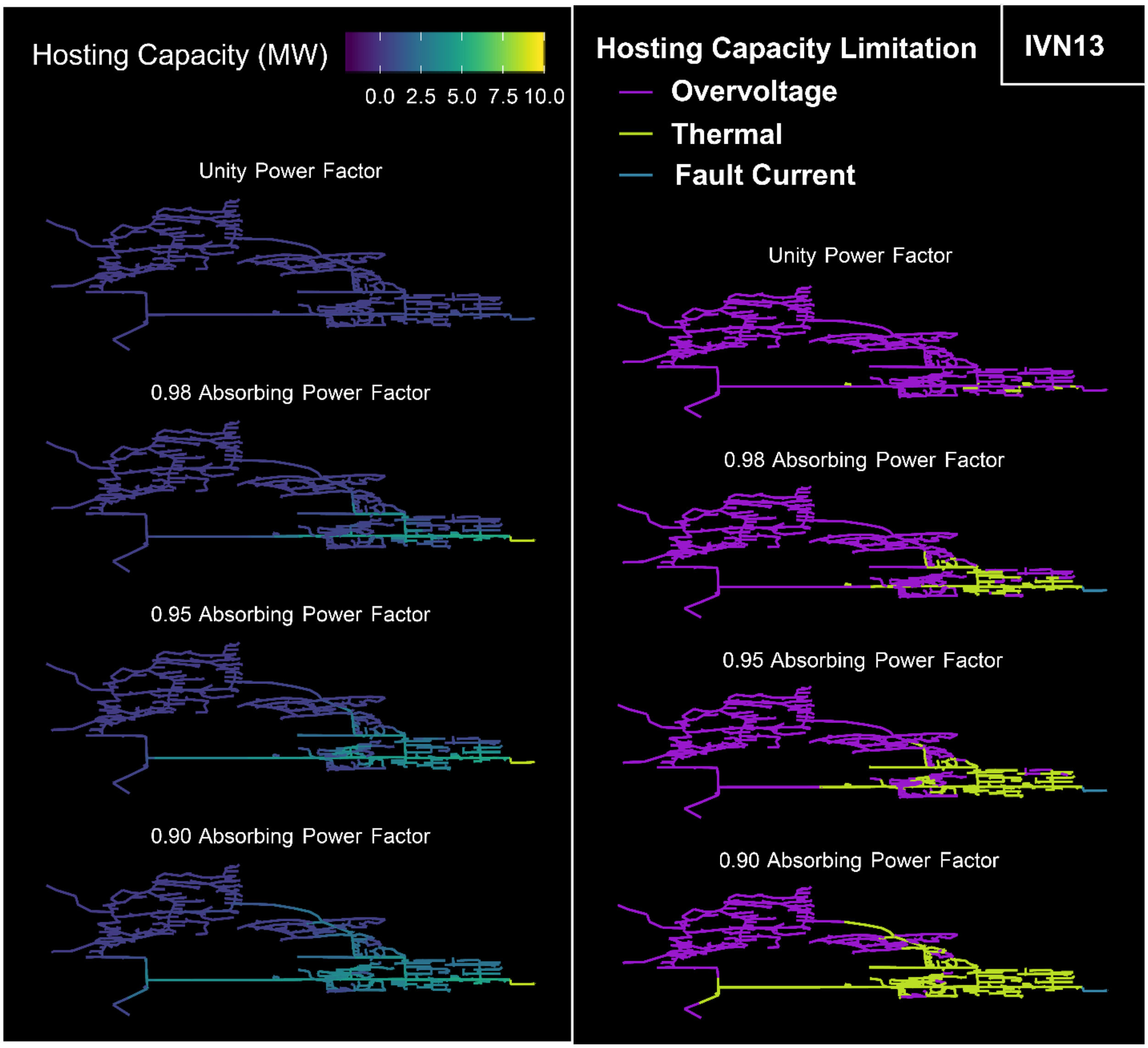
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Fault Current
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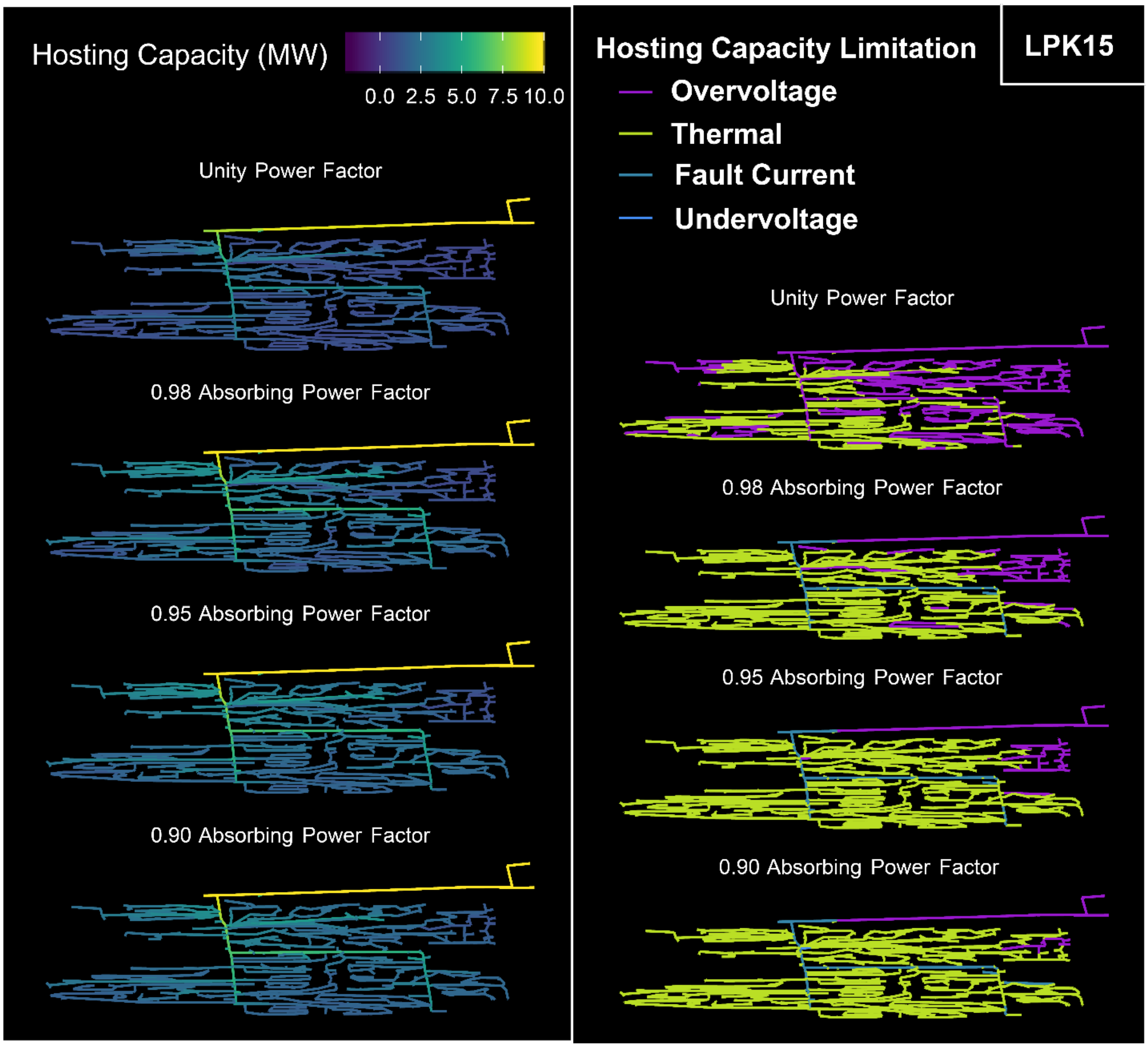
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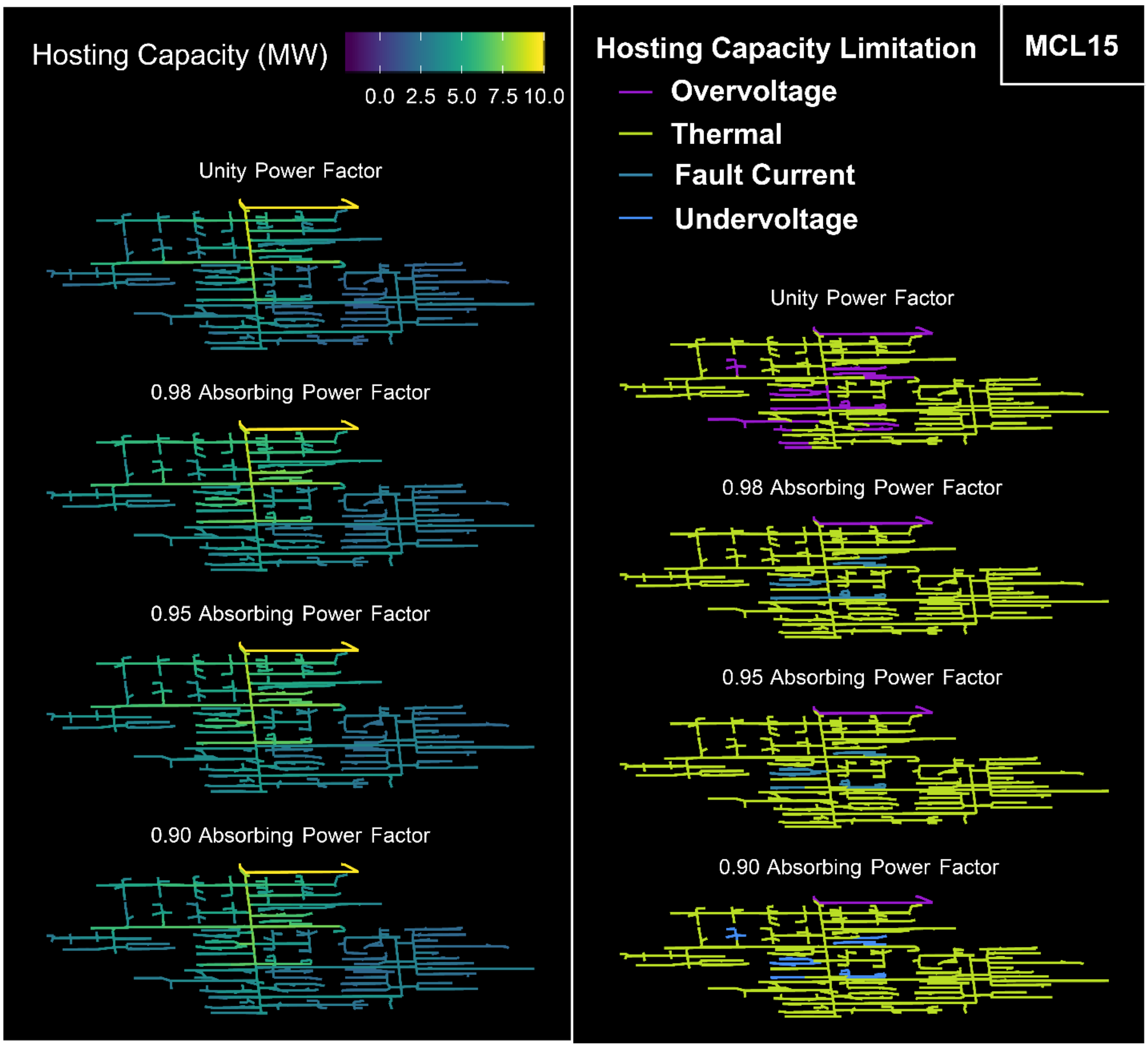
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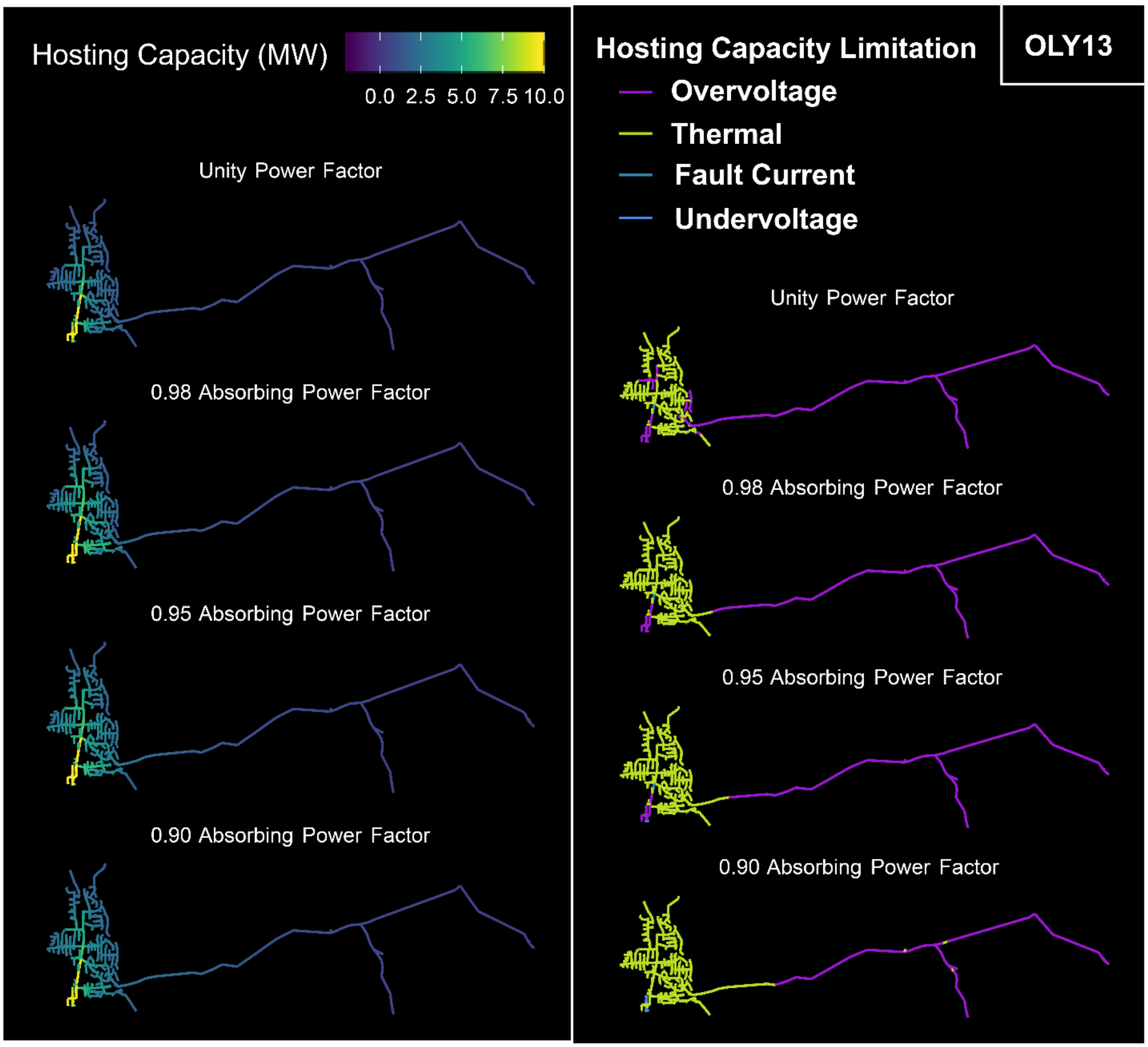

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Hosting Capacity Limitation
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OLY13
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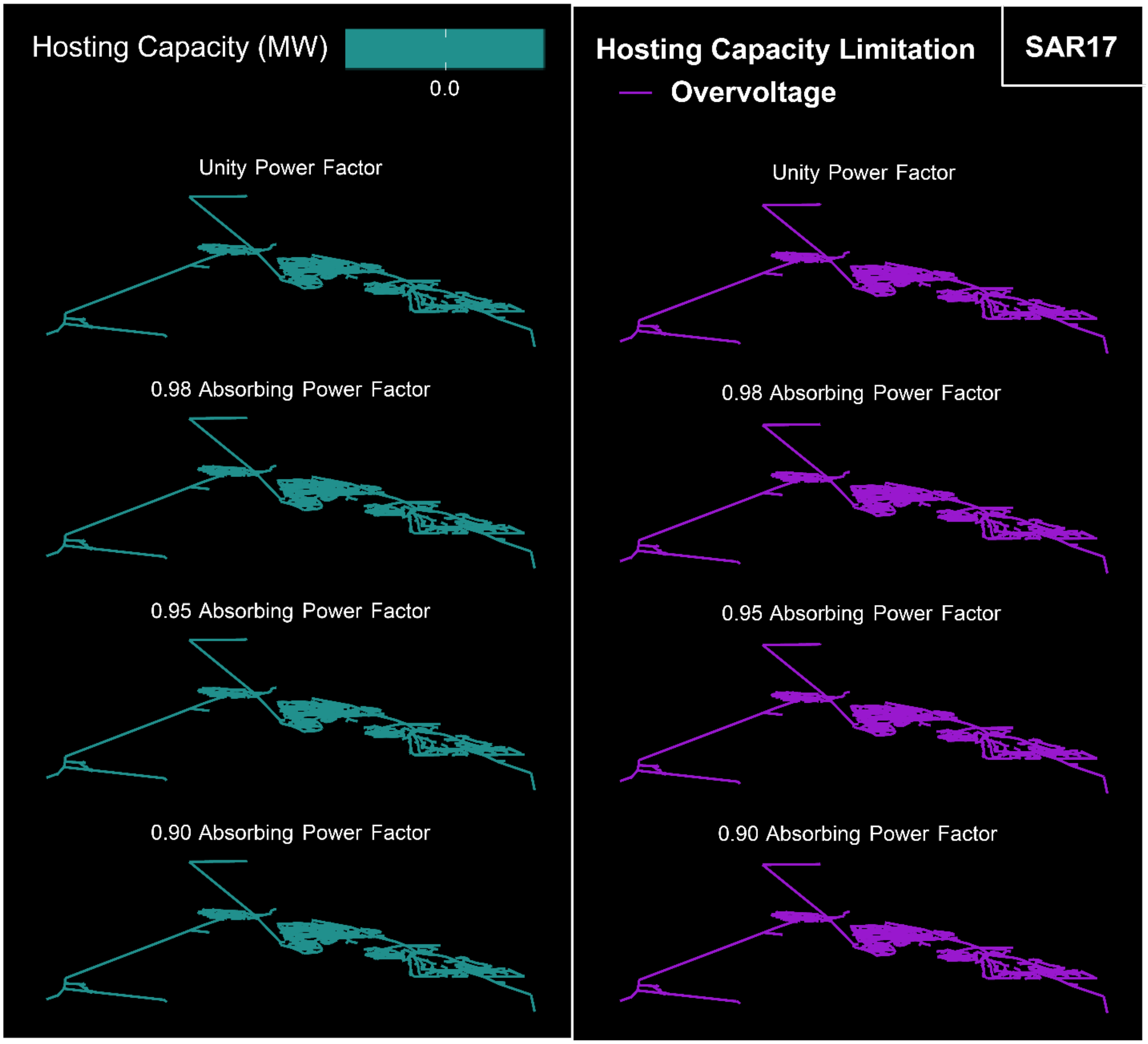
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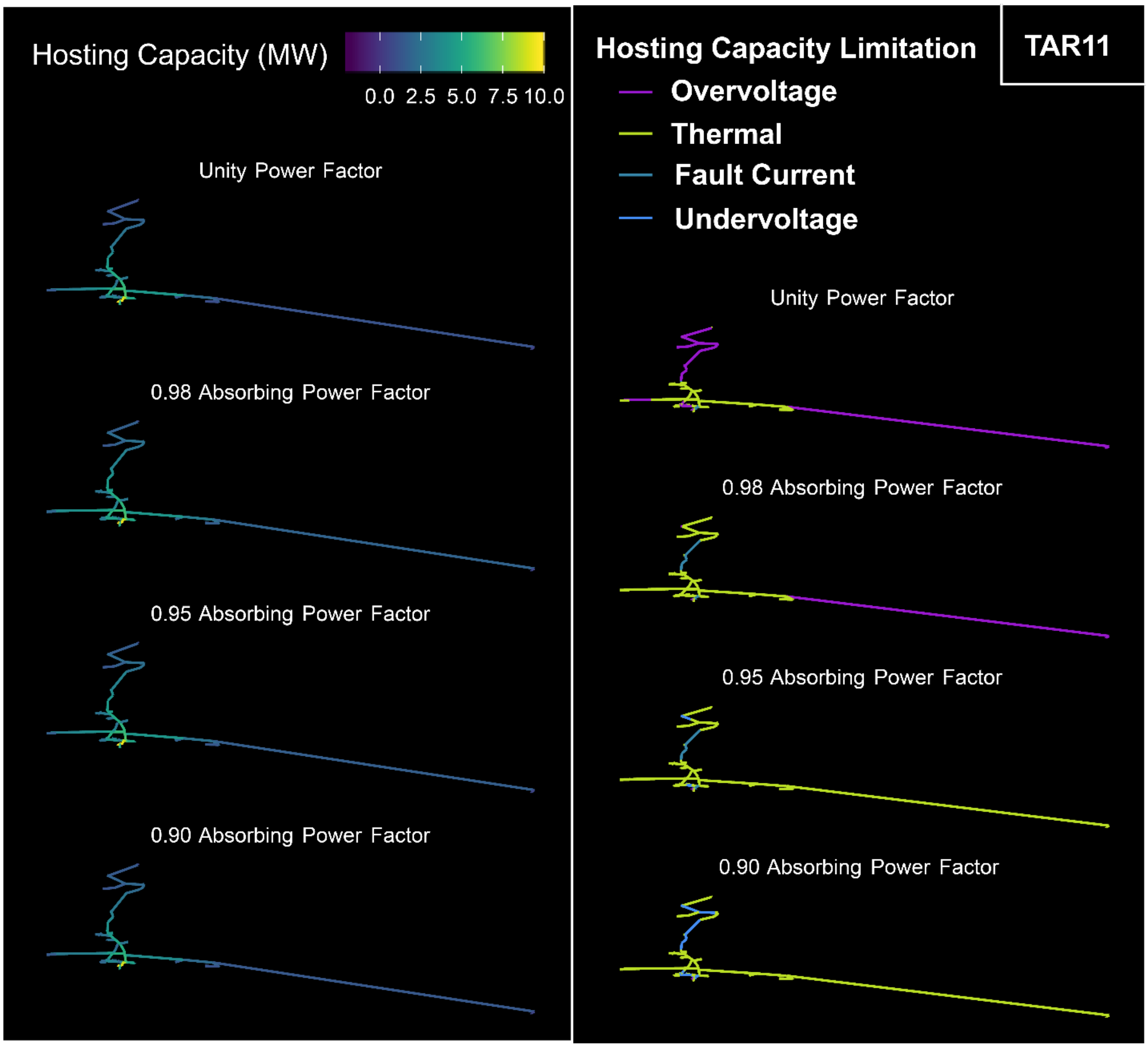
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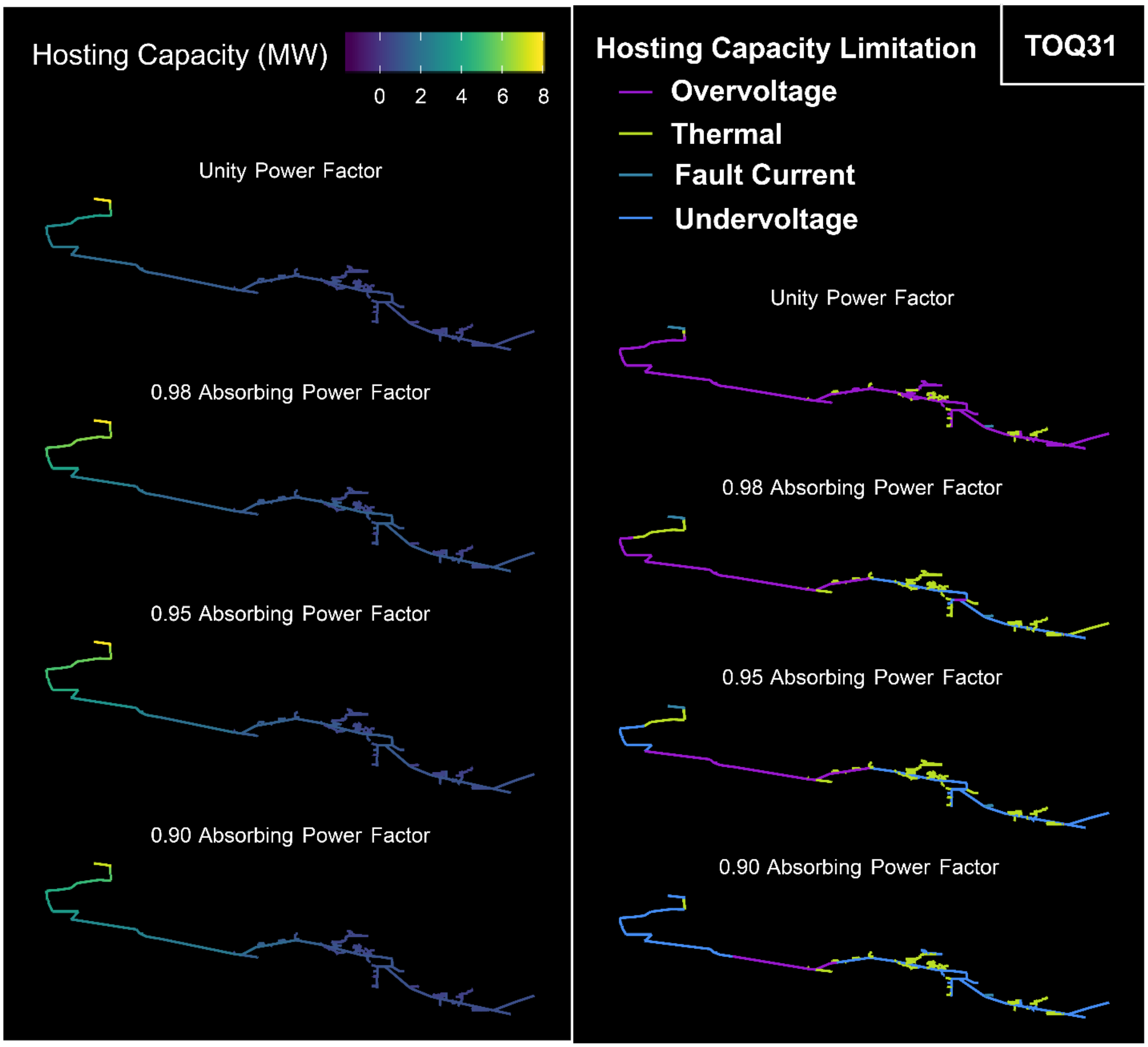
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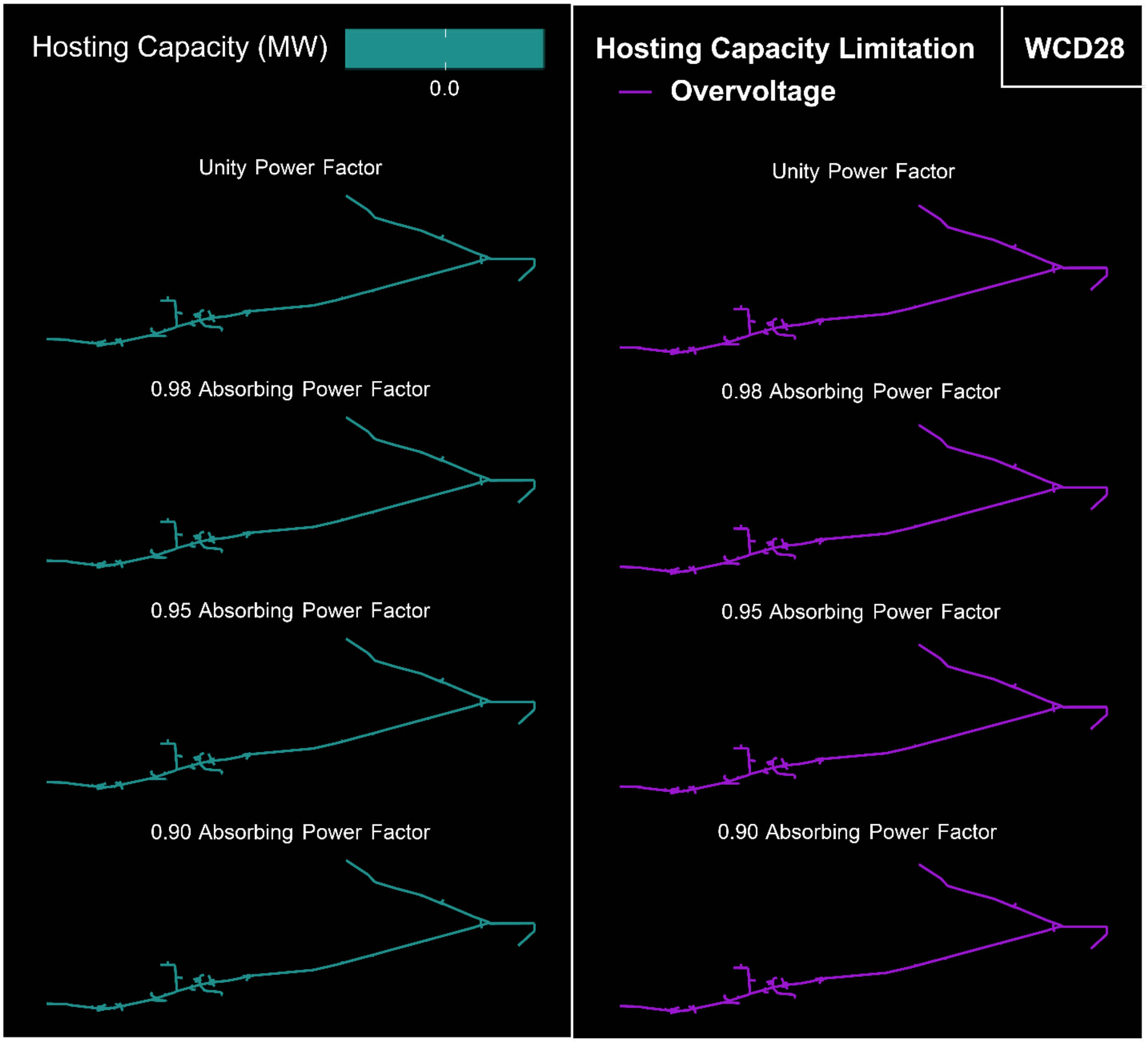
