



# IEEE Recommended Practice for Electric Power Distribution System Analysis

IEEE Power and Energy Society

Developed by the  
Analytic Methods for Power Systems Committee

**IEEE Std 1729™-2025**  
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**STANDARDS**

# **IEEE Recommended Practice for Electric Power Distribution System Analysis**

Developed by the

**Analytic Methods for Power Systems Committee**  
of the  
**IEEE Power and Energy Society**

Approved 19 June 2025

**IEEE SA Standards Board**

**Abstract:** The goal of this recommended practice is to expand the use of IEEE power distribution test feeders into a broader space of software developers, software users, and researchers. The need for new distribution software functionality evolves quickly in areas such as distributed resource modeling, load response to voltage and frequency, reliability improvement, neutral-earth voltage, active controls, interoperability, etc. By leveraging and expanding the set of test feeders, more attention can focus on providing the new functionality. The scope of the recommended practice includes steady-state, event-based, probabilistic, stochastic, and dynamic analysis of electric utility power distribution systems. Industrial and commercial power distribution systems, harmonic analysis, and electromagnetic transient analysis are all excluded.

**Keywords:** IEEE 1729™, power distribution, power system analysis

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## Introduction

This introduction is not part of IEEE Std 1729-2025, IEEE Recommended Practice for Electric Power Distribution System Analysis.

In 1991, an IEEE working group paper published the data for four different unbalanced radial distribution test feeders for the purpose of testing load flow algorithms. In 2001, a sequel working group paper added the data for a fifth test feeder that focused on transformer connections. These papers have been cited hundreds of times, indicating the value of using common test feeders in IEEE publications. Data for several new test feeders has been developed since 2001, and that process is ongoing.

This recommended practice aims to expand the use of these IEEE test feeders into a broader space of software developers, software users, and researchers. The need for new distribution software functionality evolves quickly in areas such as distributed resource modeling, load response to voltage and frequency, reliability improvement, neutral-earth voltage, harmonics, active controls, interoperability, etc. By leveraging and expanding the set of test feeders, more attention can focus on providing the new functionality.

- a) Researchers and software developers can test their calculation methods with published and accepted data sets.
- b) It is not necessary for each developer and researcher to publish custom data sets, which are sometimes incomplete.
- c) The set of test feeders helps to establish a baseline of expected software capabilities, in being able to solve the test feeders.
- d) By creating new test feeders, the horizon of expected software capabilities will expand, without imposing the rigidity of a standard specification.
- e) The feeder data can be used for schema development and interoperability tests in the International Electrotechnical Commission Distribution Common Information Model (CIM) or other modeling protocols.
- f) The lack of test feeders in a certain topic may be taken as partial evidence that new work is needed in that area.

The conditions in modern distribution systems (DS) are changing to meet the growing energy demand, increased awareness of climate change, and introduction of consumer technologies such as distributed energy resources (DERs), electric vehicles, and energy storage systems. For example, societies are now motivated to invest in renewable energy-based DERs such as photovoltaic (PV) systems due to their low investment costs and low carbon footprint. Despite the numerous benefits of these technologies, they may raise questions about possible negative impacts on system efficiency and reliability. This necessitates the need to thoroughly analyze system performance before integrating consumer technologies to maximize their integration benefits and help ensure the safe operation of the system. In this regard, hosting capacity analysis (HCA) as a planning tool has garnered the attention of utilities, researchers, and practitioners. Hosting capacity (HC) is defined as in this recommended practice as a preliminary assessment of the DER capacity (including storage and possibly electric vehicles) that can be accommodated at different locations in the DS within system operational limits and without the need for infrastructure upgrades. A comprehensive HCA studies the impact of additional DER on various system indicators (e.g., voltage stability, thermal overloading, power quality, etc.). Therefore, this document aims to present a guideline for HCA to help utilities better plan for the integration of consumer technologies in modern DSs. With the increasing use of DER, their dynamic behavior on the DSs has become significant. This document presents new guidelines and test cases for unbalanced DS dynamic analysis.

The target audience for this recommended practice includes electric power distribution utilities, DER developers, commercial vendors of engineering analysis software for DSs, and academic researchers working in this area.

## Acknowledgements

IEEE thanks ENMAX Power Corp. for permission to use the modified version of its Hosting Capacity Map in Figure 5.

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# IEEE Recommended Practice for Electric Power Distribution System Analysis

## 1. Overview

### 1.1 Scope

This document defines recommendations for steady-state, event-based, probabilistic, stochastic, and dynamic analysis of electric utility power distribution systems. Industrial and commercial power distribution systems, harmonic analysis, and electromagnetic transient analysis are all excluded.

### 1.2 Purpose

Many commercial software products and academic research projects continue to use analysis methods appropriate for transmission systems, but not for distribution systems. Many research papers submitted for publication still address questions that have been well-settled by previous work. The purpose of this recommended practice is to focus research attention on areas where legitimate needs exist, to identify methods that should not be used in software products, and to provide guidance on the application of new analysis methods to electric utility distribution systems.

### 1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).<sup>6,7</sup>

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

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<sup>6</sup> The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

<sup>7</sup> The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

## 2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C84.1, American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz).<sup>8</sup>

IEC 61968-11, Application integration at electric utilities—System interfaces for distribution management—Part 11: Common information model (CIM) extensions for distribution.<sup>9</sup>

IEC 61968-13, Application integration at electric utilities—System interfaces for distribution management—Part 13: CIM RDF Model exchange format for distribution.

IEC 61970-301, Energy management system application program interface (EMS-API)—Part 301: Common information model (CIM) base.

IEC 61970-302, Energy management system application program interface (EMS-API)—Part 302: Common information model (CIM) dynamics.

IEEE PES Test Feeders, IEEE PES Distribution Analysis Subcommittee's Distribution Test Feeder Working Group (TFWG), <https://cmte.ieee.org/pes-testfeeders/resources/>.<sup>10</sup>

IEEE Std C37.010™, IEEE Application Guide for AC High-Voltage Circuit Breakers > 1000 Vac Rated on a Symmetrical Current Basis.<sup>11, 12</sup>

IEEE Std 519™, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.

IEEE Std 1453™, IEEE Standard for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems.

IEEE Std 1547™, IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces.

IEEE Std 1547.1™, IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems.

IEEE Std 1547.2™, IEEE Application Guide for IEEE Std 1547, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems.

IEEE Std 1547.6™, IEEE Recommended Practice for Interconnecting Distributed Resources with Electric Power Systems Distribution Secondary Networks.

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<sup>8</sup> ANSI publications are available from the American National Standards Institute (<https://www.ansi.org/>).

<sup>9</sup> IEC publications are available from the International Electrotechnical Commission (<https://www.iec.ch>) and the American National Standards Institute (<https://www.ansi.org/>).

<sup>10</sup> Informative electronic versions of the Distribution Test Feeders are being migrated to an IEEE Open-Source platform [B59].

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IEEE Std 1547.7™, IEEE Guide for Conducting Distribution Impact Studies for Distributed Resource Interconnection.

IEEE Std 2800™, IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems.

