Summary of Electric Distribution System Analyses with a Focus on DERs

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Executive Summary

This report summarizes the major types of analysis conducted on electric distribution systems along with their applications and relative maturity levels. Special emphasis is placed on distribution system analyses (DSAs) required for increasing levels of distributed energy resources (DERs). This report is intended to be a resource for those interested in increasing their understanding of current capabilities and gaps in the basic types of DSA, more advanced emerging DSA capabilities, DSA as applied to DERs, and DSA as a way to enable or support market activities on the distribution system.

The authors of this report reviewed publicly available information on eight of the most commonly used commercially available DSA tools and two open-source research DSA tools. The authors also drew on their experience to categorize and characterize the types of DSA and their maturity levels.

Summary points from the report are categorized and described below.

<u>Time-Series Power Flow Analysis (TSPFA)</u>:

With DERs integrated into the distribution system, TSPFA is of increasing importance. TSPFA can help to ascertain the effects of irradiance variations or wind fluctuations on power system controls, such as voltage regulators, load tap changers (LTCs), and switched capacitors. Although offered in most DSA commercial tools, TSPFA is still not widely adopted and used by utilities due to its nascence, relative complexity, and the lack of suitable data for time-varying inputs.

<u>Dynamics</u>

Long-term dynamics analysis is very common in transmission systems but seldom used for distribution system studies and analysis. However, dynamic studies will become increasingly important with higher levels of DERs, especially inverter-based DERs, and with microgrids, where dynamics can be used to investigate whether automatic control systems can maintain voltage and frequency when subjected to disturbances.

In steady-state analysis, DERs can sometimes be modeled as negative loads that do not account for many of the DERs' protection, control, and other advanced capabilities. Modeling DERs as a negative load cannot support dynamic and transient studies such as anti-islanding function, fault-current contribution, microgrid operation, and the influence of DERs on volt/var optimization (VVO). For better results, control and protection should be modeled with specific implementation of inverter topologies and control characteristics for each model of inverter.

<u>VVO and Reactive Power</u>

DERs have created significant challenges with VVO, because DERs, when exporting power, tend to raise voltage levels on a feeder line section when capacity penetration levels increase. Many utilities have required selected DER inverters, depending on the site and circuit, to absorb reactive power at a fixed power factor to mitigate voltage rise or voltage fluctuations. Other utilities have recently evaluated, and sometimes required, inverters to dynamically absorb or supply reactive power in response to voltage conditions, or even curtail real power output in response to high voltage. However, the use of such “smart inverter functions” in actual installations is not currently predominant in the utility industry.

Harmonics

Harmonics generated by DERs could cause distortion in power system voltages and currents. In areas with high penetrations of DERs, harmonic studies become increasingly important. New loads such as electric vehicles may also cause harmonic distortion on a transformer or line section. These types of new loads may need to be studied, especially as these systems move toward being a vehicle to grid (V2G) system that can be either a load or a source, depending on the system needs.

Arc Flash Hazard

With the rapidly expanding DER market that includes battery energy storage systems, there is a significant level of interest in direct current (DC) arc flash calculations. DC arc flash studies are more complicated than alternating current (AC) arc flash studies, and mitigation of these arc flashes can be difficult. Most DSA tools are not able to calculate these DC fault current levels because they are designed for AC systems.

DER Load Forecasting

While traditional load forecasting is a mature field, DER forecasting—as a precursor to forecasting *net-load profiles*—is a relatively immature field of study. For near-term forecasts (e.g., ≤4 years) simple time-series extrapolations may be sufficient, though for longer planning processes, more-detailed methods are needed. However, a truly integrated platform that can both forecast DER deployment at the feeder level *and* understand the operational impact on specific feeders is not yet commercially viable.

Some DSA tools incorporate basic DER operational characteristics that allow the consideration of several DER system parameters such as the DC/AC power ratio of photovoltaic systems, the minimum operating level of reciprocating engine-based DER, and the weather related operational availability of wind and solar based DER.

Protection with DERs

With the integration of DERs, utility distribution systems are transforming from simple radial systems into a more complex network of load and generation devices. Previously coordinated protective devices can be affected and problems may occur. A common interconnection impact study evaluates protection coordination as DERs, which are potential new sources of fault current, are added to a distribution system.