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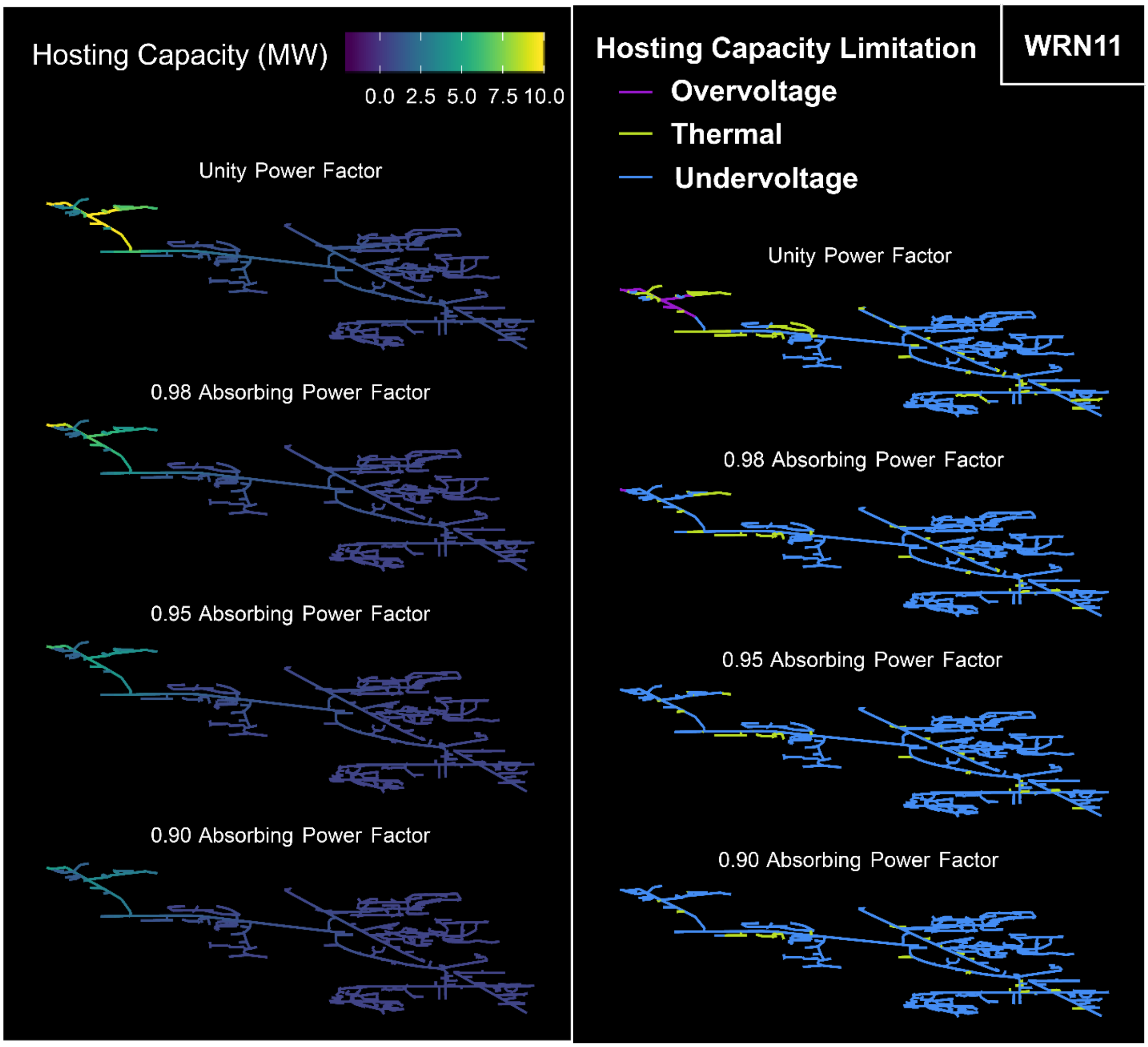
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WRN11
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Thermal
Undervoltage
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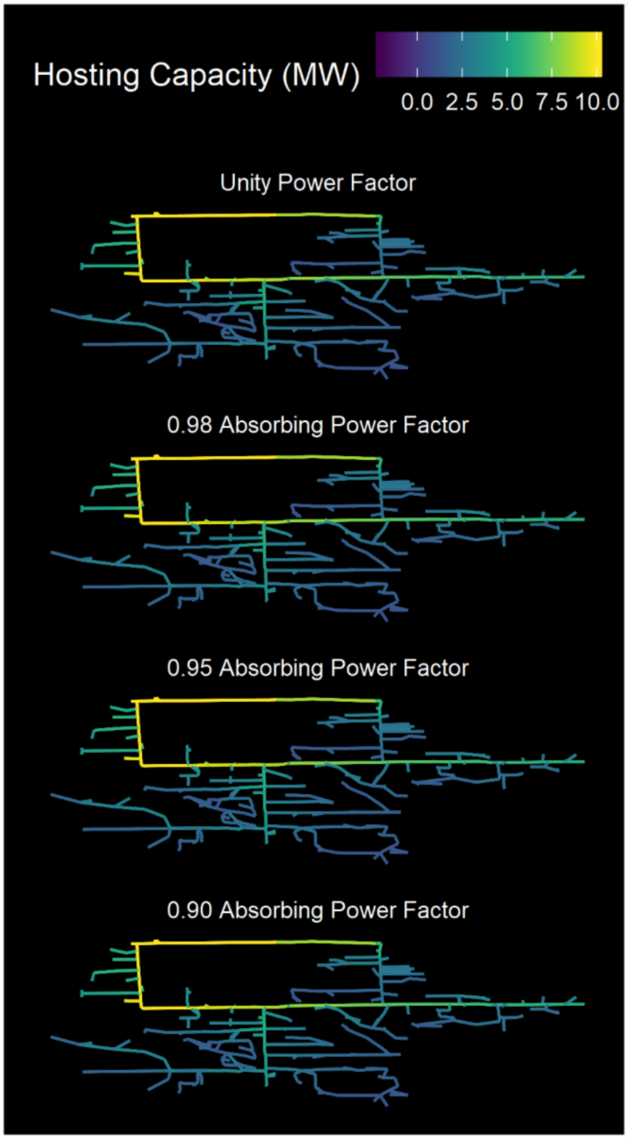
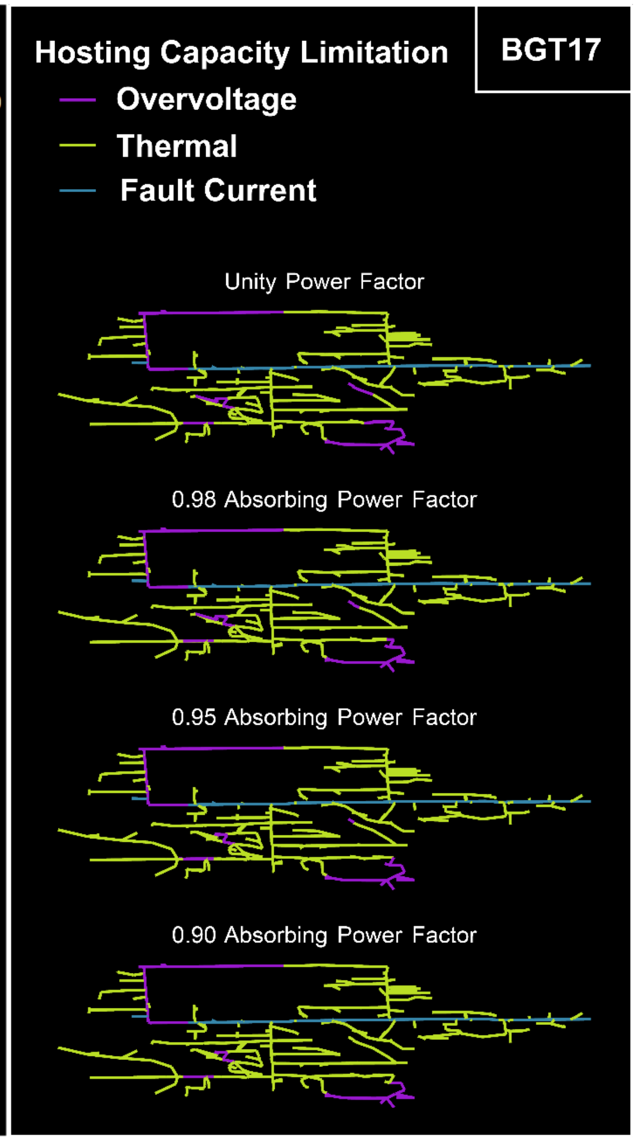
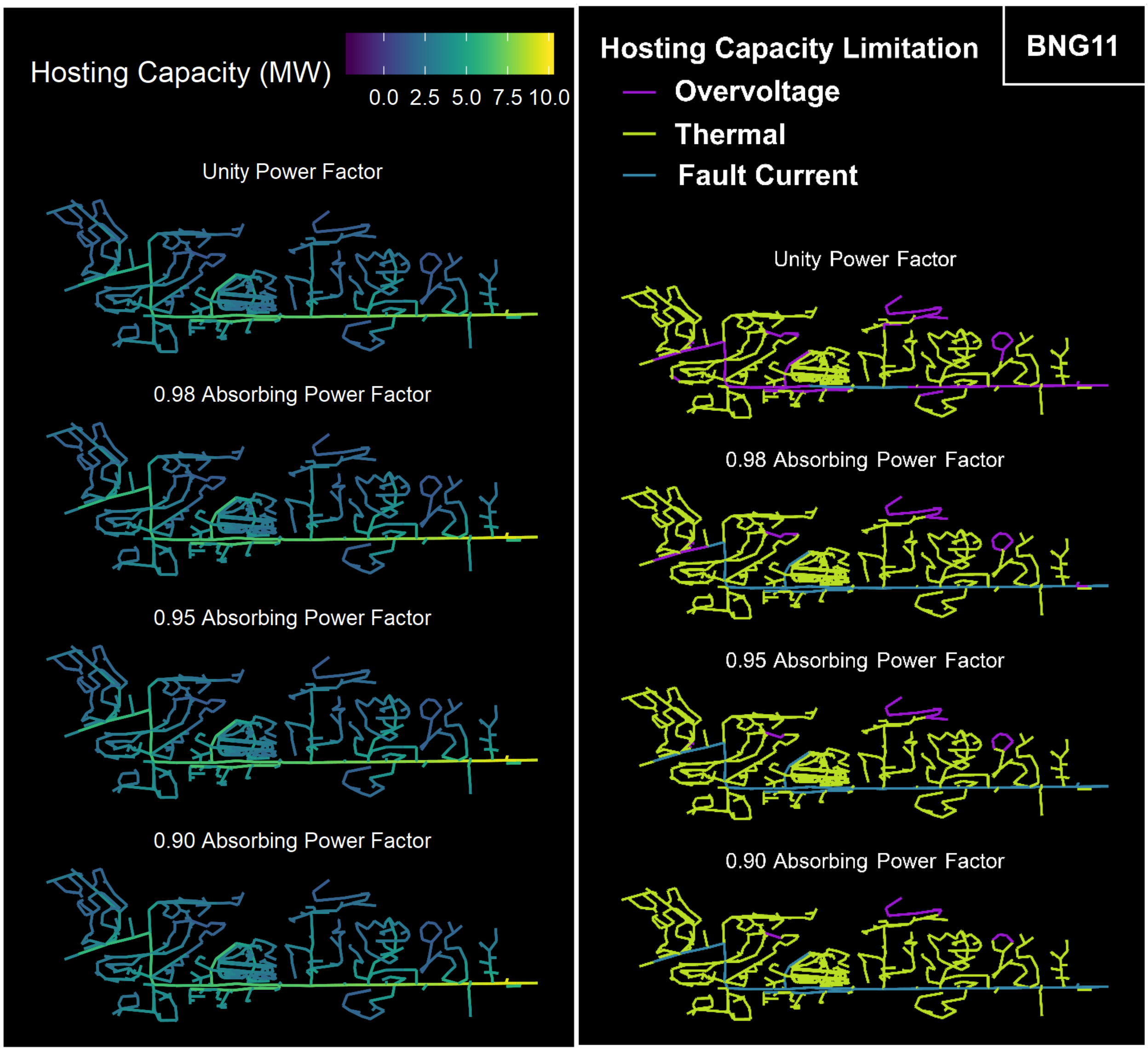
B
HOSTING CAPACITY - DETAILED RESULTS (RETROFIT-ONLY)



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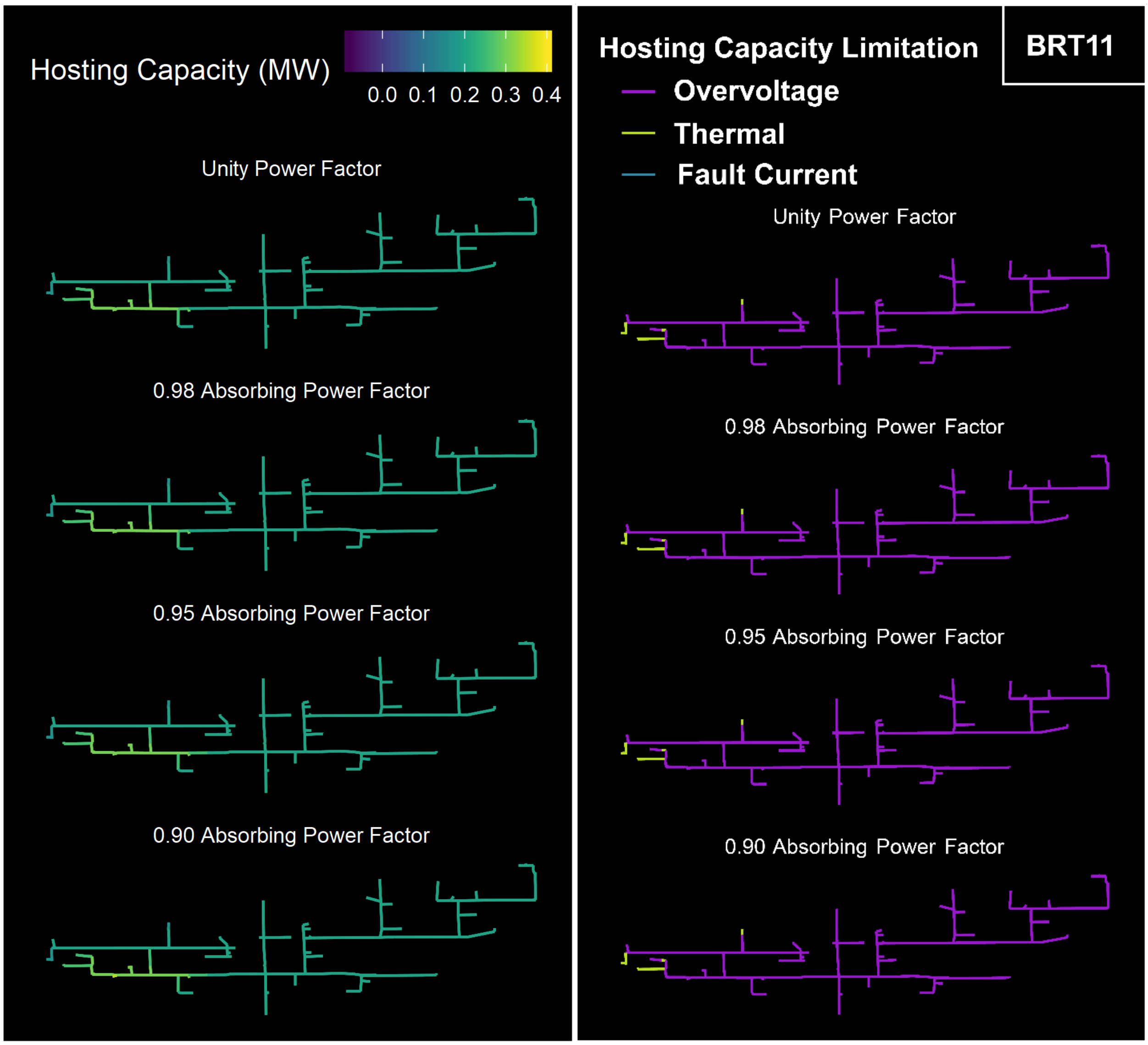
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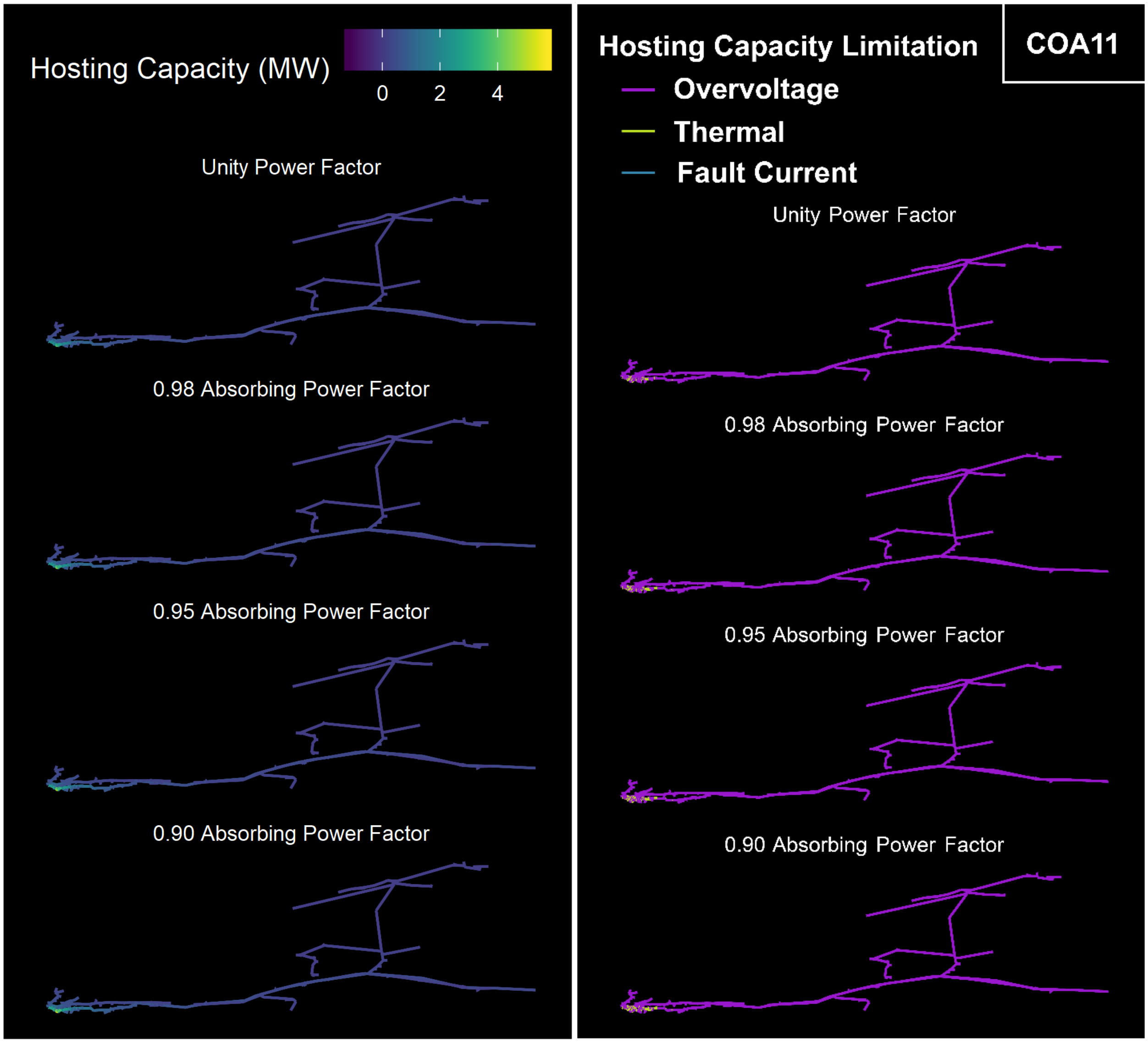
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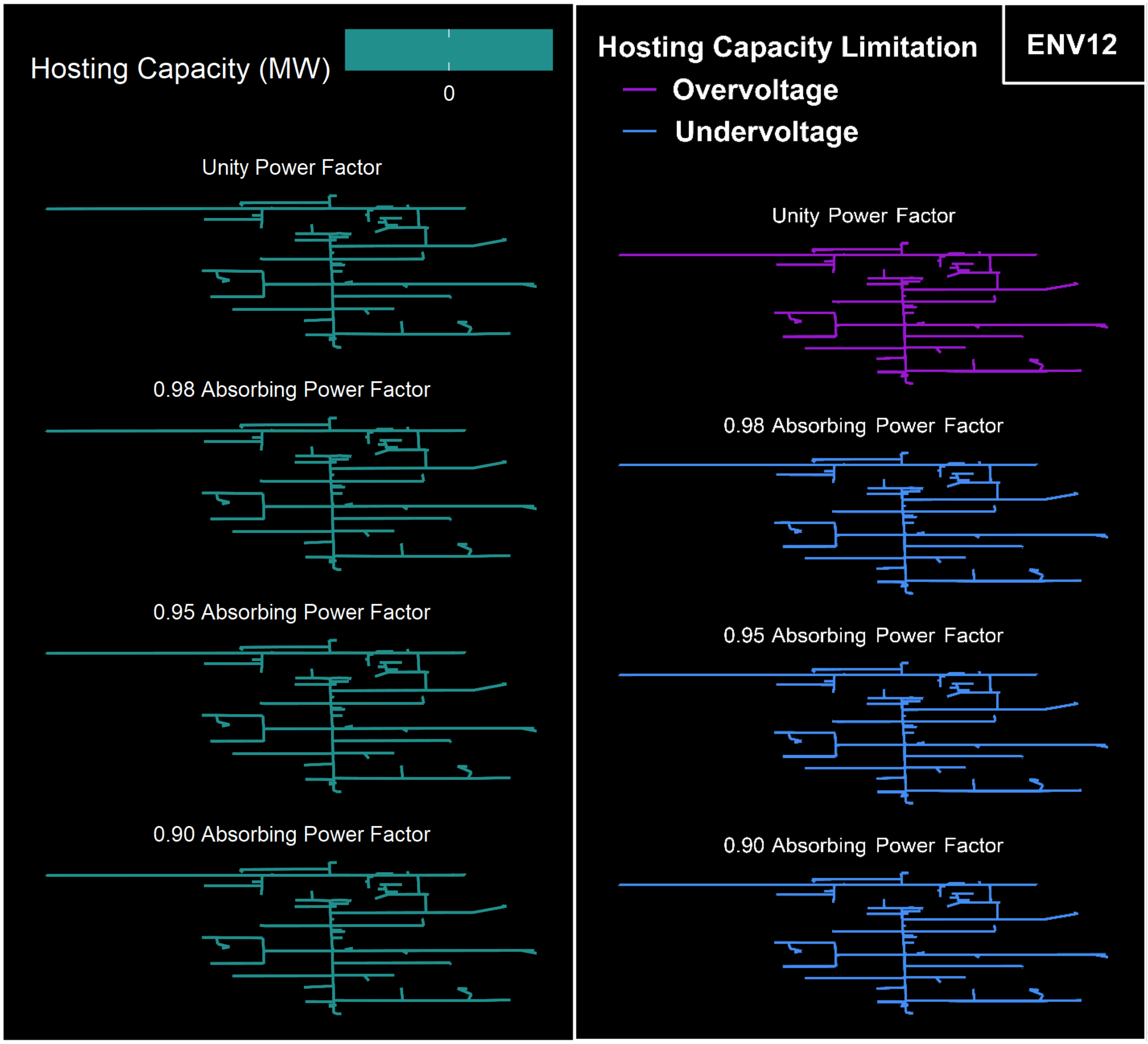
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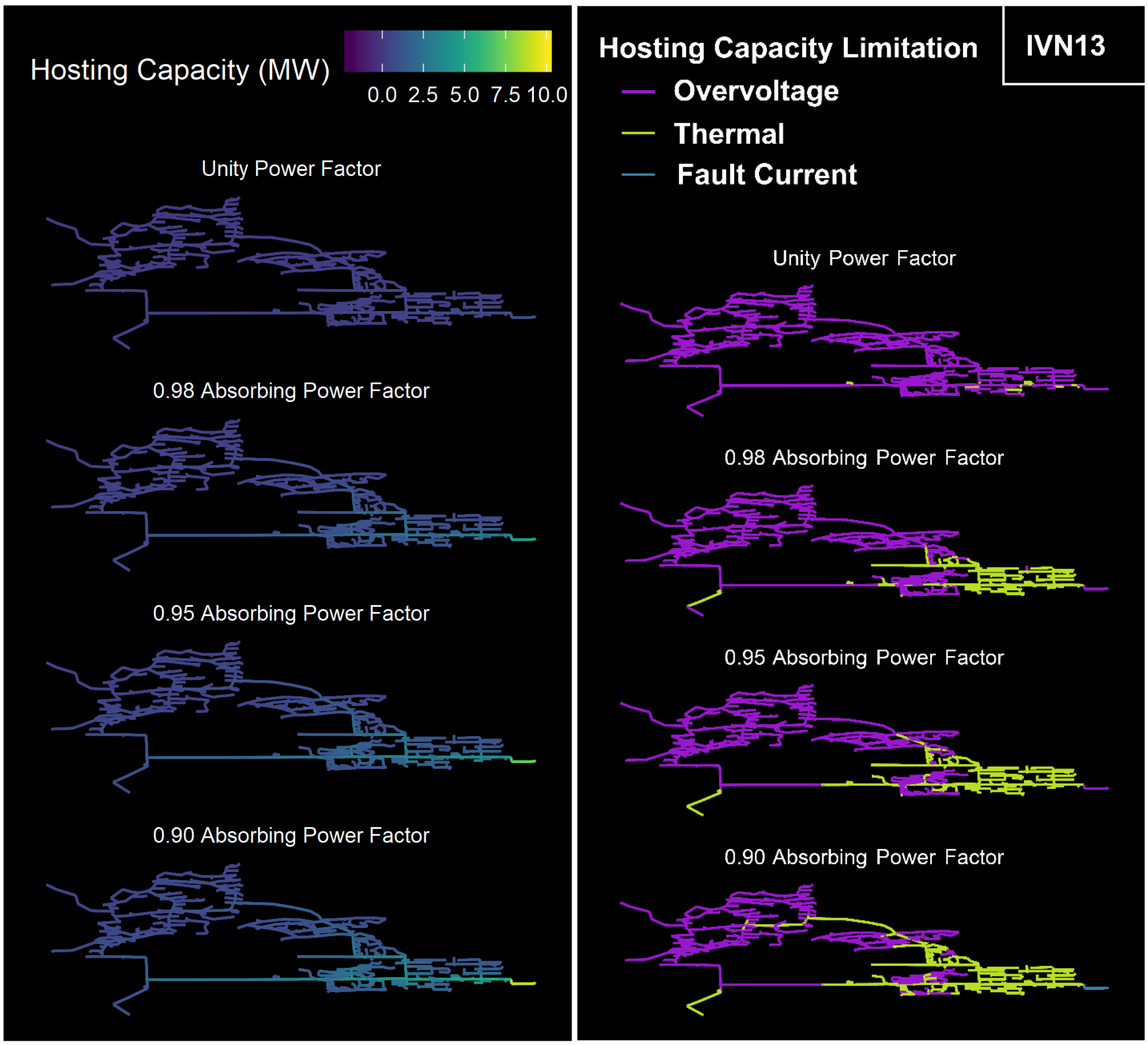