### 3. Definitions, acronyms, and abbreviations

#### 3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.<sup>13</sup>

**astable:** Capable of oscillating between two states.

**baseline hosting capacity:** Hosting capacity (HC) established using existing power system infrastructure, configuration, and control, resulting in no adverse impact on its reliability, power quality, safety, or the operation of existing or other planned connections.

**bus:** A grouping of electrical connection points consisting of one or more nodes, incorporating one or more phases, and possibly including neutral conductors. The phases at a bus need not be numbered or lettered consecutively. Connection points for communication circuits or other non-power conductors are not part of the bus.

**control (primary):** Purposeful action to stabilize voltage and frequency.

**control (secondary):** Purposeful action to eliminate steady-state deviations of voltage and frequency from their nominal values.

**control (tertiary):** Purposeful action to achieve economic operation in a fleet of resources.

**distribution system (DS):** That portion of an electric system that delivers electric energy from transformation points on the transmission system to the customer (IEEE Std 1366™).

NOTE 1—The DS is generally considered to be anything from the distribution substation boundary (fence or wall) to the customer meter. Often, the initial overcurrent protection and voltage regulators are within the substation boundary and are considered part of the DS. (Adapted from IEEE Std 1366).<sup>14</sup>

NOTE 2—Analysis of the DS should include the distribution substation transformer and at least a source equivalent of the transmission system.

NOTE 3—An isolated DS may be supplied from local generation rather than a transmission system. In such cases, a model for analysis of the DS should include at least a source equivalent of the local generation, plus the generator interconnection transformers, if present.

**distributed energy resource (DER):** A source of electric power that is not directly connected to a transmission system.<sup>15</sup> DER includes both generators and energy storage technologies capable of exporting

<sup>13</sup> *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

<sup>14</sup> Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

<sup>15</sup> IEEE Std 1547-2018 and IEEE Std 2800™-2022 ambiguously define “bulk power system (BPS): Any electric generation resources, transmission lines, interconnections with neighboring systems, and associated equipment,” which seems to encompass distribution. In this recommended practice, *transmission system* has been substituted for *bulk power system*.

active power to an electric power system. An interconnection system or a supplemental DER device that is necessary for compliance with IEEE Std 1547™ is part of a DER. (Adapted from IEEE Std 1547-2018)

**distribution system analysis tool (DSAT):** Refers to a computer program with supporting data files that performs voltage and current calculations on a model of an electric power distribution system (DS).

**dynamics:** Time-domain or fast-phasor analysis of machine and inverter-based resource (IBR) behavior on the electric power distribution system (DS), including the effects of phase unbalance and controls, simulated at time steps of 200 microseconds or longer.

**enhanced hosting capacity:** Hosting capacity (HC) established using the metrics of the baseline HC while considering adjustments to power system controls or grid support from distributed energy resources (DERs). Multiple scenarios may be provided depending on the technology and settings considered.

**feeder:** Refers to any medium-voltage distribution circuit, possibly including low-voltage secondary circuits. It need not be radially configured.

**hosting capacity (HC):** A preliminary assessment of the distributed energy resource (DER) capacity that an electric power distribution system (DS) can accommodate at specified locations without adversely impacting its operation or the operation of its clients according to a specified methodology and metrics.

**hosting capacity analysis (HCA):** A study intended to assess the ability of the distribution system (DS) to support the addition of a distributed energy resource (DER). These assessments are intended to provide public information to individuals and entities who might be interested in adding a DER to the grid. These studies are accomplished without knowledge of the location, size, or characteristics of any project(s) yet to be proposed. Once a project is proposed, further analysis is frequently required in the form of a system impact study (SIS).

**location:** Area, site, segment, bus, or node of an electric power distribution system (DS) for the purpose of analysis.

**network protector (NWP):** An assembly composed of a circuit breaker and its complete control equipment for automatically disconnecting a transformer from a secondary network in response to predetermined electrical conditions on the primary feeder or transformer and for connecting a transformer to a secondary network through manual or automatic control responsive to predetermined electrical conditions on the feeder and the secondary network. The NWP is usually arranged to automatically connect its associated transformer to the network when conditions are such that the transformer, when connected, will supply power to the network and to automatically disconnect the transformer from the network when power flows from the network to the transformer.

**node:** A single electrical connection point for power system conductors. One or more nodes may be collected into a bus. Either phase or neutral conductors may be connected at a node; all such conductors entering the node are connected to each other.

**state variable:** A variable that defines one of the characteristics of a system, component, or simulation. The values of all such variables define the state of the system, component, or simulation.

**stiff system:** A power system that is resistant to deviations in frequency and voltage resulting from disturbances in load or generation.

**system impact study (SIS):** Determines whether and how a specific distributed energy resource (DER) interconnection meets the requirements of a relevant grid code or authority having jurisdiction over the project. Hosting capacity analysis (HCA) deals with prospective interconnections; SIS deals with concrete interconnections and are covered in IEEE Std 1547.7™.

**thermal hosting capacity:** Hosting capacity (HC) calculated using the thermal limit metric of the existing and planned system and interconnection infrastructure.

**time step:** The length of time between each numerical update or iteration in a dynamic simulation.

**total harmonic distortion (THD):** The ratio of the root-mean-square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding inter-harmonics, expressed as a percent of the fundamental. Harmonic components of order greater than 50 may be included when necessary. See IEEE Std 519™.

**transmission system (TS):** A high-voltage electric power system for delivering power, usually over a long distance. (IEEE Std C37.246™).

NOTE—There is no universal voltage boundary between the distribution system (DS) and the transmission system. Other IEEE standards may define the breakpoint between medium voltage and high voltage as 35 kV, 52 kV, 69 kV, or 100 kV. Some utility DS voltages are above 35 kV, while some utility TS voltages are below 100 kV. Lower-voltage TS systems are sometimes called sub-transmission but still treated as part of the TS. The utility or a regulatory authority specifies the DS/TS voltage boundary. For example, in the United States and Canada, NERC defines the transmission-related terms bulk electric system and bulk power system (NERC Rules of Procedure [B83]<sup>16</sup>).<sup>17</sup>

**X/R ratio:** The ratio of the system inductive reactance to resistance. It is proportional to the time constant  $L/R$  and is, therefore, indicative of the rate of decay of any dc offset. A large X/R ratio corresponds to a large time constant and a slow rate of decay, whereas a small X/R ratio indicates a small time constant and a fast rate of decay of the dc offset. See IEEE Std C37.010™.

### 3.2 Acronyms and abbreviations

|      |                                   |
|------|-----------------------------------|
| AC   | alternating current               |
| CIM  | Common Information Model          |
| COG  | coefficient of grounding          |
| DC   | direct current                    |
| DER  | distributed energy resource       |
| DS   | distribution system               |
| DSAT | distribution system analysis tool |
| DTT  | direct transfer trip              |
| EFF  | earth fault factor                |
| EMT  | electromagnetic transient         |
| GFL  | grid-following inverter           |
| GFM  | grid-forming inverter             |

<sup>16</sup> The numbers in brackets correspond to those of the bibliography in Annex A.