Hosting Capacity

A hosting capacity study typically consists of a set of automated distribution system analyses (typically voltage, power quality, protection, and thermal limits) that are repeatedly performed for increasing amounts of interconnected DER until one or more of the analyses predicts a distribution system impact level above a predetermined threshold. DSA tools are generally capable of conducting the four types of analyses for hosting capacity studies, but often require the addition of external scripts in order to automate the considerable amount of analysis undertaken in such studies. Hosting capacity studies can be of the single snapshot, multiple snapshot, or time-series power flow type, depending on the scope of the study.

The inclusion of TSPFA in hosting capacity analyses allows for more accurate determination of the effect of DERs on the system under study, and thus potentially allows less-conservative, more-realistic impact thresholds to be used for the final determination of a circuit's hosting capacity. More-basic analysis, such as single snapshot analysis, typically requires the application of more-conservative impact thresholds. This typically results in a lower hosting capacity determination, albeit with less study effort and less risk from modeling uncertainties.

Some of the DSA tool developers are working to automate hosting capacity calculations within their tools. More automated analysis of hosting capacity or project impact studies would allow for automated interconnection studies and reduce overall time spent by utilities processing DER applications. Automation also fosters consistency in the process.

Effects of DERs, Time-of-Use Pricing, and Transactive Energy on Rates and Bills

In conjunction with other tools, TSPFA enables the study of grid interactions with customer-side resources (e.g., demand response, transactive energy) that are increasingly eligible to participate in markets and also potentially impact utility communication systems.

Time-series simulations are helpful for determining the effects of DERs on distribution systems in terms of reverse power flow and resulting changes in customer usage, changes in system losses, and peak-load shaving/shifting. Proposed tariffs can be coupled with time-series simulations to calculate effects of DERs on revenue and customer bills.

A time-of-use pricing analysis can be conducted using time-series simulations in order to ascertain the effects on the distribution system given projected changes in the pattern of customer demand in response to changing prices. Results from these simulations can also be used to calculate impacts on utility revenues over time of time-based rates under various scenarios.

Transactive energy is an emerging concept in which a market allows for communications and transactions between multiple levels of energy generation and consumption. In a transactive market, distributed controllers and a market clearing mechanism (e.g., a centralized auction) are used so that an interactive system is created that can provide energy services. Analyzing the potential physical and financial effects of transactive energy on a distribution system requires detailed modeling of the distribution system loads and components. This is a nascent area of analysis currently limited to research organizations (universities and national laboratories). One of the tools evaluated is capable of performing transactive energy studies.

Summary of maturity level

The percentage of analysis tools reviewed for this report that offer each analysis type are shown in Table ES.1. Based on the percentages of DSA tools that provide each type of analysis, a maturity level score, ranging from 0 to 3, is listed. At level 0, none of the DSA tools offer the corresponding function. Level 1 means that only a small number of DSA tools provide the function. Level 2 means that more than half of the DSA tools are capable of conducting the function. At level 3, the function is mature enough that almost all the DSA tools offer it.

Table ES.1. Summary of Maturity Levels

Distribution System Analysis Types and Applications	Percentage of DSA tools	Maturity Level
Power Flow Analysis		
Peak Capacity Planning Study	100%	3
Voltage Drop Study	100%	3
Ampacity Study	100%	3*
Contingency and Restoration Study	100%	3
Reliability Study	100%	3
Load Profile Study	90%	3
Stochastic Power Flow Study	60%	2
Volt/Var Study	70%	2
Real-Time Performance	50%	2
Power Quality Analysis		
Voltage Sag and Swell Study	100%	3
Harmonics Study	80%	2
Fault Analysis		
Arc Flash Hazard Analysis	60%	2
Protection Coordination Study	100%	3
Fault Location Identification	30%	1
Dynamic Analysis		
Long-Term Dynamics	20%	1
Electromechanical Dynamics	60%	2
Electromagnetic Dynamics	20%	3**

* Ampacity studies include overhead conductor ampacity and underground cable ampacity studies. All of the DSA tools reviewed include the capability to perform overhead conductor ampacity studies, and 50% of the DSA tools include the capacity to perform underground cable ampacity studies.

** Although only 20% of the reviewed DSA tools include this function, electromagnetic dynamics analysis is widely applied by utilities in other settings, and if needed for distribution systems, could be accomplished using certain DSA tools or other tools such as EMTP or PSCAD.