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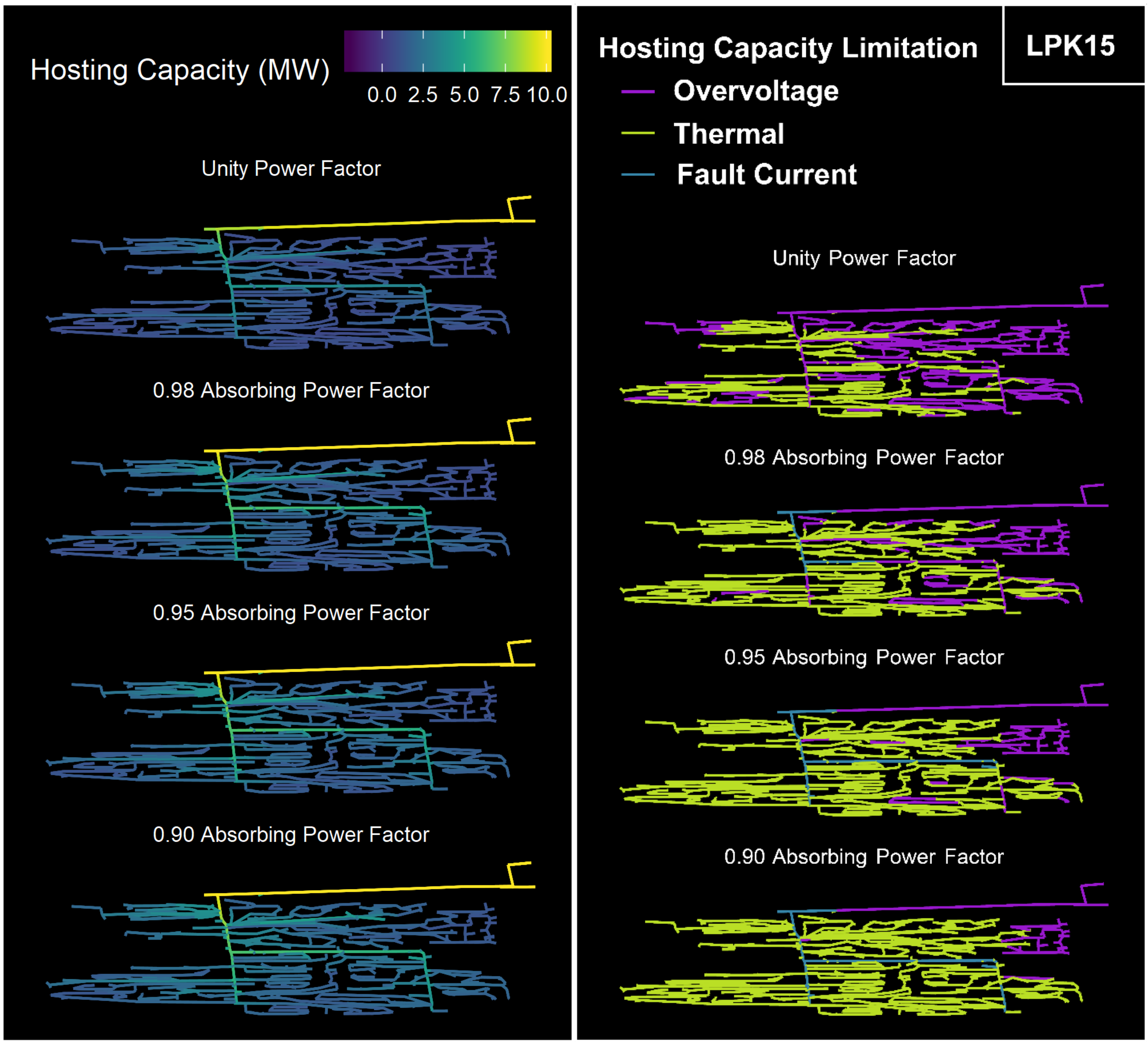
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Fault Current
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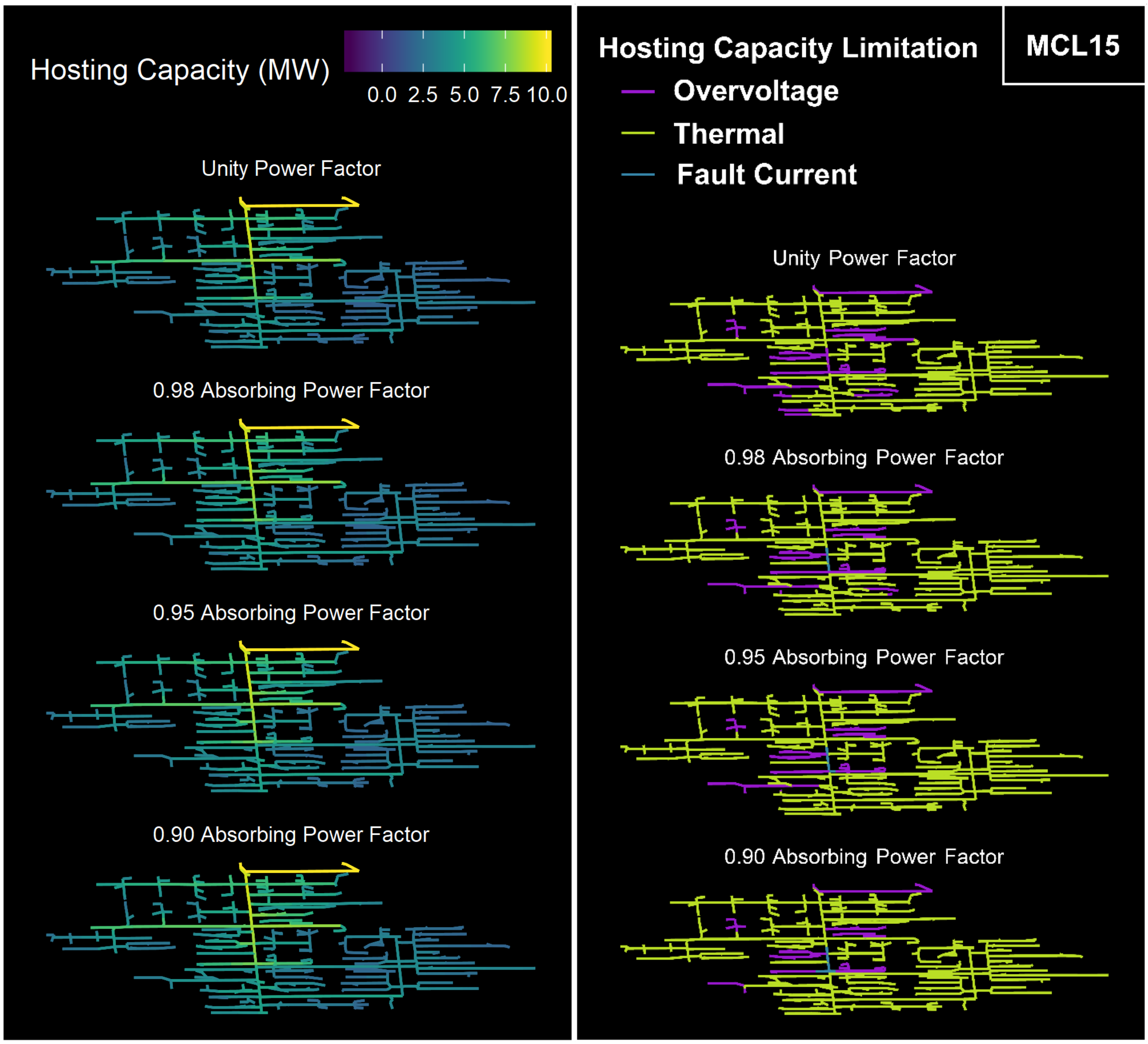
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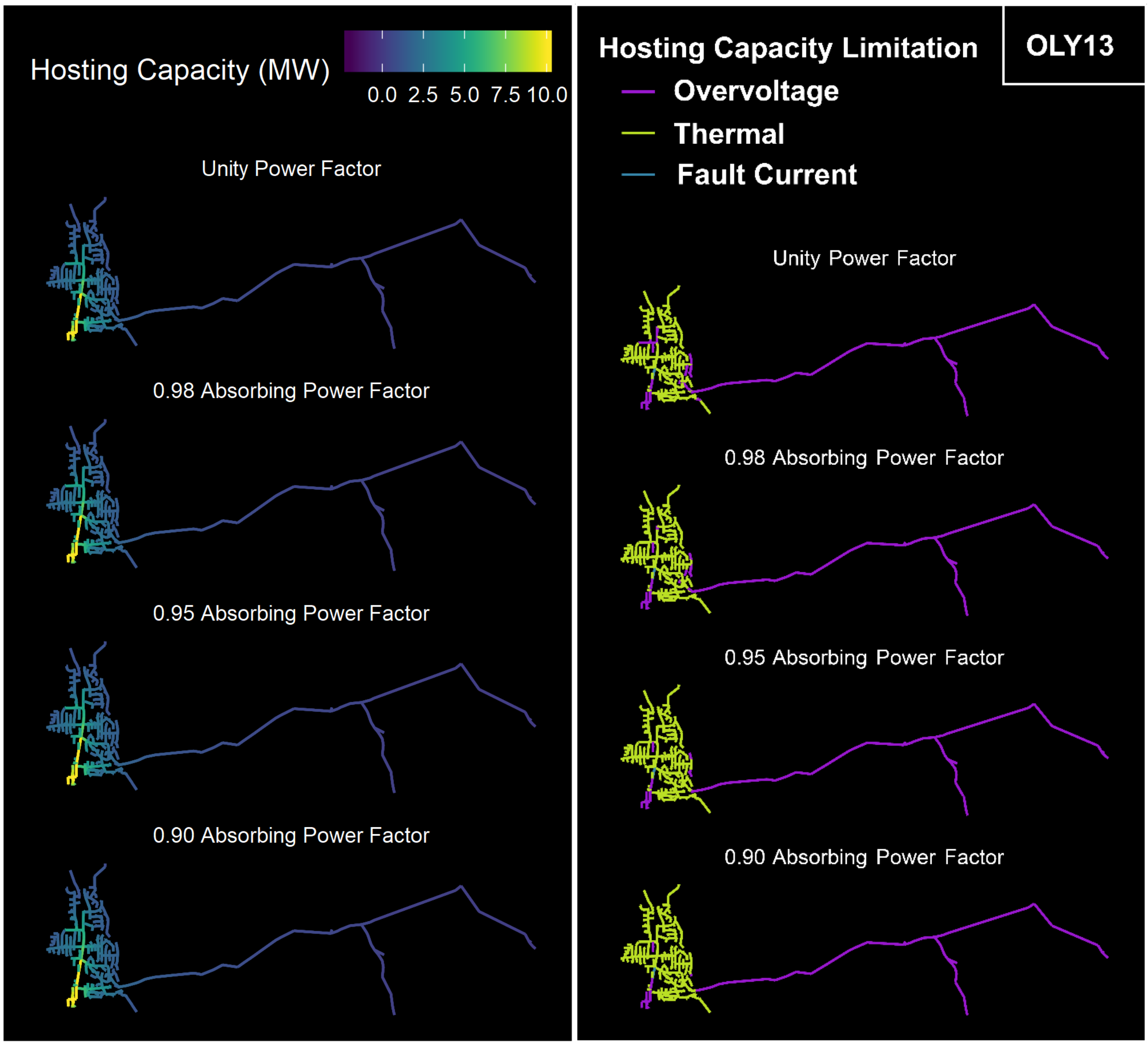
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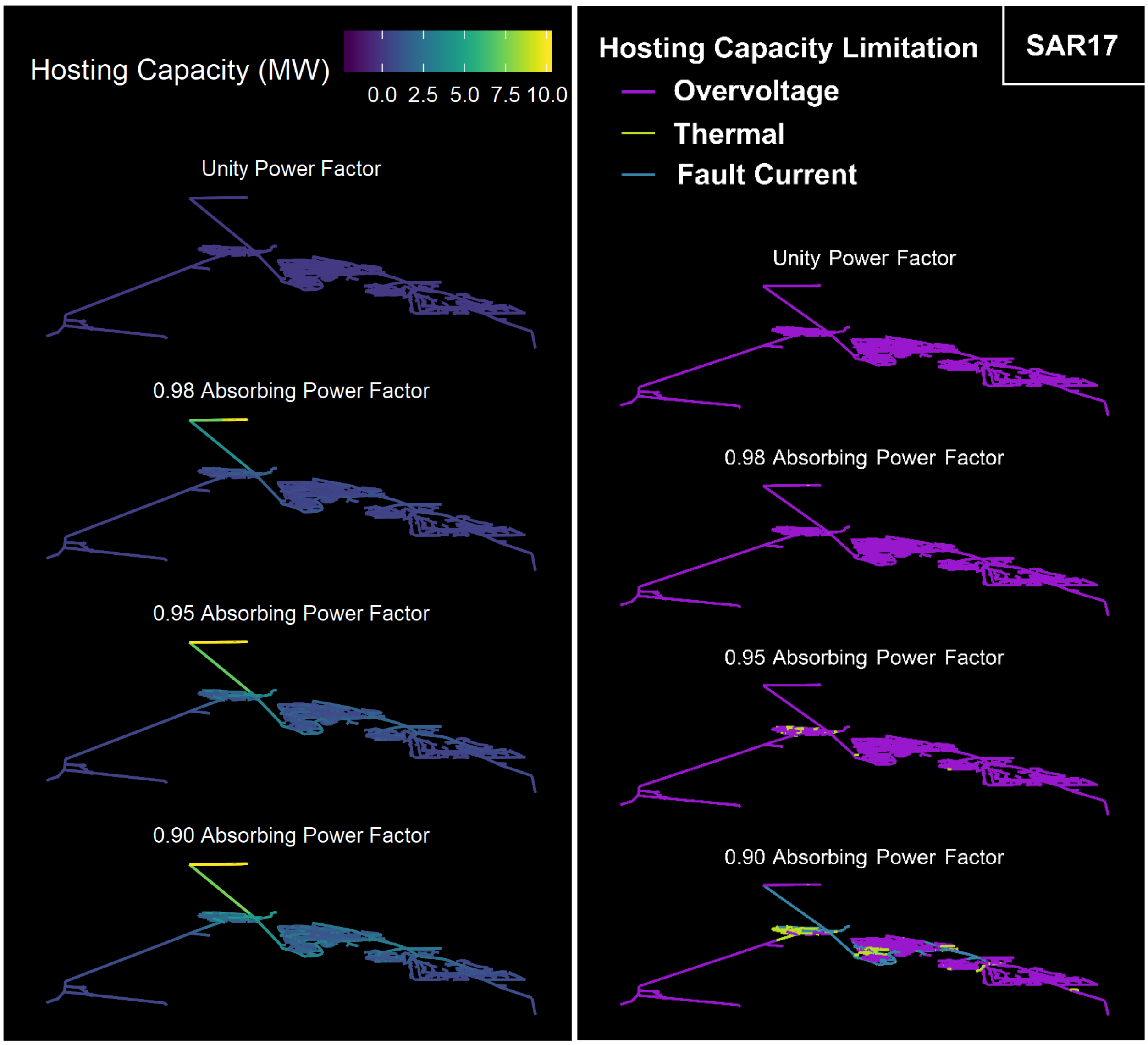
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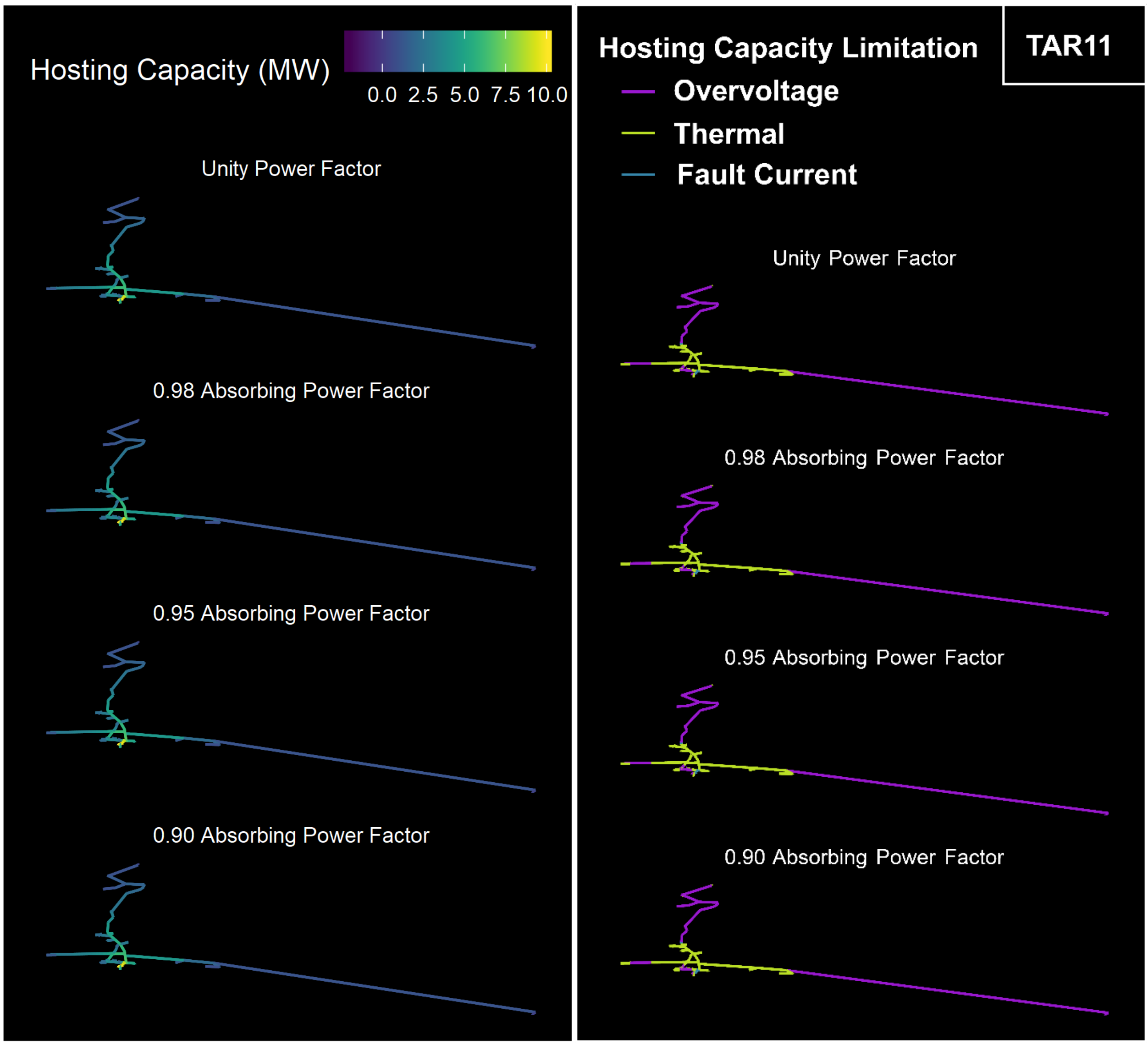
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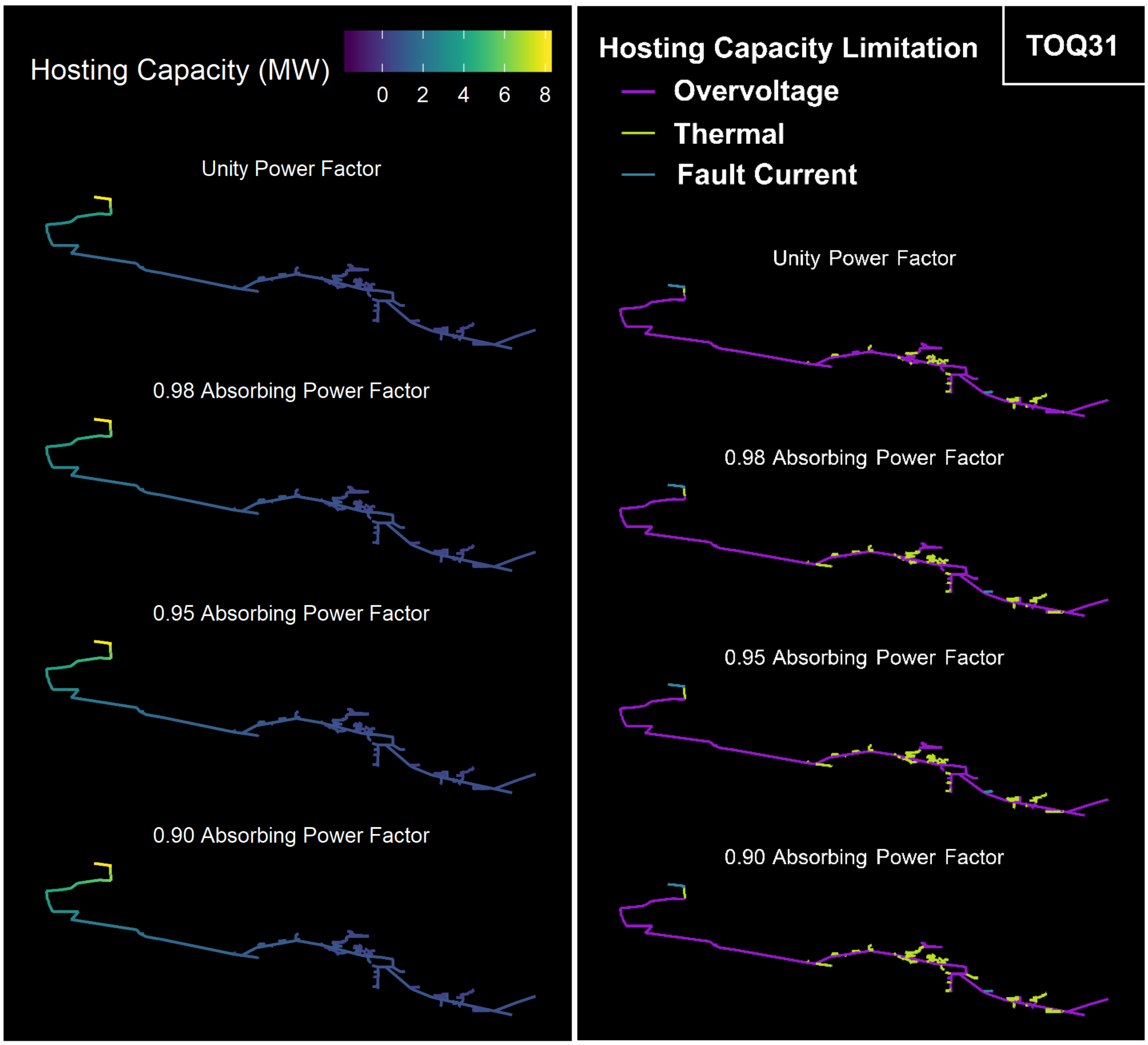
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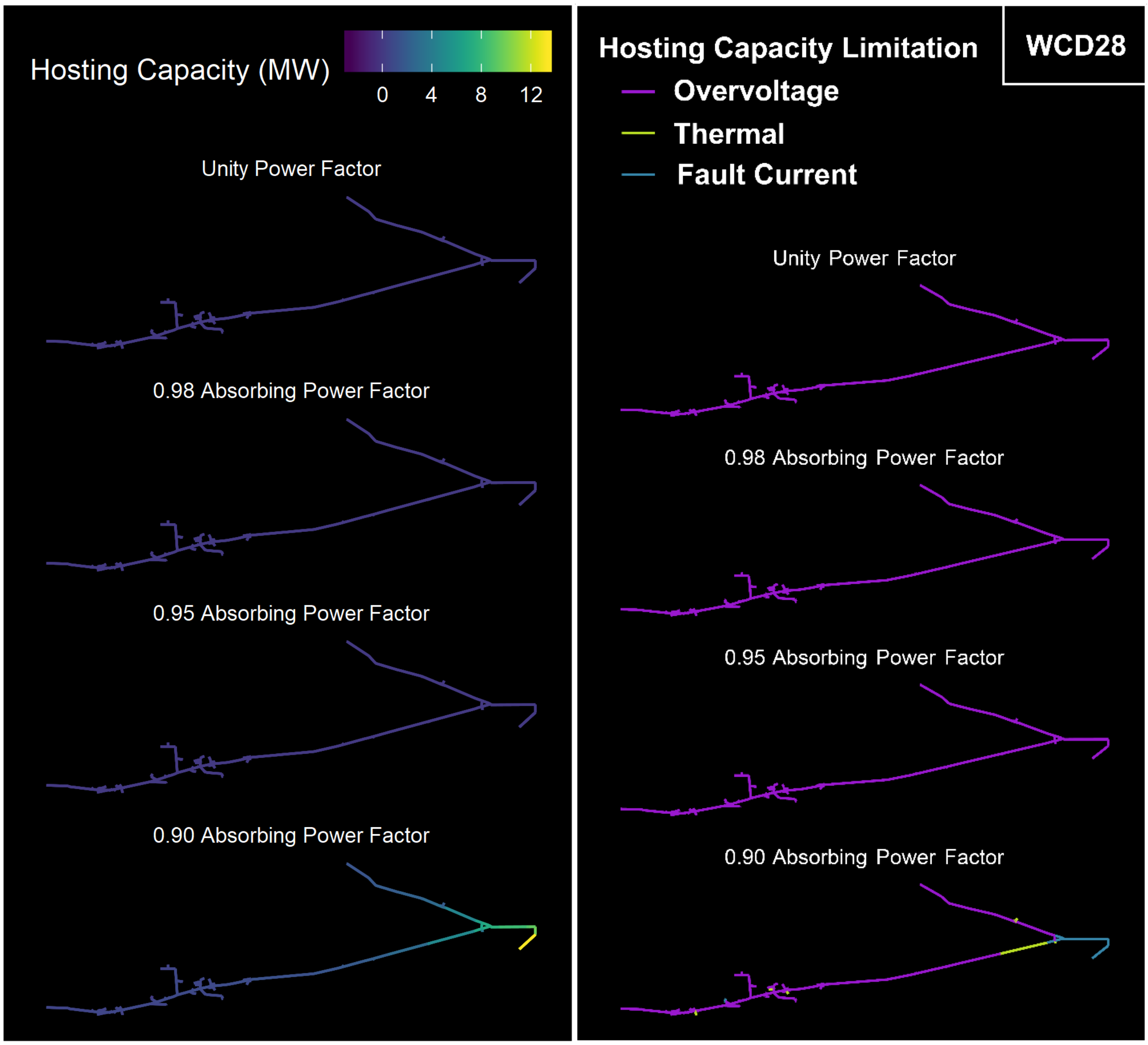
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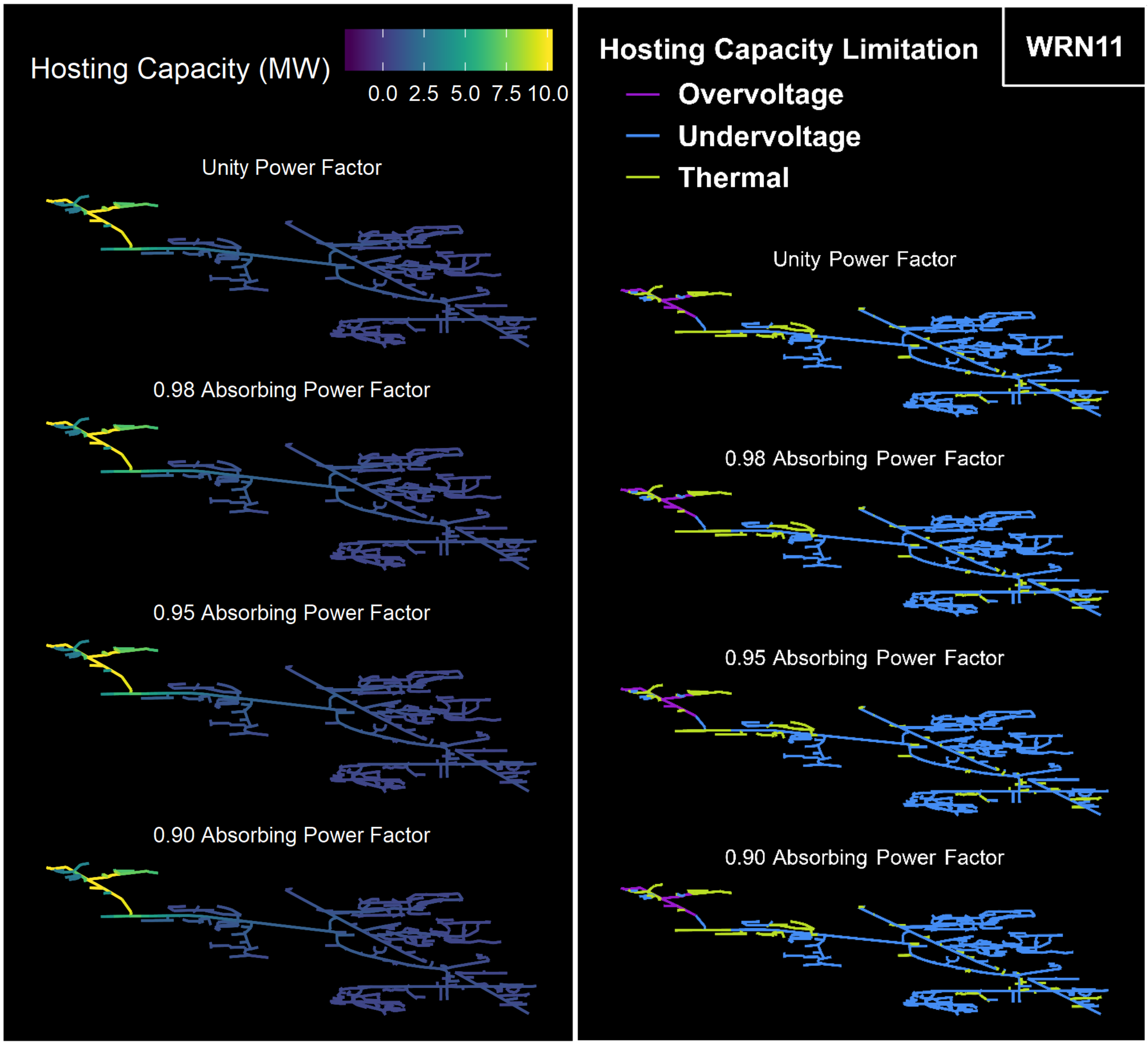
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Hosting Capacity Limitation