<sup>17</sup> Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

|      |                                                                 |
|------|-----------------------------------------------------------------|
| GIS  | geographical information system                                 |
| HC   | hosting capacity                                                |
| HCA  | hosting capacity analysis                                       |
| HVDC | high-voltage direct current                                     |
| IBR  | inverter-based resource                                         |
| ICA  | interconnection capacity analysis                               |
| IOU  | investor-owned utility                                          |
| LDC  | line drop compensation                                          |
| NWP  | network protector                                               |
| ODE  | ordinary differential equation                                  |
| OLRT | open-loop response time                                         |
| PCC  | point of common coupling                                        |
| PI   | proportional-integral controller                                |
| PLL  | phase-locked loop                                               |
| PoC  | point of connection                                             |
| PV   | photovoltaic                                                    |
| QSTS | quasi-static time series                                        |
| RMS  | root mean square                                                |
| RPA  | reference point of applicability                                |
| RVC  | rapid voltage change                                            |
| SIS  | system impact study                                             |
| THD  | total harmonic distortion                                       |
| TS   | transmission system                                             |
| VFD  | variable-frequency drive                                        |
| VSC  | voltage-source converter                                        |
| ZIP  | constant impedance, constant current, constant power load model |

## 4. Recommendations for test feeders

### 4.1 General

These recommended practices apply to electric utility power distribution systems (DSs). For industrial and commercial power DSs, the IEEE Color Books (IEEE 3000 Standards Collection®) (IEEE Std 3002.2™-2018 [B46]; IEEE Std 3002.3™-2018 [B47]; IEEE Std 3002.7™-2018 [B48]; IEEE Std 3002.8™-2018 [B49]) and IEEE P3002.9 [B42]<sup>18</sup> provide more information.

Many power system analysis textbooks focus on high-voltage transmission systems (TS), but those by Gonen [B38], Kersting and Kerestes [B60], and Short [B107] provide a starting point for the study of analytical techniques that are appropriate for medium-voltage DSs. A test feeder is a model of an electric power DS that has been published on the normative distribution test feeders website by the IEEE PES Distribution System Analysis Subcommittee. The background and motivation for test feeders has been described in papers by Dugan et al. [B18]; Dugan et al. [B19]; Kersting [B56]; Kersting [B57]; Kersting and Dugan [B58].

### 4.2 Selection of test feeders to use

The test feeders have each been developed for different applications (Schneider et al. [B106]), and users should select the corresponding test feeder to fit their applications<sup>19</sup>. Most of them are based on simplifications of actual feeders.

- a) 4-bus test feeder covers unbalanced transformer connections.
- b) 13-bus test feeder provides a severely unbalanced system, designed for testing algorithm convergence.
- c) 34-bus test feeder is very long, designed for testing the voltage regulator models.
- d) 37-bus test feeder provides a three-wire delta ungrounded (and underground) system, designed for testing algorithm convergence without ground connections. This configuration is uncommon.
- e) 123-bus test feeder provides a mixture of overhead and underground, single-phase and two-phase laterals, voltage regulators, and shunt capacitors. It has been used to test switching algorithms.
- f) 8500-node test feeder provides a large system, with 2500 medium-voltage buses and 2300 low-voltage buses, comprising different numbers of phases at each bus.
- g) Comprehensive test feeder provides one system with nearly every possible type of DS component and connection.
- h) Neutral-earth voltage test feeder provides a situation with circuits coupled on the same right-of-way, explicitly modeled neutral conductors, and neutral-to-earth impedances.
- i) Low-voltage network test system provides a densely meshed secondary network, served by four radial primary feeders and two substations, typical of urban distribution in North America.
- j) European low-voltage test feeder provides a 400-V radial unbalanced distribution circuit, typical of the United Kingdom. Unlike the others, this feeder operates at 50 Hz.
- k) 9500-node test system has been proposed but has not yet been adopted (Fuller [B35]). This was based on the 8500-node test feeder, adding two substations, distributed energy resources (DER), and switching devices for islanding and reconfiguration.

<sup>18</sup> IEEE 3000 Standards Collection® (formerly known as the IEEE Color Books®) is the family of industrial and commercial power systems standards that is organized into “dot” standards that cover specific technical topics, which have been reorganized and, in some cases, updated from the content of the IEEE Color Books (<https://ieeexplore.ieee.org/browse/standards/collection/ieee/power-and-energy/3000StandardsCollection>).

<sup>19</sup> Informative electronic versions of the distribution test feeders are being migrated to an IEEE open-source platform (Kersting [B59]).

### 4.3 Method of reporting results

The reported result of a test feeder solution should contain at least the following items:

- a) Injected P and Q at the source, independently by phase. For wye systems, the phase-to-neutral values are reported, and for delta systems, the phase-to-phase values are reported; six values.
- b) Summation of  $I^2R$  and  $I^2X$  losses in series elements (lines and transformers) and shunt elements, summing all phases; four values.
- c) Minimum and maximum voltage by phase; six values.
- d) If applicable, the tap setting of each regulating control. N tap setting values for N regulators.
- e) If applicable, the on/off status of each capacitor bank. N status values for N capacitors.
- f) If applicable, the on/off status of each switch. N status values for N switches.
- g) If applicable, the mechanical speed and air-gap torque of each rotating machine.  $2 \times N$  values for N machines. In summary reports of circuits with many machines, the total active and reactive power injection over all machines may be reported instead.
- h) If applicable, the active and reactive power injection from each inverter.  $2 \times N$  values for N inverters. In summary reports of circuits with many inverters, the total active and reactive power injection over all inverters may be reported instead.
- i) Statement of which distribution system analysis tool (DSAT), including version, was used to obtain the solution.

Two solutions should be compared on the above items, in addition to:

- The sum-of-squares difference between their voltage profiles at every node, normalized by the number of nodes; one value
- The sum-of-squares difference between their current magnitudes in every branch, normalized by the number of branches; one value

For example, the 13-bus test feeder has three regulators, and the capacitor banks are fixed, so this reporting format would include 19 values. In comparing two solutions of this test feeder, there would be 32 nodes for normalization of the voltage profile difference.

The preceding describes a minimum set of compared solution variables for summary reports and publications. It is recommended that each node voltage and each branch current be compared systematically, by phase, in both magnitude and angle. Summary comparison reports should include:

- Maximum and mean absolute errors in all node voltage magnitudes
- Maximum and mean absolute errors in all branch current magnitudes

### 4.4 Method of developing new test feeders

At any given time, it is unlikely that the published set of test feeders will satisfy every need for DSAT test circuit data. To extend the test feeders, users should first consider the following options, listed in order of increasing complexity:

- a) Switch published test feeder components in or out of service.
- b) Add controller parameters to regulators, capacitor banks, loads, and switches.
- c) Add parameter variations to the published test feeder data.
- d) Add new shunt components (e.g., a distributed resource) to an existing test feeder bus.
- e) Add switches to the published test feeder data. Switches should be located within a published test feeder line segment, at either end of the segment as specified by the nearest bus number.