Next Steps

The next steps in this research are to send questionnaires to DSA tool vendors and utilities. Information from tool vendors will help to better quantify existing capabilities and areas under development. Questionnaires sent to utilities will help to better characterize current utility practices, emerging needs, and key questions/concerns around DSA for distribution system planning with increased DERs and market activity.

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Acronyms and Abbreviations

AC	alternating current
ANSI	American National Standards Institute
ASAI	Average Service Availability Index
BESS	battery electric storage system
CAIDI	Customer Average Interruption Duration Index
CVR	conservation voltage reduction
DC	direct current
DER	distributed energy resource
DMS	distribution management system
DR	demand response
DSA	distribution system analysis
DSM	demand-side management
DSSE	distribution-system state estimation
EDP	electric distribution planning
EMS	energy management system
EMTP	Electromagnetic Transients Program
ENS	Energy Not Supplied
FERC	Federal Energy Regulatory Commission
FLISR	fault location, isolation, and service restoration
GIS	geographic information system
HVAC	heating, ventilating, and air conditioning
IEEE	Institute of Electrical and Electronic Engineers
LTC	load tap changer
MAIFI	Momentary Average Interruption Frequency Index
NERC	North American Electric Reliability Corporation
NFPA	National Fire Protection Association
OMS	outage management system
PPE	personal protective equipment
PSCAD	Power System Computer Aided Design
PV	photovoltaic
QSTS	quasi-static time series
RTP	real-time pricing
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	supervisory control and data acquisition
TE	transactive energy

THD	total harmonic distortion
TOU	time-of-use
TSPFA	time-series power flow analysis
UL	Underwriters Laboratory
VVO	volt/var optimization

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Tables

1.0 Introduction

Electric distribution planning (EDP) engineers design the distribution systems for each feeder that originates from an electrical substation. Distribution circuits, or feeders, serve most consumer loads in the United States, while a small number of industrial class customers or municipal utilities are served at transmission levels. Distribution system analysis (DSA) tools are often used by the EDP engineers to conduct different types of DSAs to support safe and reliable operation of the distribution system under a variety of conditions.

This document summarizes types of electric DSAs along with their application and relative maturity. Particular emphasis is placed on analyses associated with distributed energy resources (DERs), which include generation sources such as solar photovoltaic (PV) systems, battery electric storage systems, small wind generators, small hydro generation, small geothermal generators, natural gas and diesel generators, and in some cases demand response and energy efficiency systems. With increasing DERs being integrated into the power system, detailed DER studies can be conducted to investigate the potential effects of DERs on the grid. DERs are discussed throughout the report, but are specifically addressed in detail in Section 3.0. States such as New York are increasingly interested in markets not just at the wholesale level but also markets that involve customer assets at the distribution system level. DSAs that can be used to support market activities in the distribution system are described in in Section 4.0.

This report is intended to be a resource for those interested in increasing their understanding of current capabilities and gaps in the basic types of DSA, more advanced emerging DSA capabilities, DSA as applied to DERs, and DSA as a way to enable or support market activities on the distribution system.

The remainder of this report is organized into three sections. In Section 2.0, different types of DSAs and their corresponding applications are reviewed. In addition, maturity levels of the DSA tools for use in different applications are summarized. Section 3.0 includes details of the DSAs that are associated with DER studies. The capabilities and gaps of the DSA tools to conduct different DER studies are given. Section 4.0 describes DSAs that are used to support market activities on the distribution system and summarizes the relative maturity level of each.

2.0 Distribution System Analyses

2.1 Introduction

In this report, DSAs and studies are separated into the following four categories: power flow, power quality, fault, and dynamic analyses. As part of this study, 10 different DSA tools were researched; eight relatively common commercial tools and two open-source tools. The maturity level of each distribution system application is characterized at the end of each subsection. At the end of this section, a summary of the maturity levels for all the applications is given.

2.2 Power Flow Analysis

Power flow analysis is the core of power system analysis, and is the foundation for other types of power system analyses and studies. Power flow analysis includes steady-state snapshot and time-series simulations. In distribution-system power flow analysis, voltages, currents, real and reactive power flows, and losses in distribution circuits and feeders are calculated. Information such as whether the system voltages remain within American National Standards Institute (ANSI) limits (NEMA 2016) or whether equipment is overloaded can be obtained from power flow analyses. Power flow analysis plays a key role in traditional distribution system operation and planning, and is a critical factor in understanding the impacts of DERs.