WRN11
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Undervoltage
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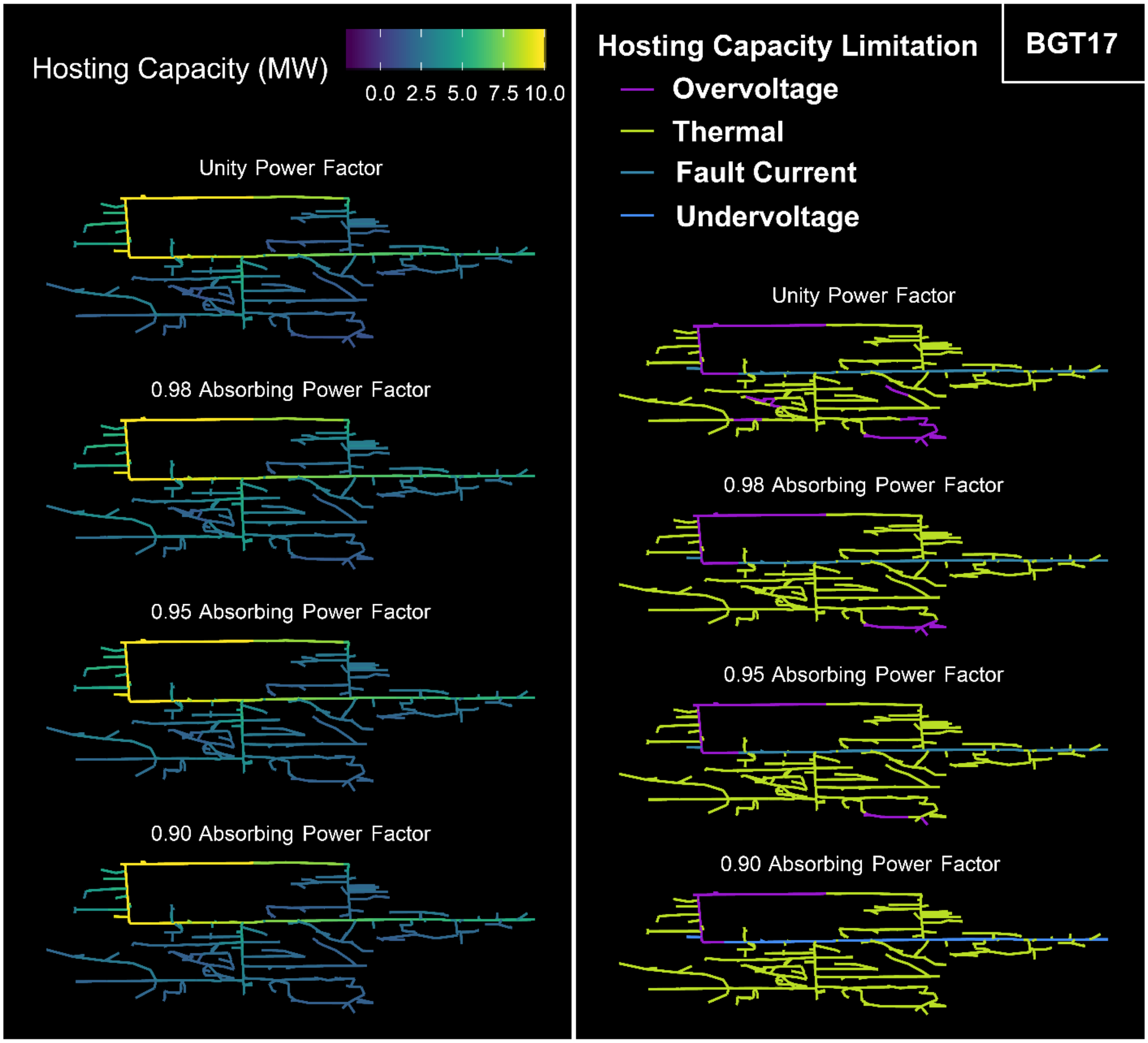
C
HOSTING CAPACITY - DETAILED RESULTS (FULL RETROFIT)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Hosting Capacity Limitation
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Fault Current
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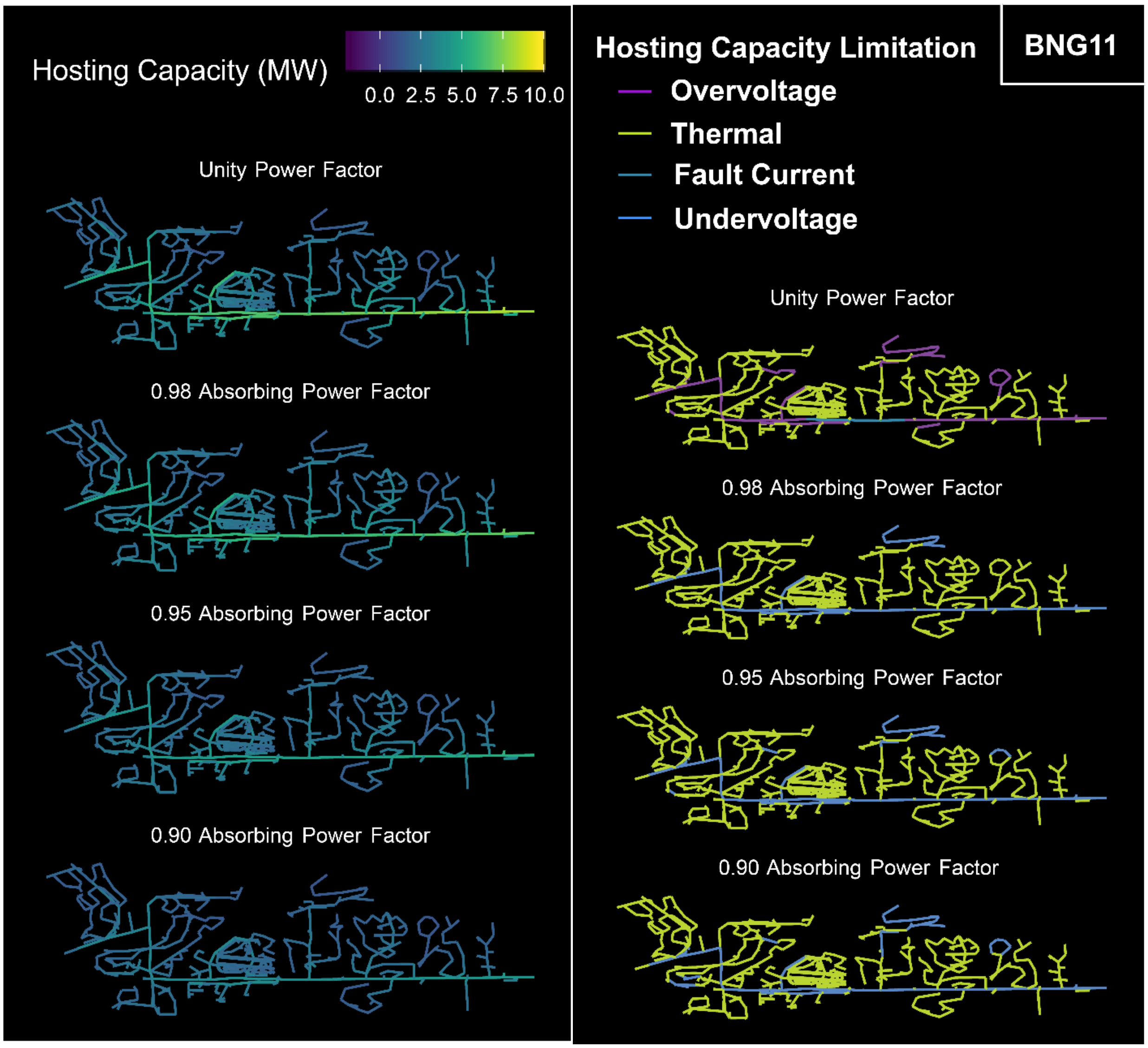
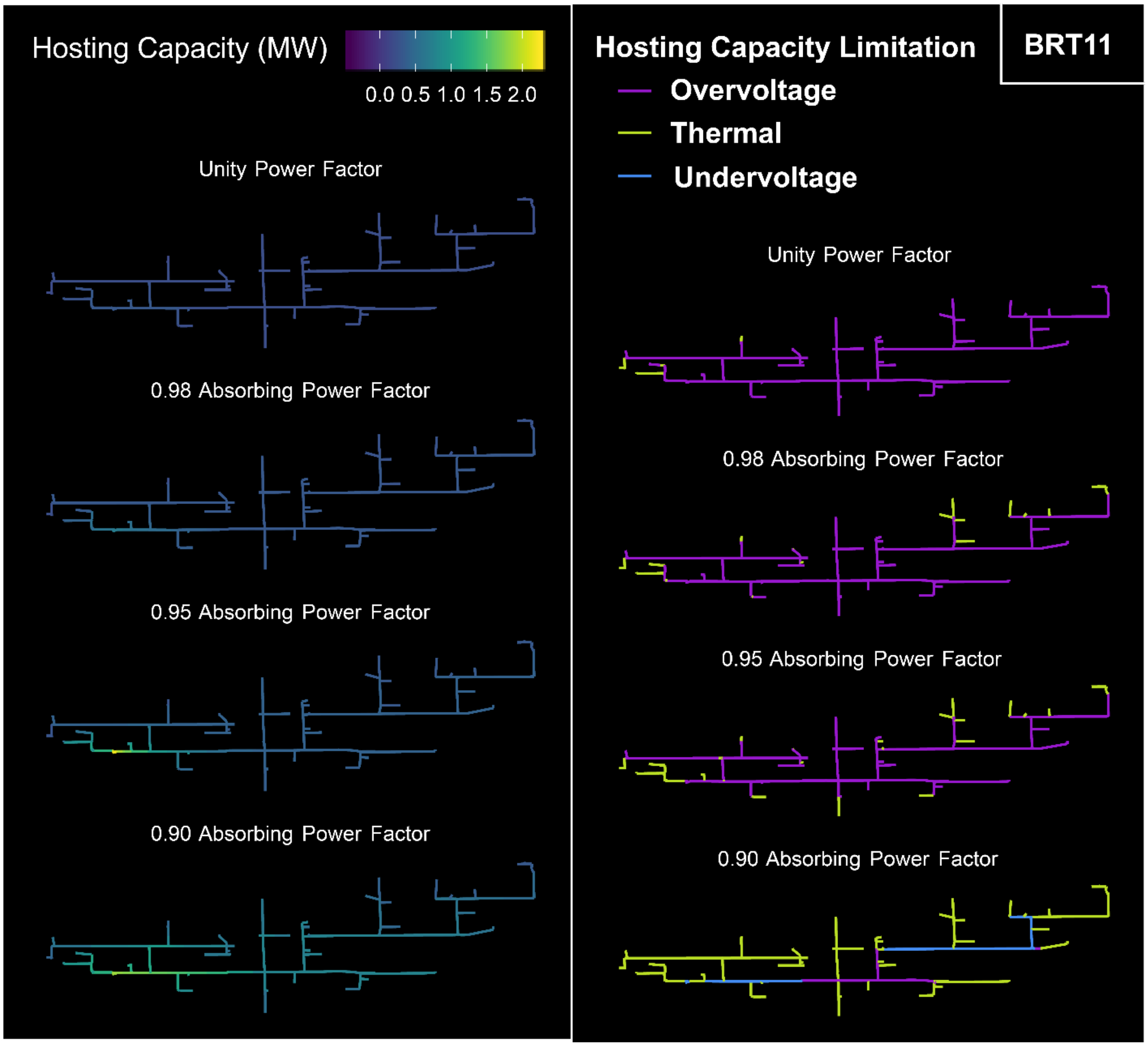
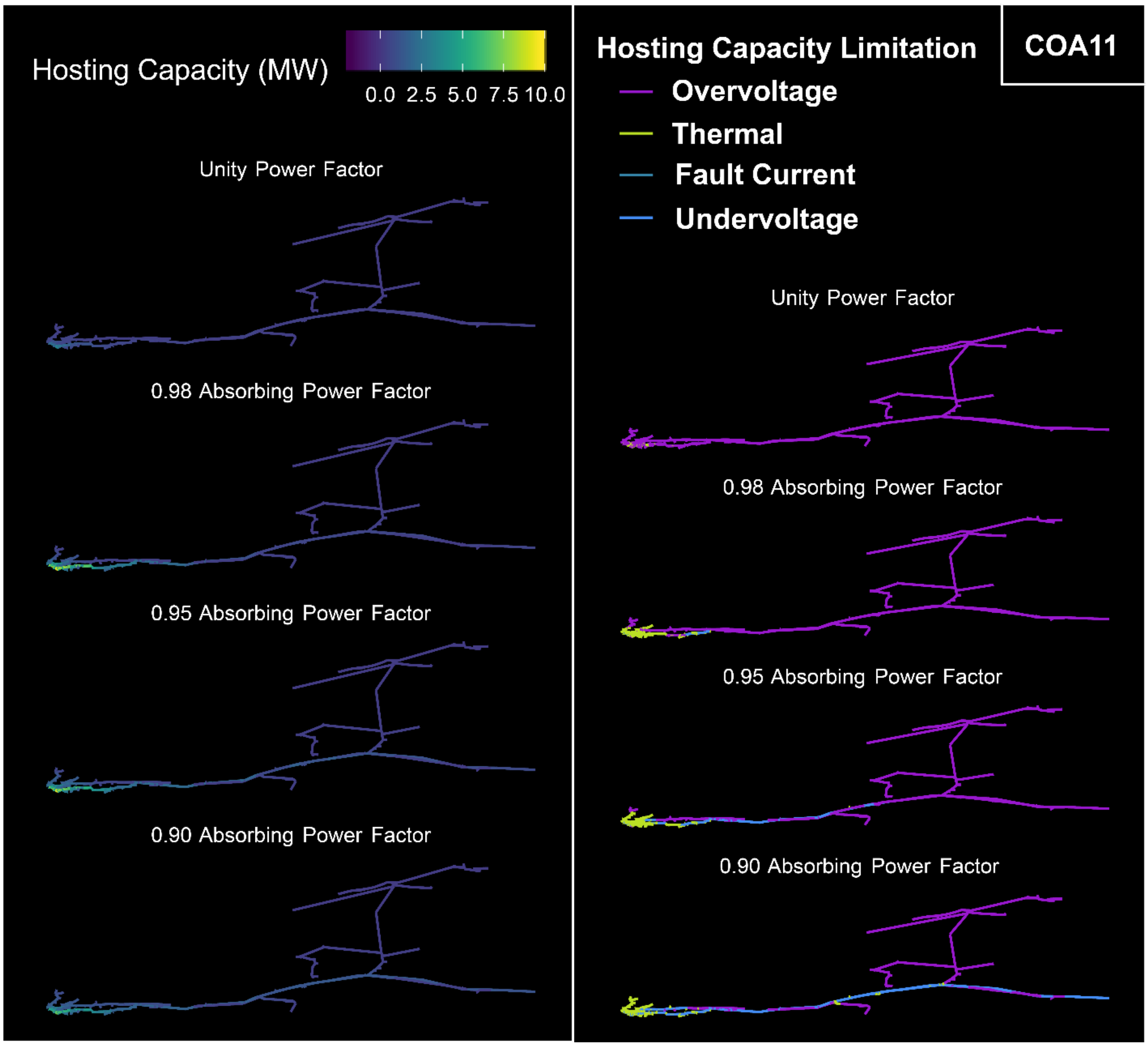
0.90 Absorbing Power Factor



Hosting Capacity (MW)
0.0 2.5 5.0 7.5 10.0
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
BNG11
Overvoltage
Thermal
Fault Current
Undervoltage
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
0.0 0.5 1.0 1.5 2.0
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