In each case, the model changes should be documented with reference to the published test feeder data as the base case. Once approved, test feeders should not be withdrawn. Instead, corrections and clarifications should be published as necessary. To add a new test feeder, users should contact the Test Feeder Working Group (TFWG), which functions under the technical committee structure of the IEEE PES. The TFWG meets regularly at IEEE PES general meetings and at some other IEEE PES conferences.

#### 4.5 Recommendations for researchers

Researchers should include results from at least one test feeder in their submitted papers. This practice will help authors clearly identify their contributions while reducing their burden of publishing system data. It will also help readers understand the paper's contribution and replicate its results.

Researchers should consider the addition of time-series analysis and stochastic analysis to the test feeders.

#### 4.6 Recommendations for DSAT providers

DSAT providers should supply example data files for one or more test feeders. This practice will provide documented and accepted examples for user education and training.

#### 4.7 Recommendations for DSAT users

DSAT users should evaluate their DSAT's ability to solve each of the test feeders, including these points:

- a) Phase component modeling and analysis should be offered in addition to or instead of symmetrical components.
- b) Single-phase and two-phase components and subsystems should be modeled and solved.
- c) Transformers with center-tapped secondary windings should be modeled and solved.
- d) Open wye, open delta, and other unbalanced transformer connections should be modeled and solved.
- e) It should be possible to either retain the neutral conductors or eliminate them from the model by matrix reduction operations.

These points only address potential weaknesses in the correct load flow solution of unbalanced power DSs. For many applications, additional modeling and analysis features will be needed.

#### 4.8 Recommendations for data exchange formats

DSAT providers should support IEC 61970-301<sup>20</sup> and IEC 61970-302 for distribution network model exchange, including control functions from IEEE Std 1547 and other dynamics. During a transition period in the reorganization of common information model (CIM) standards, IEC 61968-11 and IEC 61968-13 should also be consulted for information on CIM asset attributes that contribute to a network model. DSAT providers should also consider supporting other non-standard but widely adopted data exchange formats such as the MultiSpeak Specification (National Rural Electric Cooperative Association [B81]). These practices will reduce the burden of collecting data from disparate sources. They will also allow users to extend their DSAT capabilities, and more readily provide actual system data to researchers (Melton et al. [B74]; Mukherjee et al. [B77]).

For new CIM adopters, a freely available tutorial introduction has been provided in EPRI Report 3002026852 [B31]. Open-source documentation, examples, conversion code, and solution comparison code for CIM-based distribution models have been provided by the Battelle Memorial Institute [B9]. Annex F of

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<sup>20</sup> Information on references can be found in Clause 2.

IEEE 1547.2™-2023 [B43] describes the use of CIM for DER modeling. It also provides the information needed to map comma-separated value files of DER control and rating attributes, as defined in IEEE Std 1547.1™, into CIM attributes for IEC 61970-302.

Developers of these data exchange formats should use one or more test feeders in their interoperability tests and should verify that all published test feeders can be expressed and exchanged in the subject format.

## 5. Hosting capacity analysis

### 5.1 General

Distribution system impact studies (SISs) for DER interconnection, as defined in IEEE Std 1547.7, require well-defined system models, DS analysis software, and an accurate time series for system loads and connected generation to be effective. The rigor, complexity, and cost required to do this type of analysis may not allow utilities to provide DER proponents with timely and accurate responses to connection requests. Automating the data management and analysis steps should be considered to improve responses to connection requests. Even with such automation, the industry requires a quick and accurate framework using agreed-upon parameters to separate and flag those DER connections that will pass the more rigorous SIS; those that may pass or fail, and those that will fail. This will provide proponents with the ability to understand the project risk they face and make decisions to proceed, or not, early in the project process.

In this regard, hosting capacity (HC) as a planning tool has attracted the attention of utilities, researchers, and practitioners (IEC TS 63276:2024 [B41]). HC refers to the maximum additional capacity of DER that an electric power DS can accommodate at specified locations without adversely impacting its operation or the operation of its clients according to a specified methodology and metrics. The hosting capacity analysis (HCA) discussed in this guide uses similar methods as SIS but with less information. Stakeholders may use HC results to de-risk proposed DER connections. A comprehensive HCA monitors technical constraints like voltage violations, power loss, power quality, thermal overloading, or protection devices for different DER penetration levels.

HC is a term that was in use prior to and contemporaneously with the creation of this guide. The definition adopted here synthesizes the various definitions and provides a reference that is believed to be compatible with existing usages. A simple search for “hosting capacity” in any Internet search tool will bring up a variety of existing but similar definitions. The state of Illinois, USA, uses the term in its laws and regulations as follows: “**hosting capacity** is an estimate of the amount of DER and electric vehicles that may be safely and reliably accommodated under current configurations at the overall circuit level without significant system upgrades to address adverse system impacts” (Commonwealth Edison [B13]). A utility definition from Canada offers that an HC calculation provides “general information to customers to allow them to identify areas where interconnections could be added which may require fewer significant modifications” to the utility distribution system (ENMAX [B23]).

Therefore, this clause:

- Describes the technical constraints and metrics that should be considered in HCA
- Highlights the information required to be collected to perform HCA
- Discusses existing evaluation methods and techniques

The acceptable limits of these technical constraints are not specified in this clause. Instead, these limits are to be determined by the user, from international standards, national standards, or local regulations. However, Annex B provides illustrative examples of how such limits may be determined, which may be generalized to different systems. The limits should be used as inputs to the evaluation methods described in this clause. The acceptable HCA limits are based on existing system topology, consumer assets, and system operational

support mechanisms. The process considers normal system operation configuration and does not consider optimal system configuration, expansion studies, or system reconfiguration.

The methodology is tailored to the size and technical ability of the utility responding to a proponent. The guide applies to voltage levels that are customary for DSs in the jurisdiction under study. This clause does not discuss the market aspect of the DS with the presence of consumer technologies, and therefore the financial impacts of technical decisions. Although this clause does not specifically discuss mitigation techniques, the constraining technical parameters discussed as part of the HCA will assist users in identifying suitable HC improvement strategies (Radatz, Rylander, and Kerr [B92]). Mitigation measures, such as new control settings, equipment, conductors, and control loops for curtailment during peak events, may not be cost prohibitive to the project. An example of mitigation using var support is provided in B.5.

This clause also identifies various ways to present the evaluation results in the public domain. Tabular and geospatial presentations are discussed. This clause describes the technical constraints that should be considered in evaluating HC, the information required to be collected to undertake an HC evaluation, and evaluation methods.

Note that whereas the proponent of a DER installation is attempting to find a suitable geospatial location (address) to build the DER upon, the utility is concerned about the impact of the DER on the DS at the point of connection (PoC), the point of common coupling (PCC), or the reference point of applicability (RPA). Therefore, when calculating the limitations for a DER at a given geospatial location, the utility should communicate whether the HCA metrics are applied at the PoC, the PCC, or the RPA.