2.2.1 Peak Capacity Planning Studies

- **Summary**

In peak capacity planning studies, electric utilities look out over a planning horizon (often 20 years) and project a load growth. Studies are performed to determine whether there is a need to upgrade substation transformers, feeder line sections, or other equipment to meet load growth and keep the distribution system operating reliably and safely. It is typical for utilities to run multiple snapshot power flow analyses (often one for each year) to see how the overall distribution system performs, and to plan for system changes and upgrades. The two key building blocks of a peak capacity planning study are power flow analysis and projected load growth.

- **Maturity Level**

Peak capacity planning studies are the foundational power flow analyses conducted by utilities. Almost all utilities will do this type of analysis in some form, although the level of detail varies. All DSA tools considered for this report are capable of performing peak capacity planning studies.

2.2.2 Voltage Drop Studies

- **Summary**

The ANSI C84.1 national standard (NEMA 2016) has established the nominal voltage ratings and steady-state voltage tolerances for 60 Hz power systems above 100 volts. The voltage tolerances have two types of ranges: Range A and Range B. Range A is the optimal voltage range, and it specifies the voltage limit as $\pm$5% of the nominal voltage in 120 V to 600 V systems. Range B has a wider range than Range A in consideration of practical design and operation conditions of the distribution systems but for limited duration. Range B is acceptable, but not optimal. Utilities commonly regulate the feeder voltages within the defined ranges by using transformer load tap changers (LTCs), tap changing line voltage regulators, and switched or un-switched capacitors. Power flow analysis is used to perform voltage drop studies as long as the utility engineer has sufficient line and load information.

- **Maturity Level**

Voltage drop studies are helpful to utilities in investigating the possibilities of voltage limit violations and planning the operations of regulators and capacitors. Voltage drop calculations are typically performed when the distribution system is initially designed or when significant changes are planned for the feeder or line section. Voltage drop studies are one of the basic power flow functions in DSA tools and are one of the most powerful tools used by distribution planning engineers. Traditionally, low voltage results indicated the need for voltage regulation devices or load relief measures. Significant penetration of DERs may cause high voltage results when power flows back to the distribution circuit. Power back flows are one of the major concerns of utility planning engineers at utilities that are integrating large amounts of DERs. The DSA tools investigated for this report, including both open-source and commercial tools, are capable of conducting voltage drop studies.

2.2.3 Ampacity Studies

- **Summary**

Ampacity studies are used to calculate the maximum current-carrying capacity of a conductor. The ampacity of a conductor is affected by ambient temperature; therefore, ampacity ratings under different temperatures are usually given and used by EDP engineers when designing feeders and line sections. Overhead lines may sag when overheated, creating safety and operational problems. Underground lines may be damaged if overheated and will face premature failure. Conductors of sufficient size should always be used when designing a feeder in order to prevent the lines from overheating. The current through each line in a feeder can be calculated and compared with the rating of the line. If a line is overloaded on a continuous basis, damage may occur, and replacement of the line by one with a larger rating will be considered or switching operations may be used to move loads to adjacent feeders. Overhead line ampacities usually come from tables provided by the conductor vendor, and may be adjusted by the utility for local climate conditions. The ampacities of power cables in underground installations are more limiting and more difficult to calculate than for overhead line conductors, due to the effects of ductwork and soil properties.

- **Maturity Level**

Conductor ampacity is one of the basic power flow inputs in DSA tools, and all the investigated DSA tools accept these inputs, which are obtained outside the tool. Cable ampacity studies are a mature function in commercial DSA tools, and usually are provided as an add-on. Over 60% of the commercial DSA tools are capable of conducting cable ampacity studies. None of the open-source DSA tools currently offer the cable ampacity study function.

2.2.4 Contingency and Restoration Studies

- **Summary**

Contingency studies are common in electric transmission systems, however, they are not typically performed by distribution planning engineers. Contingency studies are used to identify potential overloads and other problems that may occur during a planned or unplanned “contingency event,” such as an outage of power lines and bulk power generators, as well as the closure of normally open lines (EPRI 2010). Modern electric utility operating policies for transmission systems (those of the North American Electric Reliability Corporation, [NERC], for example) require that all system loads can be restored on the system if any single component fails (i.e., N−1 components are still available). This requires a level of redundancy in both generation and transmission. Some critical policies may extend to an “N−2 contingency” requirement so that the power system is able to withstand and recover from any subsequent single failure. A relatively small number of urban distribution systems are networked to provide some redundancy, and they can be designed to meet N−1 or N−2 requirements. Typically, only large cities are networked, but small cities and rural areas are not.