Overvoltage
Thermal
Undervoltage
BRT11
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
0.0 2.5 5.0 7.5 10.0
Unity Power Factor
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0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
COA11
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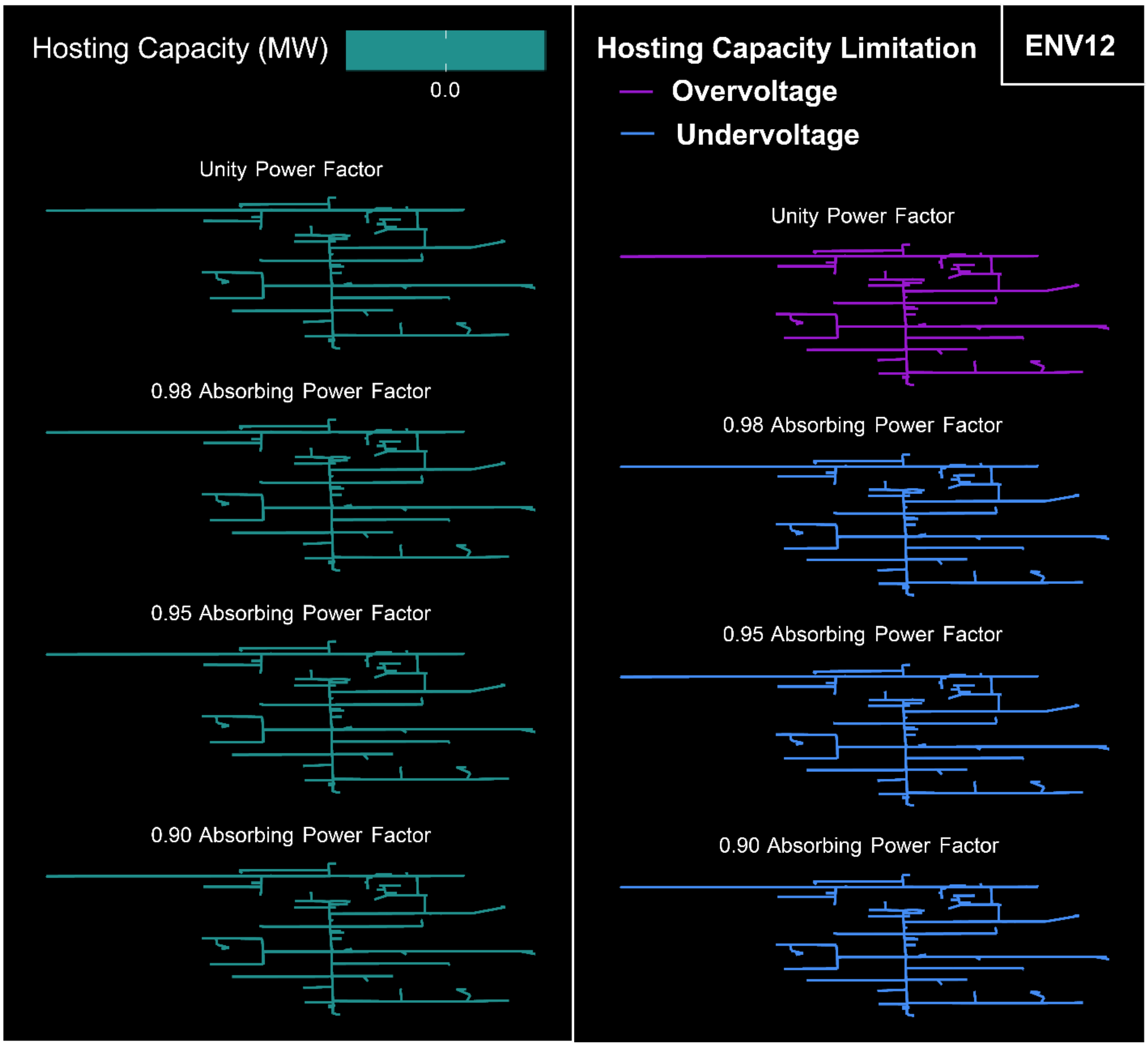
Thermal
Fault Current
Undervoltage
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
0.0
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
ENV12
Overvoltage
Undervoltage
Unity Power Factor
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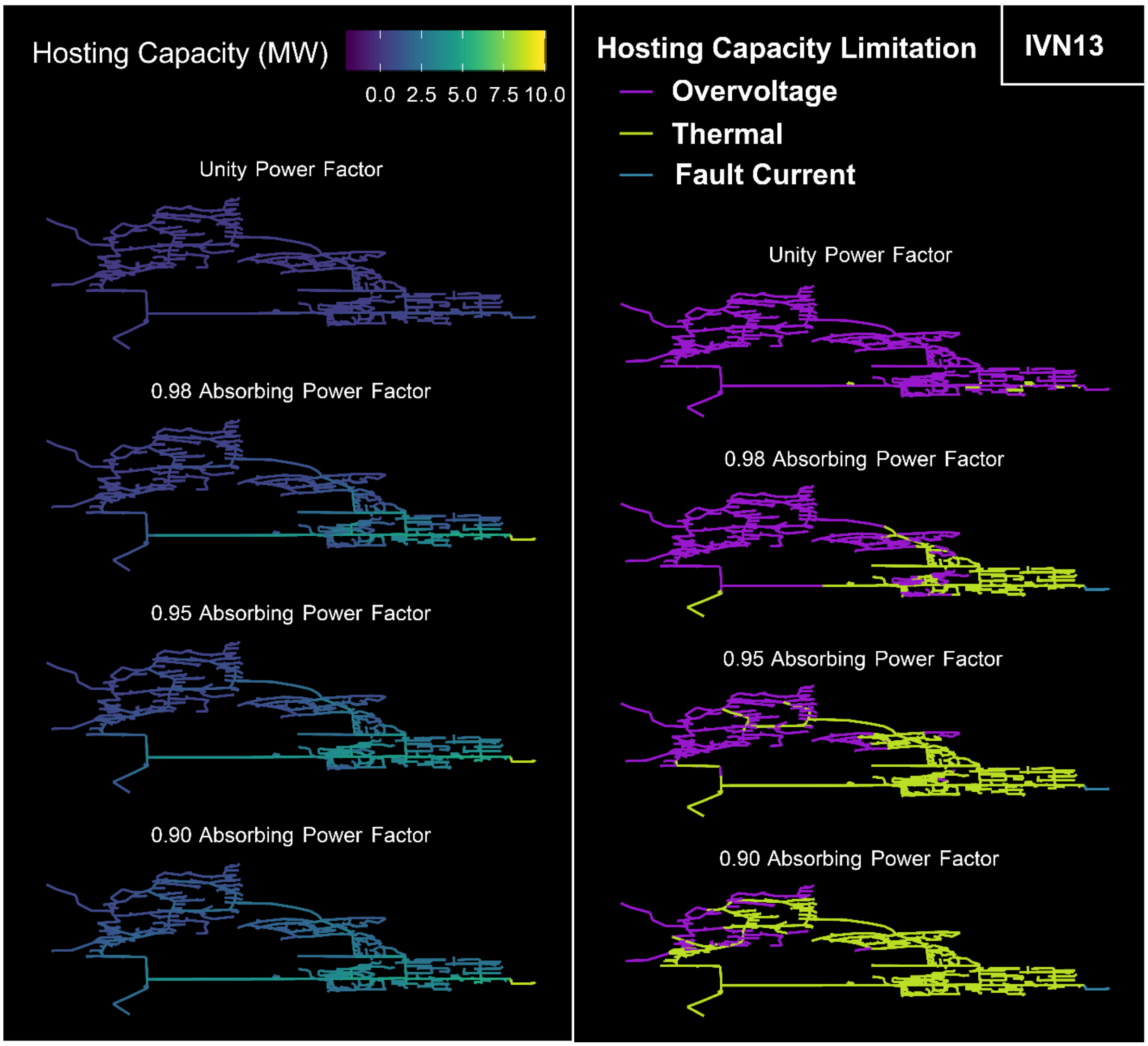
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor



Hosting Capacity (MW)
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Unity Power Factor
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0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