While HCA can provide a significant indication of the feasibility of a project, it does not encompass all the parameters needed to assess the innocuity of an interconnection. Consequently, utilities will generally proceed with an SIS to assess the project in more detail. In some cases, utilities will use interconnection screens to simplify the study for those projects that, due to their nature, location, or size, are deemed to satisfy some or all system impact requirements without proceeding to all the detailed analysis. One example of an interconnection screening criterion is based on DER type, e.g., if the DER is a large rotating machine, the utility may mandate direct transfer trip (DTT) without further study. In contrast, for PV systems, DTT may only be required after electromagnetic transient (EMT) simulations. Another common screening criterion is based on DER size. For example, smaller systems, such as those under 25 kW, may not require additional study. Figure 1 illustrates the continuum of studies.

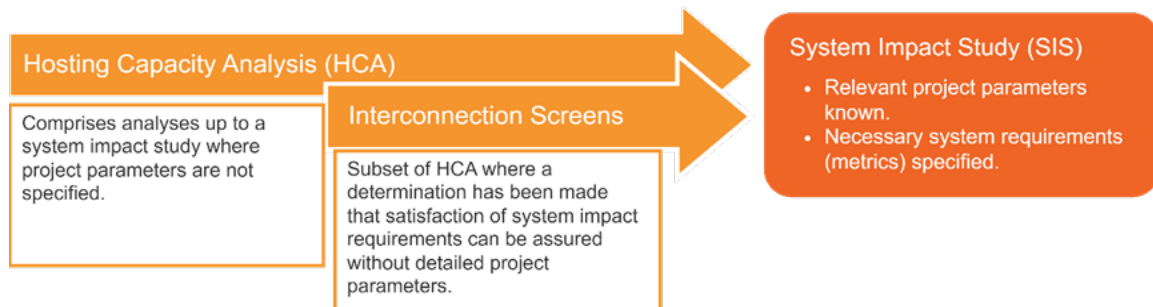


Figure 1—Scopes of HCA, interconnection screen, and SIS

## 5.2 Hosting capacity analysis evaluation metrics

### 5.2.1 General

The metrics that may be used to evaluate the HC of a DS are listed below. The choice of which metrics to use to evaluate the HC of a given DS in each jurisdiction depends on:

- The chosen evaluation method

- The grid codes and regulatory requirements to which the utility are subjected
- Utility preference, where permitted

The rest of this clause describes how HCA metrics derive from the possible system impacts of DER.

## 5.2.2 System or equipment thermal limits

Establish thermal limits for all equipment at all voltage levels of the DS, including transformers, fuses, breakers, regulators, conductors, etc., based on maximum continuous permissible amperage or kVA rating. Thermal limits would be based on typical data, manufacturer's recommendations, or established computational methods.

## 5.2.3 Voltage deviation

### 5.2.3.1 General

Maintain the voltage characteristics within limits in the system under study based on local or national standards. Table 1 summarizes the potential voltage deviations and their relevance for HCA.

**Table 1—Voltage issues that can be caused by DER interconnection**

| Type of deviation/issue              | Definition                                                                                                                                                                                                                                                                                                                                                                                                                                           | Relevance to HCA                                                                                                                                                                                                                                                                             | Metric(s)/methods if any                                                                                                            |
|--------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| 5.2.3.2 Voltage change               | Voltage change is defined in IEEE Std 1159™ as a variation of the root-mean-square (RMS) or peak value of a voltage between two consecutive levels over some time interval.                                                                                                                                                                                                                                                                          | Yes, considering the amount of active and/or reactive power injected at PCC. Depends on DER size in proportion to system strength.<br><br>Reporting limits with and without this metric can provide an indication to the added value of local equipment or control to reduce voltage change. | Typically 3% to 5%<br>ANSI C84.1 Range A tables<br>IEEE Std 1159<br>IEEE Std 1453<br>Evaluation method described in IEEE Std 1547.2 |
| 5.2.3.3 Undervoltage and overvoltage | Undervoltage and overvoltage are defined in ANSI C84.1 as sustained voltages that exceed the limits of Range A ( $\pm 5\%$ ).                                                                                                                                                                                                                                                                                                                        | Yes, considering the amount of active and/or reactive power injected at PCC. Depends on DER size in proportion to system strength.                                                                                                                                                           | ANSI C84.1 Range A tables<br>IEEE Std 1159                                                                                          |
| 5.2.3.4 Voltage unbalance            | Voltage unbalance in a three-phase system can be calculated in different ways depending on the available data.<br><br>The simplest method is to calculate the absolute value of the maximum deviation of the line voltage from the average voltage on a three-phase system, divided by the average.<br><br>The preferred method is to calculate the ratio of negative sequence to the positive sequence voltage components. See 5.2.3.4 for details. | Yes. This metric can be addressed in HCA, though it has not been commonly adopted in industry. If done, single-phase DER should be included.                                                                                                                                                 | ANSI C84.1 recommends that voltage unbalance should be limited to 3%, measured under no-load conditions.                            |
| 5.2.3.5 Voltage flicker              | The subjective impression of fluctuating lighting luminance caused by fluctuations in the supply voltage.                                                                                                                                                                                                                                                                                                                                            | No. This metric needs to be addressed in the SIS.                                                                                                                                                                                                                                            | IEEE Std 1453 defines the metrics.                                                                                                  |

### 5.2.3.2 Voltage change

Voltage change is a measure of the magnitude of the voltage difference between two separate conditions on the power system, nominally the difference between the system with and without (or reduced) any proposed DER (considering active and reactive power). In the case of storage systems, charging to discharging conditions can be considered appropriate, unless operating restrictions or limitations preclude rapid transition between full charging and full discharging. Furthermore, energy storage use cases may or may not require rapid changes of output. If ramping limits are to be imposed on such systems, this should be reflected in studies. Other conditions may be appropriate, such as the presence of reactive support (capacitors or reactors), or voltage regulator, or distribution transformer tap settings. Voltage change is a measure of the power system strength, regulation, and voltage stability margin and, along with thermal limits, is a primary indicator of the utility's capacity to accommodate the prospective connection or operation of a DER. Because they are easier to check and require less data, thermal limits might be checked first, but voltage limits and voltage change at each bus within the evaluation scope should be considered unless the HC predicted by thermal limitations is prohibitive.

There are various situations where voltage change is considered in the evaluation of power system behavior:

- *Voltage stability*, as voltage change is a primary indication of the relative strength of the DER with respect to the DS point of connection. It is an indicator of voltage collapse margin.
- *Synchronization voltage change* is limited to no more than 3% to 5% according to IEEE Std 1547-2018 subclause 4.10.5.
- *Rapid voltage change (RVC)* is defined in IEEE Std 1453<sup>21</sup>. In IEEE Std 1547-2018, the RVC is to be evaluated over a period of one second and is limited to no more than 3% to 5% in subclause 7.2.2. RVC focuses on repeated energization events, such as capacitor switching or transformer inrush, and is explicitly not intended for weather-related DER fluctuations. Repeated instances of RVC are also related to flicker.
- *Change of regulator taps*, e.g., due to a change in DER production, could indicate the potential for increased wear and tear.

In HCA, considering all four situations, the same evaluation technique can be used to obtain the voltage change, the only difference being the time component.