Due to the meshed topologies and the typically large loads served by most transmission systems, contingency analysis is widely applied in transmission system studies. Because most distribution systems are radial by design, the failure of a single system element will result in loss of downstream loads for hours, unless there are cross-connections to other adjacent radial feeders. In that case, power can be restored from alternative feeds via manual or automated switching operations. In radial distribution systems, contingency studies are often referred to as “tie capacity studies” or “restoration studies.” For radial distribution systems, a restoration study is used to optimize the number of utility customers that can be reenergized without overloading any part of the power system.

In distribution-system restoration studies, valid contingencies are listed and weighted by likelihood of occurrence, and an outage simulation is performed for each one. Decisions will be made on whether part of the feeder will be dropped to solve overloads and voltage problems. If available, the de-energized feeder segments will be reenergized by adjacent feeders or possibly by other power sources (e.g., a mobile diesel generation unit), depending on the locations of the switches, overloading limits of the feeder lines and equipment (e.g., transformers, regulators), and feeder voltage limits (Carr 1999).

Restoration studies are among the major analyses conducted in distribution systems. Utilities differ in the level of detail and complexity of their studies.

- **Maturity Level**

Almost all of the commercially available DSA tools are equipped with a contingency analysis function or they may provide restoration analysis as an add-on function if a utility or consultant requests that capability. User-defined scripts may also be added into some of the open-source DSA tools to conduct contingency and restoration studies, but the level of complexity may be beyond the abilities of the utility engineer, as many of these open-source tools are generally used by the research community rather than the average utility user.

2.2.5 Reliability Studies

- **Summary**

Contingency and restoration studies assess responses to operational disturbances, whereas reliability studies, also referred to as sectionalizing studies, are used to identify or predict the probability that the system can provide utility customers with continuous service (with the voltage and frequency kept within ANSI or similar limits) given potential disturbances. Model results inform the utility about what types of options are available for engineering and operations to improve reliability, including sectionalization (e.g., fuses, reclosers, sectionalizers), switches, tree removal, etc., and the associated improvement in outage duration and frequency. Reliability indices have been standardized and codified; these include System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Momentary Average Interruption Frequency Index (MAIFI), Average Service Availability Index (ASAI) and Energy Not Supplied (ENS), and are used to characterize system and feeder reliability performance (IEEE 2012). Reliability indices are generally categorized into three types: load interruption indices, loss of load probability, and frequency and duration indices (Prada 1999).

- **Maturity Level**

Almost every utility will do some variation of reliability studies, yet it is estimated that less than half of the utilities conduct advanced reliability studies. Frequently those utilities hire consultants to perform their reliability analyses. Based on the results of the studies, actions may be taken by the utility on feeders and line sections where reliability can be improved. Mitigation strategies include installation of additional fuses, reclosers, and sectionalizers; wildlife protection; and regular tree trimming to maintain necessary clearances from power system lines, poles and transformers (Lovelace 1996).

The reliability analysis function in DSA tools, which is often an add-on function, is available with all the commercially available DSA tools. The open-source DSA tools are capable of conducting reliability analysis but may require user-defined scripts.

2.2.6 Time-Series Power Flow Analysis

- **Summary**

Time-series power flow analysis (TSPFA), sometimes referred to as quasi-steady-state analysis or quasi-static time series (QSTS), is composed of multiple steady-state power flow calculations with user-defined time step sizes between each calculation. TSPFA does not incorporate true dynamics from differential equations; thus, it ignores effects like inertia and damping. However, it does maintain discrete states (e.g., tap positions and switch and relay status) from one power flow solution to the next. The simulation periods can range from seconds to hours or years, and the time intervals depend on the need of the analyst and the availability of data.

Utilities typically use TSPFA for load profile studies (Section 2.2.7). With DERs integrated into the distribution system, the TSPFA can help to study the effects of irradiance variations or wind fluctuations on power system controls, such as voltage regulators, LTCs, and switched capacitors. TSPFA can help verify the sequence and performance of automatic switching, voltage control, and protection system operations. It may include the effect of end-use load components turning on or off, which sometimes creates short-term overloads or voltage disturbances. In conjunction with other tools, TSPFA enables the study of grid interactions with customer-side resource (e.g., demand response, transactive energy) that are increasingly eligible to participate in markets and also potentially impact utility communication systems. In addition, TSPFA may also be used for power quality studies, such as studies looking at voltage swells and sags, but sub-second time steps are generally required.