IVN13
Overvoltage
Thermal
Fault Current
Unity Power Factor
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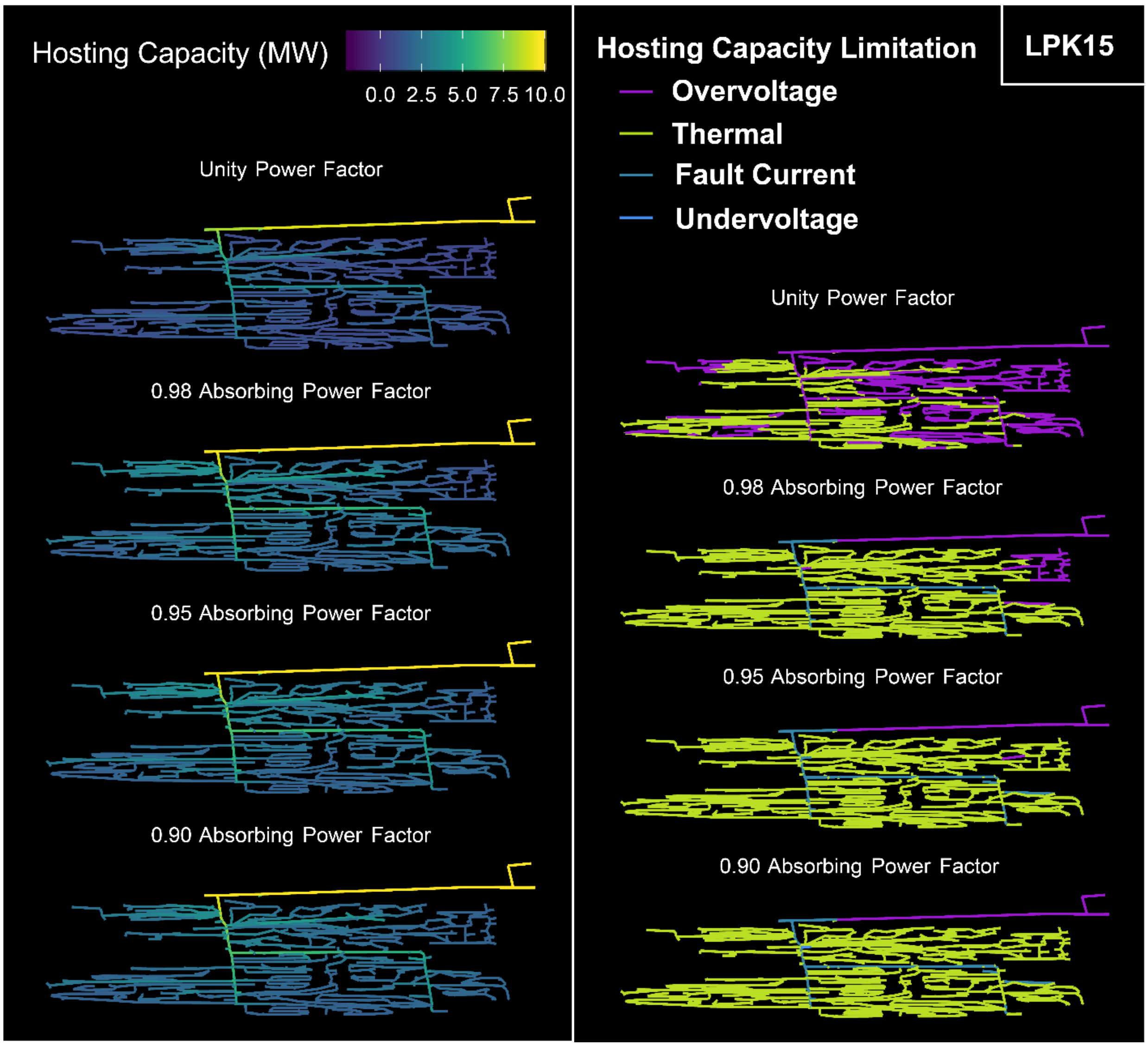
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
0.0 2.5 5.0 7.5 10.0
Unity Power Factor
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0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
LPK15
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Thermal
Fault Current
Undervoltage
Unity Power Factor
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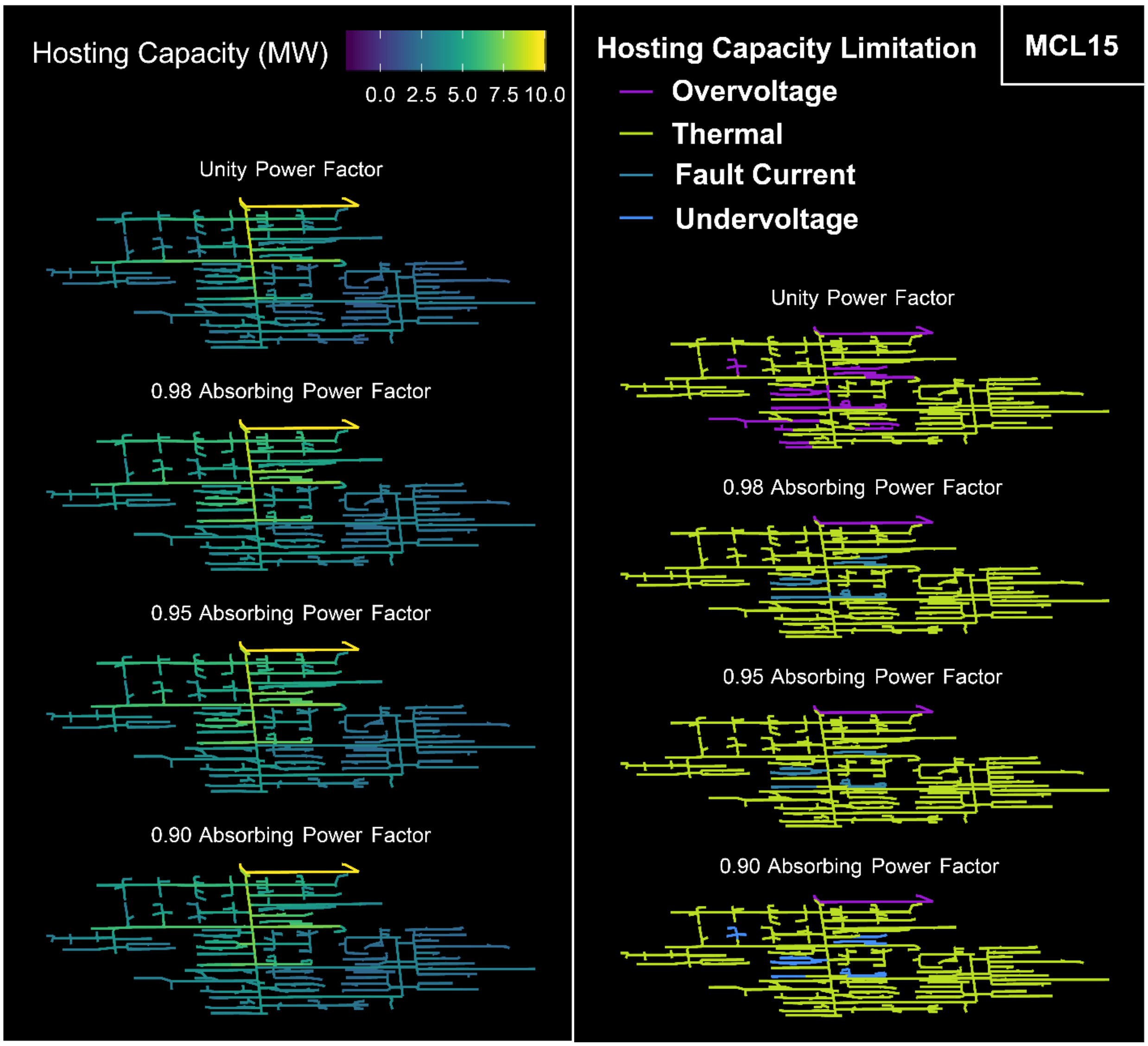
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
0.0 2.5 5.0 7.5 10.0
Unity Power Factor
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0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
MCL15
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Thermal
Fault Current
Undervoltage