Given the various motivations, industry practice is frequently to lump everything together and perform a simple change of voltage test between a system with and without (or with reduced) DER output. As the use cases suggest, however, care should be given to the location where the metric is enforced and its magnitude. For example, regulator tap changer concerns should focus on voltage changes at regulator buses only, unless line drop compensation (LDC) is used. If LDC is used, this focus should be on the voltage changes at the apparent regulation point as determined by the LDC resistance and reactance settings. Voltage change at the regulator bus (or apparent regulation location) may be limited to less than the regulator bandwidth (typically 3%) to make sure no tap is changed. Reporting HCA limits with and without voltage change enforced could be useful to convey that, with some additional equipment/controls, larger DER capacities may be accommodated.

### 5.2.3.3 Overvoltage and undervoltage

The maximum positive and negative voltage deviation should be based on the principle that the voltage remains within the allowable envelope(s) after all existing DER and the proposed DER are connected. The voltage of each bus within the evaluation scope should be checked. Maximum and minimum loading on the connecting circuit should be considered as well.

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<sup>21</sup> rapid voltage change (RVC): An abrupt transition in RMS voltage occurring over several cycles between two steady-state conditions and during which the RMS voltage does not exceed the dip or swell threshold; rapid voltage changes may also be in the form of cyclic changes. NOTE—Rapid voltage changes are often caused by start-ups, inrush currents, or switching operations of equipment.

### 5.2.3.4 Voltage unbalance

In a three-phase DS, the connection of the proposed DER should not cause the three-phase voltage unbalance in the DS to exceed the limit. If the limit is exceeded under existing operational conditions, the connection of the proposed DER should not exacerbate but may improve the unbalance. The voltage of each three-phase bus within the evaluation scope should be checked.

The preferred metric is the ratio of negative sequence to positive sequence voltage magnitude. If the phase voltage angles are not available for this calculation, the method of IEEE Std 1159 should be used in Equation (1).

$$\%Imbalance = 100 \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \quad (1)$$

where

$\beta$  is defined in Equation (2).

$$\beta = \frac{|V_{AB}|^4 + |V_{BC}|^4 + |V_{CA}|^4}{(|V_{AB}|^2 + |V_{BC}|^2 + |V_{CA}|^2)^2} \quad (2)$$

### 5.2.3.5 Voltage flicker

Flicker is the subjective impression of fluctuating lighting luminance caused by fluctuations in the supply voltage<sup>22</sup>. Flicker severity is measured and calculated with respect to both short-term and long-term effects. Flicker evaluation includes the frequency of occurrence, whereas RVC evaluation only includes the magnitude of  $\Delta V$ . Table 3 of IEEE Std 1453 allows no more than ten RVC events per hour at 3% at medium voltage. For more frequent fluctuations, e.g., due to wind turbines, subclause 7.2.3 of IEEE Std 1547 allows flicker emission limits of 0.35 for ten minutes ( $E_{Pst}$ ) and 0.25 for two hours ( $E_{Pht}$ ).

Wind-based DER may have flicker test reports available according to IEC 61400-21-1 (Barahona et al. [B6]). Flicker performance depends on the wind turbine and interconnection control design, so these test reports are valuable for impact studies of specific projects, but unsuitable for HCA.

For DER other than wind, the RVC evaluation should already suffice with a limit of ten RVC per hour. The evaluation should establish that  $\Delta V$  is within the limit for the maximum expected variations in DER output averaged over 1 second, and for any frequent transformer or capacitor switching expected in normal operation. The evaluation should include the effects of system load on the magnitude of  $\Delta V$ , which may increase with system loading due to a lower  $X/R$  ratio. The load effect on  $X/R$  ratio may also result in different magnitudes of  $\Delta V$  for different polarities of the same  $\Delta P$  magnitude. Per IEEE Std 1547-2018 subclause 7.2.2, RVC does not include infrequent switching operations, e.g., unplanned tripping, fault restoration, or maintenance. Nor does RVC include slow DER output variations, i.e., those taking longer than 1 second.

### 5.2.4 Reverse flow

DSs are typically radial with power flowing from the substation to loads. Adding DER may result in power flowing in the opposite direction on any point of the system when the downstream load is lower than the local generation. The amount of steady-state current flowing in the opposite direction, e.g., from a DER or aggregation of DER to the DS, or from the DS to the TS, may be limited, constrained, or prevented by the following:

- Regulatory requirements, e.g., national, provincial, or state grid codes

<sup>22</sup> See IEEE Std 1453 and CSA Std C22.3 No.9:20, subclause 8.3.13.

- Utility practice or preference, e.g., islanding concerns
- Existing utility equipment, e.g., voltage regulator capabilities, network protection
- Technical requirements, e.g., station design limitations

The consideration of reverse power flow in HCA is important for ensuring the reliability, safety, and efficiency of DSs in the face of growing DER integrations. Reverse power flow occurs when DERs, like solar panels, generate more power than the demand. Reverse power flow can pose challenges to the operational integrity of voltage regulators, protection devices, and automation systems in the DS. Exceeding limits on these devices can lead to service disruptions, equipment damage, and violations of safety protocols. Protection systems, traditionally designed to recognize conventional flow patterns, may not function correctly under reverse power flow conditions. This potential malfunction increases the risk of network failures and safety incidents. Furthermore, reversed or reduced power flow contributes to the risk of unintentional islanding. In such cases, local DERs keep parts of the grid energized during broader outages, complicating restoration efforts and posing risks to maintenance personnel. To help ensure the DS's automation and protection devices operate correctly, it is important to manage reverse power flow effectively.

Utilities typically restrict reverse power flow at substations and areas close to critical network infrastructure, such as protection equipment and voltage regulators, to help prevent operational disruptions and degradation of system performance. Setting these limitations involves a careful assessment of the network, with restrictions tailored to the specific needs and capabilities of local infrastructure. Each utility should define its limits on the reverse power flow based on the factors discussed above. Utilities may consider updating some of the settings of protection and automation equipment to enable reverse power flow to increase HC.

For performance reasons, HCA should consider reverse power flow only for those elements of the feeder that have identified limitations to reverse power flow. At the HCA mapping stage, it is typically too onerous to analyze the full generation/load profile. That should be left to the screening stage or for the SIS. Maximum generation and minimum load is the operating scenario to consider if the reverse flow is a concern.

### 5.2.5 Excessive operation of voltage management equipment

The introduction of DER to the DS may increase the number of operations of existing or new voltage regulators, including tap-changers and shunt capacitor banks on the DS, including on-load tap changers in the substation. Although it is often assumed that the increased operations result in increased maintenance of the equipment, this may or may not be the case and requires study to determine the correct conclusion. Typically, maintenance of voltage management equipment is determined by two parameters:

- The number of operations of the device
- The current level at the time of operation

Both factors should be reviewed to determine if or when the addition of a DER is having a detrimental effect on the operation of the equipment. Typically, HCA does not extend to this detail.