Unity Power Factor
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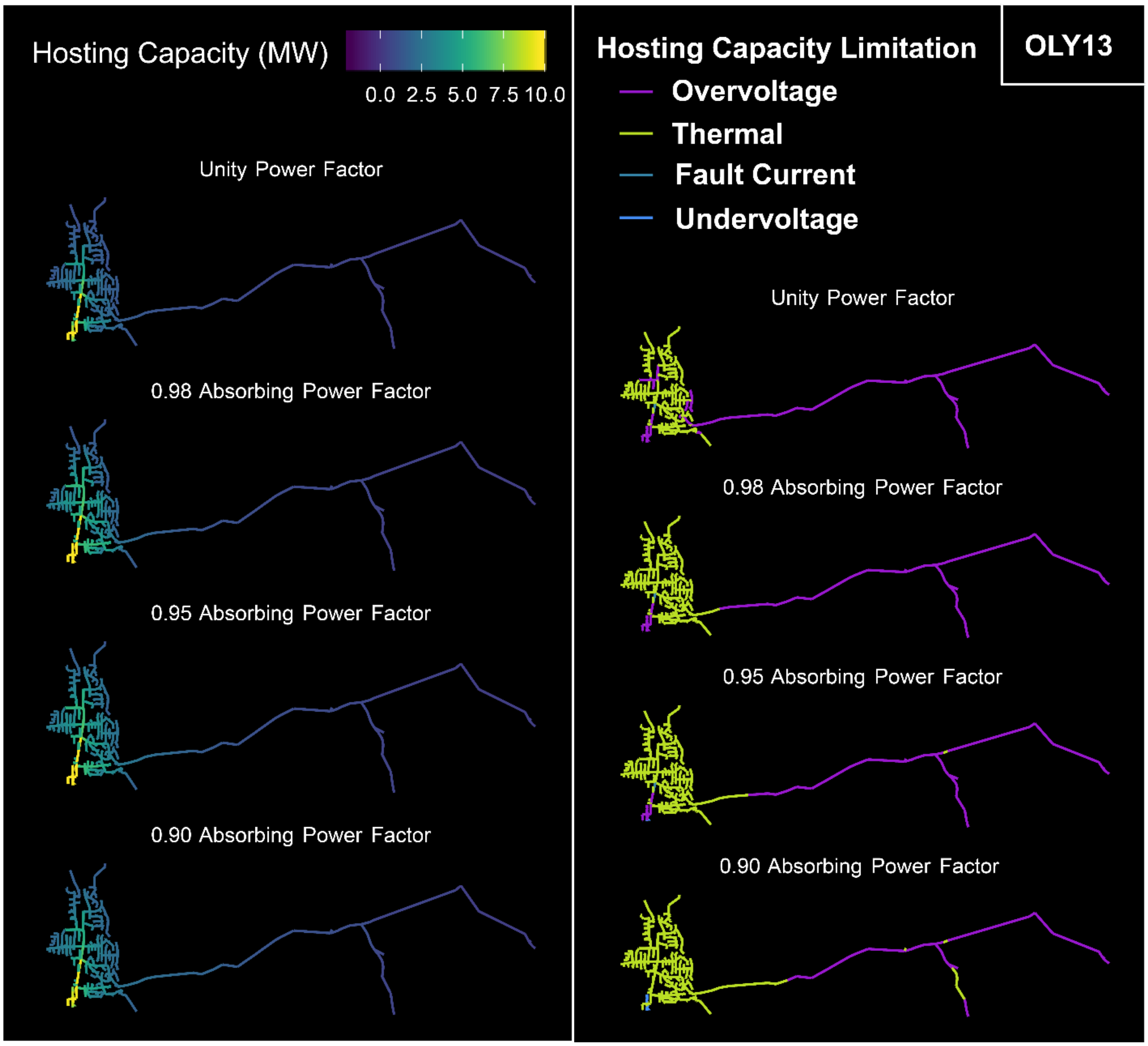
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
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Unity Power Factor
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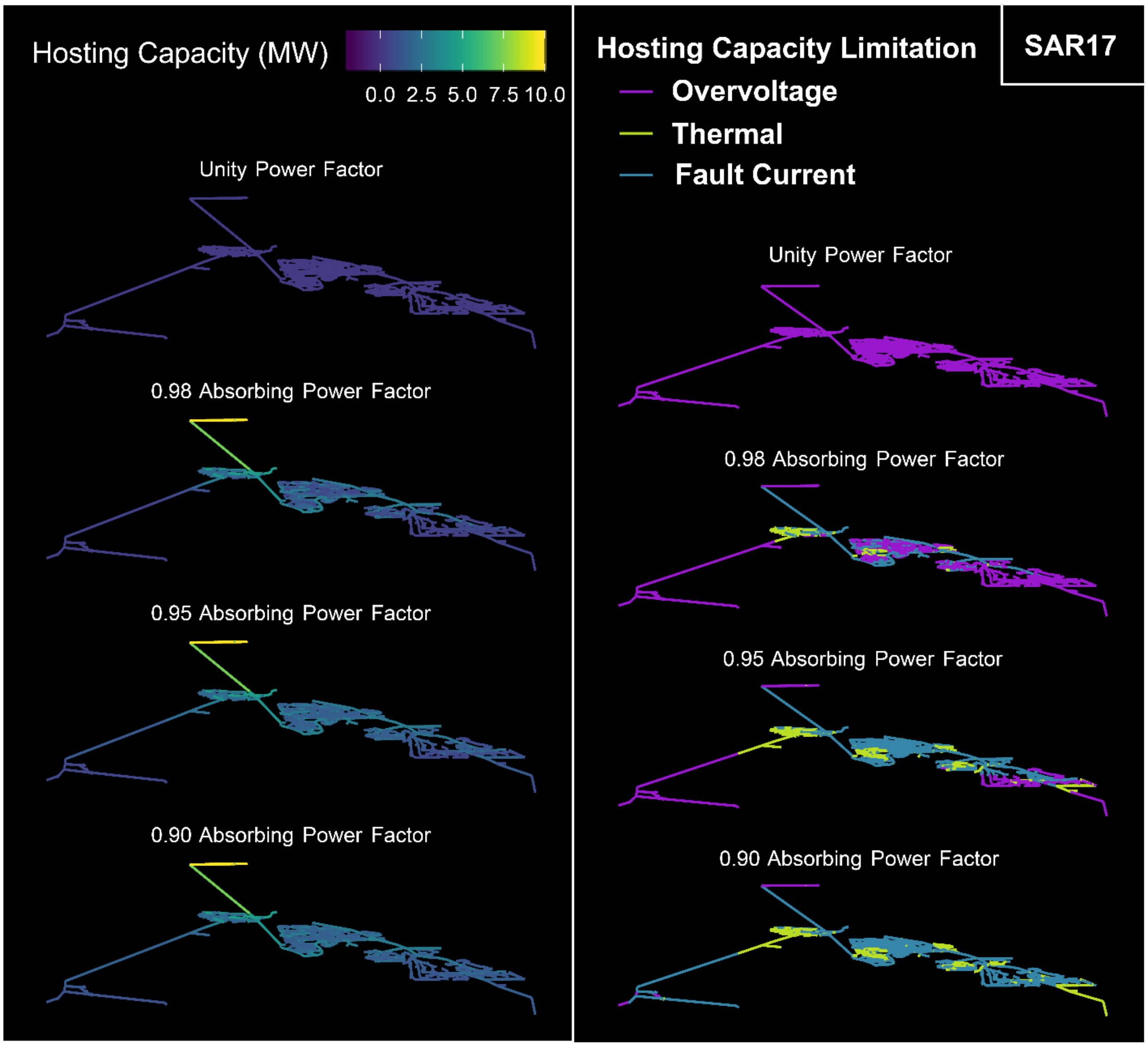
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
OLY13
Overvoltage
Thermal
Fault Current
Undervoltage
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
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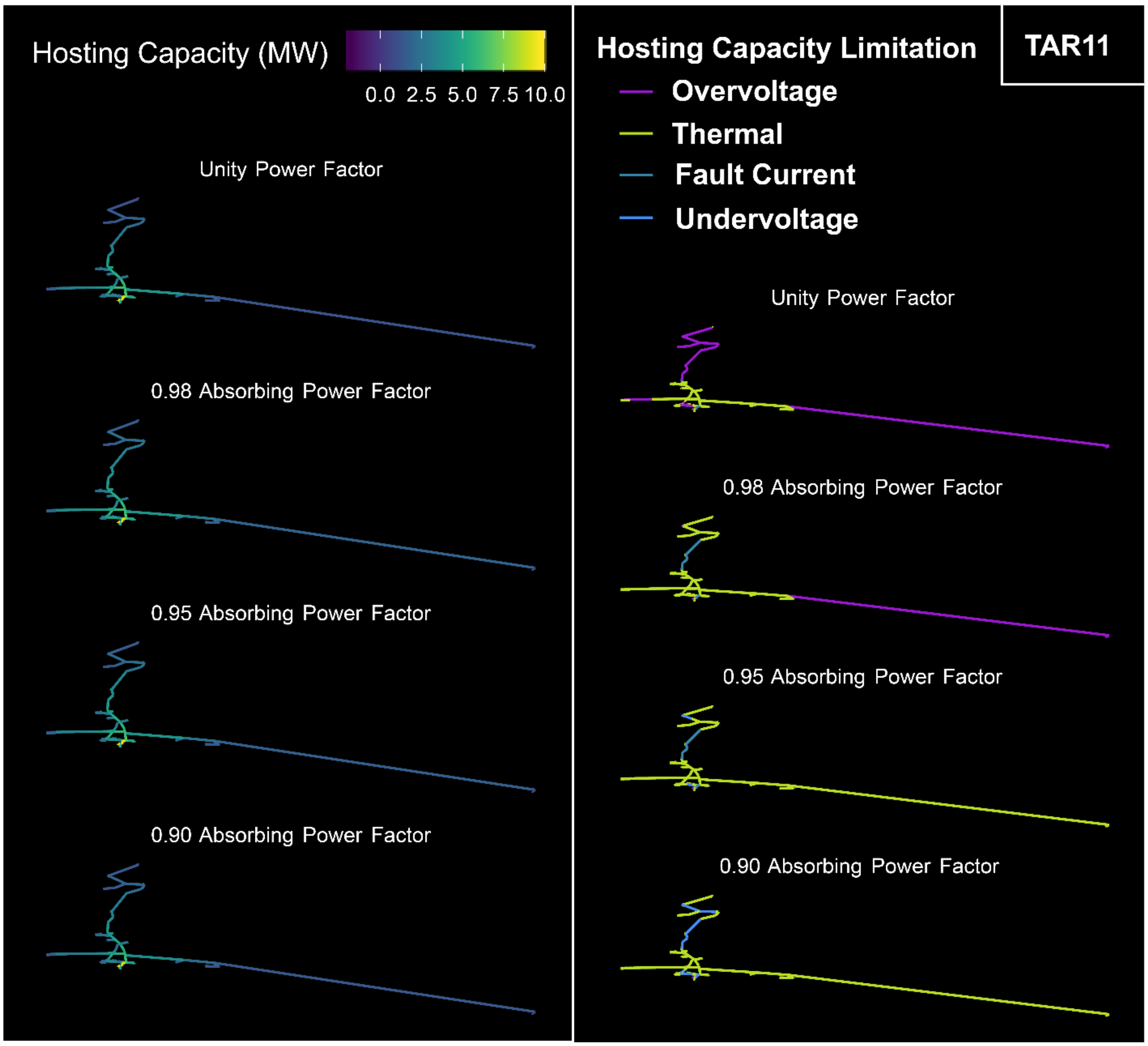
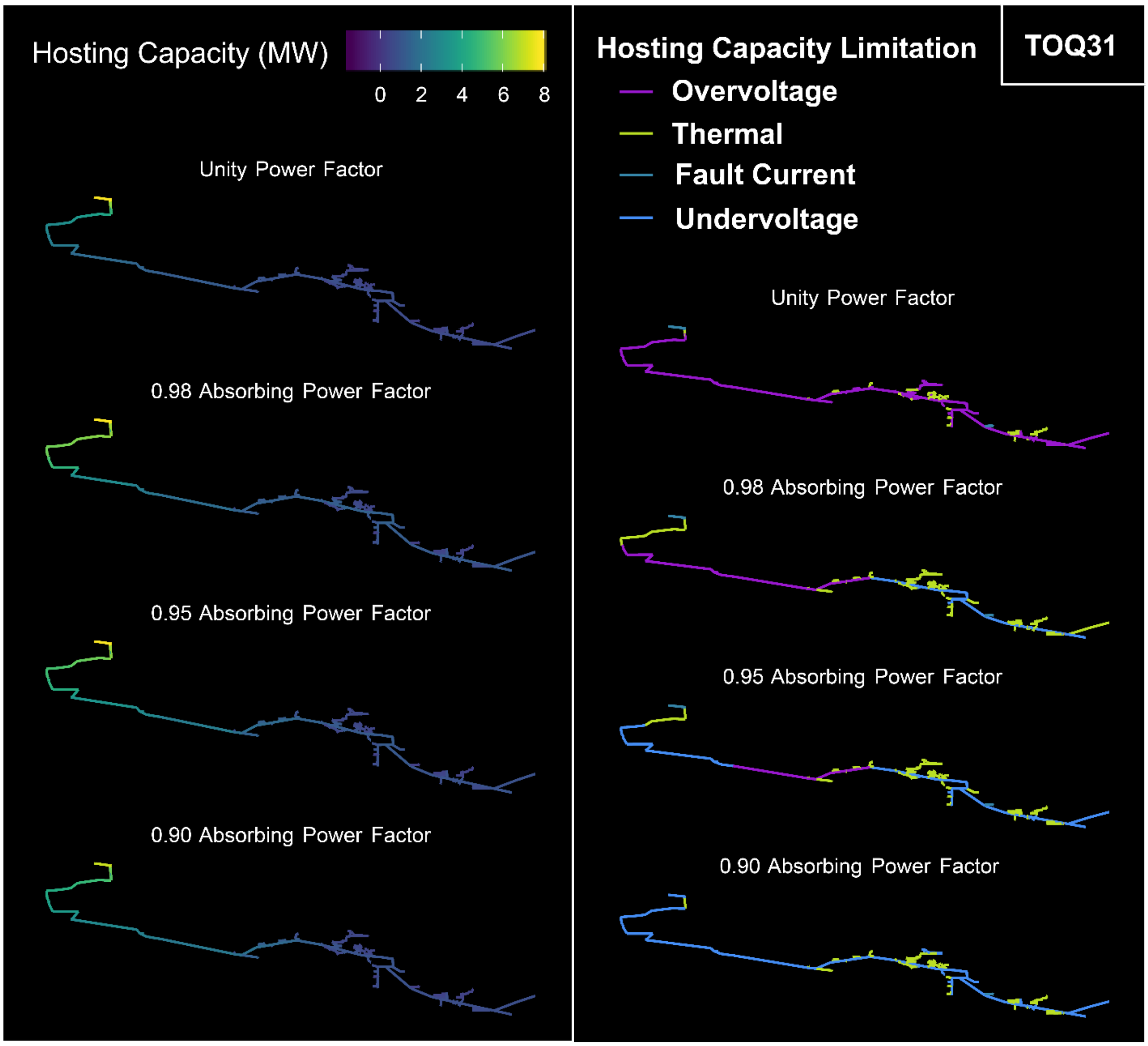
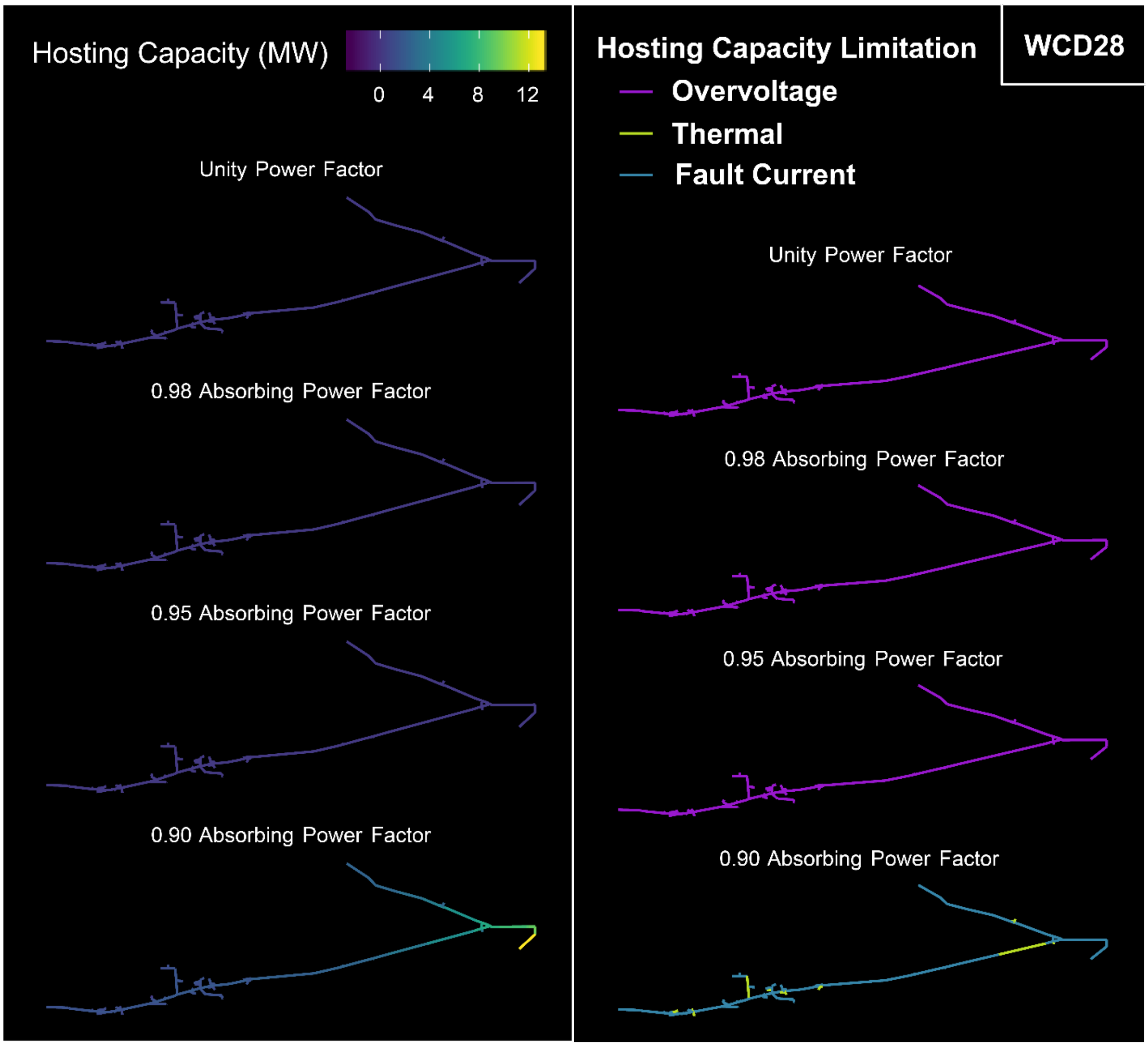
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
SAR17
Overvoltage
Thermal
Fault Current
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
0.0 2.5 5.0 7.5 10.0
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