### 5.2.6 Reactive power consumption limitations

DSs feed loads that require both active and reactive power. Where a DER is connected to the DS, it is common that the DER only supplies active power to the DS, potentially leaving the TS as the primary source of reactive power. In addition, in some cases, DER will be required to draw reactive power to avoid overvoltage at the PCC. This may result in a deficit of reactive power at the substation (low power factor) or increased losses in the power system. Reactive power/power factor should be evaluated at every point of exchange where the power factor is constrained.

HC may be limited by:

- Existing reactive power compensation capacity (capacitors, static var compensators)
- TS requirements
- Power factor regulatory requirements

### 5.2.7 Short-circuit current

The short-circuit current at any point in the DS should not exceed the allowable limit to help ensure compliance with the equipment current rating. The available single and three-phase short-circuit current, including the effect of angle, should be calculated with all existing DER and the proposed DER connected and operating at rated nameplate output.

Given typical  $X/R$  ratios of machines and power systems, fault current supplied by a rotating machine typically has a phase angle close to negative 90 degrees with respect to its internal electromotive force. For power systems dominated by rotating machines, the fault current also has a phase angle close to negative 90 degrees with respect to the source voltage. Fault current contributions from two or more sources should be added as complex numbers. However, when all contributions have nearly the same phase angle, the simpler addition of magnitudes could be justified, and the resulting values would be slightly higher fault current magnitude. The simplified addition of magnitudes is less valid when the phase angles differ by more than 10 degrees, i.e., the results will overestimate the total. One such condition occurs when the fault occurs out on the feeder, because distribution line conductors have low  $X/R$  ratios, so the utility source fault contribution may be close to negative 40 degrees, while contributions from local rotating machine DER are still close to negative 90 degrees. Another such condition occurs when local inverter-based resources (IBR) provide fault current contributions, which are close to 0 degrees. If the HC criteria include a limit on fuse fault currents, this angle effect should be included, especially if there are separate hosting capacities for IBR and rotating machine DER<sup>23</sup>. There are other important effects of phase angle, e.g., on ground relay desensitization or distance relay applications, but these effects are more relevant to SIS. B.3.7 contains an example with fuse fault currents.

### 5.2.8 Protection schema

Protection can be incorporated into HCA, assuming existing utility devices and IEEE 1547-compliant DER devices. A rule-based protection system analysis may be performed based on fault current calculations. An event-based protection system analysis may be performed based on quasi-static time series (QSTS) simulations (6.2.3). The protection schema integrity should be investigated with

- All existing DER and the proposed DER connected, and
- All existing DER and the proposed DER disconnected

Minor adjustments to the settings of protection equipment should generally be acceptable if they do not require replacement of equipment or a protection strategy upgrade. For example, adjust minimum trip settings of devices so they do not trip due to downstream DER, replace older mid-feeder devices with directional devices, replace single-phase devices with gang-operated devices, etc. DER operation conditions when connected should capture viable worst-case conditions.

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<sup>23</sup> Lacking details of future DER interconnections, this requires assumptions for the short-circuit magnitudes and angles of DER short-circuit contributions. Use typical values from Table 7 or IEEE 1547.2-2023, subclause 11.6.

### 5.2.9 Harmonics

The harmonic limits should be based on the principle that the total harmonic distortion (THD) of the voltage of the DS under study should not exceed the allowable limits(s) within the standard adopted by the authority having jurisdiction.

Since harmonic injection is very device specific, it is generally not practical to include harmonic assessment in HCA, except when the assessment targets a restricted set of equipment for which the injected current harmonic content is known.

Note: Harmonics assessment may be included in specific impact studies. Refer to IEEE Std 1547.7 for details.

## 5.3 Applications and evaluation methods

The metrics developed in 5.2 can be evaluated with different approaches, each with their own advantages and disadvantages. Based on the method that is used, the result may be suitable for one or more applications, namely:

- Mapping  
This process generates a map of selected or all the power system nodes, segments, or feeders with one or more HC value(s) depending on the metric, method, targeted technology, or available grid-support services. Mapping can be tabular (identifying nodes and value by text) or geographical (identifying nodes by coordinates and value by color, for example). This will generally be used by project developers to select appropriate locations for their future DER. Additionally, these maps are used by regulators to evaluate requests for feeder upgrades.
- Screening  
Screening is the process of using a minimal set of parameters for a given prospective interconnection and evaluating the HC at a given point. Since screening is generally performed on request by utilities, a more extensive set of criteria (including settings and configuration permutations and combinations) may be investigated.
- Planning  
Planning is generally used by utilities and system operators to analyze the needed improvements to system capacity and configuration in order to meet the evolution of customer needs. HC techniques can be used to identify areas in need of improvement and investigate the impact of mitigation approaches. This can include long-term and short-term planning.
- SIS  
Techniques used for HCA, when refined, can also be used by utilities for the SIS. This promotes transparency and consistency between HCA and SIS outcomes.

Table 2 provides a summary of identified methods, associated metrics, and applications, as well as a short description of their pros and cons.

**Table 2—Summary of HCA methods in order of increasing complexity**

| Method                                                                                                 | Strategy                                                                                                                                                                                                                                           | Metrics                                                                                                                                                 | Applications                                                       | Advantages                                                                                                                                                                     | Disadvantages                                                                                                                                                                                         |
|--------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Simple/manual                                                                                          | Create a two-bus Thevenin equivalent of the network from TS to PCC<br><br>Apply the worst-case scenarios (e.g., min load/max gen and max load/min gen) to evaluate the metrics                                                                     | Thermal limits<br>Voltage change<br>Over- and undervoltage<br>Short-circuit current contribution<br>Reverse-flow<br>Reactive power consumption limits   | Mapping<br>Screening<br>Planning                                   | Computationally efficient<br>Low-cost solution                                                                                                                                 | Highly simplified calculations<br>Not very accurate<br>Considers only the two nodes involved; does not consider impact on the rest of the feeder, see B.2<br>Cumbersome to scale across large systems |
| Iterative power flow (Aguirre et al. [B2]; EPRI Report 3002011009 [B27])                               | Use a detailed model of the system<br><br>For each location, increase DER size until a violation is observed on any node or element of the system during the snapshot power flow analysis                                                          | All. Some require add-ons:<br>Protection schema, with short-circuit analysis and data<br>Excessive operation of voltage regulation equipment, with QSTS | Mapping<br>Screening<br>Planning<br>Interconnection                | Well-understood<br>Available in many vendor tools<br>More accurate than the simple method for feeder/node HC level<br>Considers side effects on adjacent feeders and locations | Time and data intensive (requires a power system model)<br>More computation-ally intensive than the simple method<br>Provides a single HC value per metric and feeder conditions                      |
| Streamlined (EPRI Report 3002011009 [B27]; Rajabi et al. [B93]; Rylander, Smith, and Sunderman [B103]) | Use a detailed model of the system<br><br>Run power flows under multiple time periods to derive an equation set of the behavior at each node of the power system<br><br>Use the equations with load and generation sets to establish the HC limits | All                                                                                                                                                     | Mapping<br>Screening<br>Planning                                   | Computationally efficient<br>Time-based                                                                                                                                        | Data intensive<br>Simplified calculations<br>Limited scenarios<br>Low accuracy for feeder/node HC level<br>Single-site DER only                                                                       |
| Data-driven (Deboever et al. [B15]; Procopiou et al. [B87])                                            | Train a model with past operational conditions<br><br>Optionally add a few simulation scenarios to expand the range of conditions                                                                                                                  | Depends on the input features and complexity of the data-driven model                                                                                   | Mapping                                                            | Computationally efficient                                                                                                                                                      | Data intensive—requires an excellent visibility of the power system<br>Not good at predicting behavior in unforeseen conditions                                                                       |
| Hybrid (EPRI Report 3002011009 [B27]; Radatz et al. [B91] Rajabi et al. [B93])                         | Use a combination of methods as most appropriate for each metric in 5.3                                                                                                                                                                            | All                                                                                                                                                     | Mapping<br>Screening<br>Planning<br>Interconnection<br>Educational | Potential for increased computational efficiency and accuracy                                                                                                                  | Requires knowledge of multiple methods and platforms<br>Need to develop and maintain a coordination platform to present coherent results                                                              |

### 5.3.1 Model-based approach

#### 5.3.1.1 General

The model-based approach uses methods that rely on a physical knowledge of the power system layout and equipment. This information is generally collected in a geographical information system (GIS) and can be used to manually or automatically generate a power system network model. Figure 2 provides a general overview of the workflow associated with a model-based method.

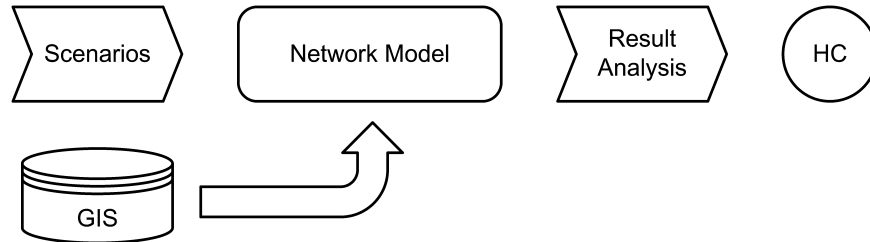


**Figure 2—Illustration of model-based approach workflow**

#### 5.3.1.2 Simple/manual method

A simplified method of HCA refers to analysis done without the use of a full-power flow model of the distribution circuit. (In this recommended practice, the term does not refer to simplified methods of increasing the circuit's HC.) The purpose and main advantage of the simplified method of analysis is to provide rapid results with minimal requirements on data, engineering labor, and software tools. The calculations may be done on a spreadsheet and are used either for pre-application HC estimates or as part of an application screening process. See B.3 for an example of the simplified method using information available from a map and other basic knowledge of the feeder, which is sufficient for estimating voltage deviation, thermal overload, unintentional islanding screens, and grounding requirements. For instance, the simple method can be used to evaluate thermal HC when the analysis is limited to the thermal metric. Thermal HC represents the ultimate limit that can be reached without requiring equipment replacement or upgrade. Some of these calculations go beyond HCA into the screening or impact analysis of DER.

Simplified methods ignore interactions with other DER, interactions with utility controls, the variability of some DER outputs, and the variability of circuit loads. The voltage and current estimates from simplified analysis methods are less accurate than with other approaches, especially when other large DER have already been connected (see B.2 for an example).

#### 5.3.1.3 Iterative method

In proceeding R.14-08-013, the California Public Utilities Commission (CPUC) required investor-owned utilities (IOUs) to develop various approaches to HCA, or integration capacity analysis (ICA), as it was known in California. The three large California IOUs, along with various stakeholders, formed an Integrated Capacity Analysis Working Group that reported back to the CPUC.

The working group came up with two methodologies to evaluate: the streamlined method and the iterative method. "The iterative ICA methodology is based on the iterations of successive power flow simulations at each node on the DS, whereas the streamlined method uses a set of equations and algorithms to evaluate power system criteria at each node on the DS." (Pacific Gas and Electric Company [B86])

The iterative method:

- Performs iterative power flow simulations at each node by increasing the size of the DER applied to determine the maximum amount of DER that can be installed without triggering criteria violations; and
- Uses short-circuit analysis to evaluate protection criteria that are not dependent on power flows

This method uses a traditional engineering analysis model of the DS and applies DER to the model “to identify HC limitations. A power flow simulation is run iteratively at each node on the DS until a violation is identified” (Stanfield and Safdi [B108]). It requires many iterations and, therefore, long processing times. “However, the use of an iterative simulation parallels what IOUs would perform as part of an SIS, and therefore produces more accurate results” (Pacific Gas and Electric Company [B86]).

For each location:

- Set load scenario.
- Set DER size.
- Run power flow.
- Check for violations at each node and element of interest.
- If no violations, increase DER size and run again.

#### 5.3.1.4 Streamlined method

- As mentioned in 5.3.1.3, the CPUC Working Group identified two methodologies. In contrast to the iterative method, the streamlined method: “Uses an abstraction approach, applying a set of equations and algorithms to evaluate power system criteria at each node on the distribution circuit” (Pacific Gas and Electric Company [B86]).
- Sets initial conditions by performing a baseline power flow and short-circuit simulation.
- Evaluates thermal, voltage, and protection limits to determine maximum HC at each node.

The streamlined method uses “simplified algorithms” in place of power flow calculations and is the fastest method of calculating HC because it “approximates system variables to determine DS nodal HC limits, allowing for faster computations on more scenarios and hours.”<sup>24</sup> However, the simpler methods utilized “may not capture some of the more dynamic effects on the more complex circuits” (Pacific Gas and Electric Company [B86]).

#### 5.3.2 Data-driven approach

The data-driven approach can be used with or without a power system model (Procopiou et al. [B87]). In Figure 3, data from grid operations is used to improve results from a model-based analysis. With enough redundant data, state estimation techniques can be applied to reduce error residuals in grid model parameters, thereby improving the accuracy of HCA (and SIS) results. Machine learning techniques can be applied to select and refine scenarios for HCA, treating the results as data (Deboever et al. [B15]). “Model-free” analysis replaces the grid model with a purely data-driven model, i.e., there is no power flow analysis. The available types of data include:

- Feeder-head voltage magnitude measurements
- Supervisory control and data acquisition system measurements, or other voltage, current, active power, and reactive power measurements from points along the feeder
- Load power and voltage measurements from automated meter infrastructure systems
- Thermal constraints of line segments and transformers

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<sup>24</sup> The streamlined method was developed from stochastic methods that study the impact of resources at multiple locations over a range of scenarios (Aguirre, Caampued, and Dayapera [B2]; EPRI Report 3002011009 [B27]; Rylander and Smith [B102]; Tang and Chang [B112]). Stochastic methods sample a subset of scenarios from the very large possibility space whose resulting analysis is deemed representative of the whole space. It was the most compute-intensive approach to HCA used so far, typically producing millions of unique scenarios. The resulting variability in feeder HC values may seem non-transparent. However, these results helped researchers identify the key variables to use in the development and validation of the streamlined method (Rylander, Smith, and Sunderman [B103]).