TAR11
Overvoltage
Thermal
Fault Current
Undervoltage
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
0
2
4
6
8
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
TOQ31
Overvoltage
Thermal
Fault Current
Undervoltage
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
0
4
8
12
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
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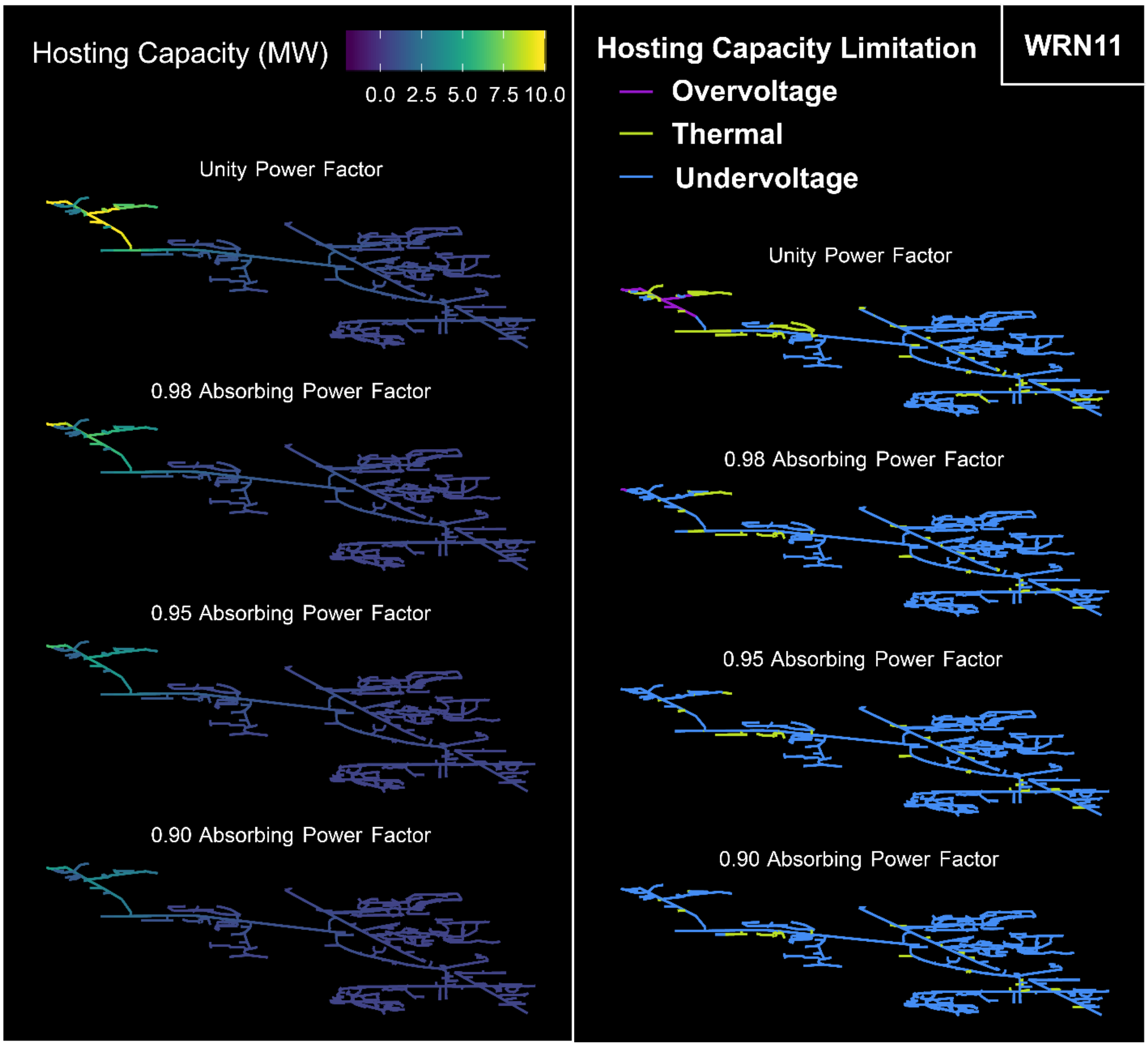
Overvoltage
Thermal
Fault Current
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor


Hosting Capacity (MW)
0.0 2.5 5.0 7.5 10.0
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor
Hosting Capacity Limitation
WRN11
Overvoltage
Thermal
Undervoltage
Unity Power Factor
0.98 Absorbing Power Factor
0.95 Absorbing Power Factor
0.90 Absorbing Power Factor

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