It should be noted that most distribution modeling systems use static data or a series of static "snapshots" that will yield TSPFA study results. This type of analysis is generally unable to perform dynamic or transient analyses that are common in the bulk power modeling arena. The use of data in the second to sub-second range is gaining greater levels of interest by researchers and utility engineers alike. Thus there is some emerging focus on the gap between dynamic and transient analysis and traditional distribution analysis, which focuses on longer periods of time. Issues such as flicker, perhaps due to cloud-induced variability in solar PV systems or wind gusts, can potentially be problematic for utilities and their customers if not mitigated. With greater levels of DER penetration, there is a higher level of interest in accurately modeling those impacts.

- **Maturity Level**

TSPFA is provided in most commercial DSA tools as an add-on, while still in a nascent form. Ninety percent of the commercial DSA tools, and all the open-source DSA tools, offer the TSPFA function. However, the adoption and use rate of TSPFA is still quite low with utilities due to its nascence, relative complexity, and the lack of suitable data for these time-step functions.

Some of the tools that offer TSPFA do so in a relatively limited capacity in terms of the temporal resolution and the length of time investigated in a single automated analysis.

2.2.7 Load Profile Studies

- **Summary**

Load profile studies are commonly conducted by utilities for planning purposes. In a load profile study, TSPFA may be used with daily hourly loads to determine whether there is a risk of any overloading. Alternatively, time-series analysis can be applied in a time frame of several hours, months, or years with estimated load-duration curves, in order to investigate the possibilities of overloading issues over time. Because most DERs have time-varying power outputs, time-series simulations are seen as increasingly important. In distribution systems with larger amounts of DERs, peak and minimum daily load snapshot analyses do not capture the full picture of distribution system operations and requirements. Distribution feeder devices, such as conductors, protective devices, and transformers, may need to be replaced if the load study projects overloads. Some utilities may choose to allow short-term overloads if they are infrequent and only reach 125% or 150% of the device ratings.

- **Maturity Level**

The snapshot power flow simulation is included as a basic function in all commercially available DSA tools. The time-series simulation, which is usually an add-on, is provided by 90% of the commercial DSA tools evaluated. The open-source DSA tools investigated are capable of conducting snapshot as well as time-series simulations directly.

2.2.8 Stochastic Analysis

- **Summary**

Stochastic analysis is a repetitive evaluation of a deterministic model, which solves a probabilistic problem with random inputs. This type of simulation is often used for complex, nonlinear models, or cases with one or more uncertain parameters. For example, stochastic analysis has been extensively used for power flow reliability studies, by applying random faults onto the feeder and calculating the resulting reliability indices (Billinton and Wang 1999). With the increasing numbers of DER integrations in distribution systems, stochastic simulation techniques may be helpful in evaluating the uncertainties of the power production from DERs (El-Khattam et al. 2006). Stochastic approaches may also be used to simulate the appearance of new loads, DERs, and electric vehicle chargers on the distribution system.

- **Maturity Level**

Due to the computational complexity and advanced concepts involved, stochastic analysis is conducted mainly within research organizations (e.g., universities and national laboratories), and is not typically used for distribution system assessment or distribution planning within utilities or utility consultants.

Half of the investigated commercially available DSA tools offer stochastic power flow inputs, and all of the open-source DSA tools are capable of accepting stochastic power flow inputs.

2.2.9 Volt/Var Studies

- **Summary**

Volt/var optimization (VVO) is a fundamental operating strategy used within many distribution systems that both maintains proper reactive power for loads and may be used to maintain acceptable voltage levels at all line sections on a feeder under varying loading conditions. The voltage limits have been defined by ANSI Standard C84.1 (NEMA 2016) for 60 Hz power systems above 100 volts. Traditionally, substation LTCs, voltage regulators, and capacitors may be used to control voltage levels as well as reactive power in distribution systems to optimize voltage profiles. A traditional volt/var study is used to calibrate system settings and locations of these devices. It is important to point out that some utilities may only use capacitors for distribution voltage control, while not using LTCs or voltage regulators. Other utilities may strictly rely on LTCs and voltage regulators for voltage control while using capacitors for reactive power optimization. Thus, the strategy for operating a distribution system can be quite different from one utility to the next.

Conservation voltage reduction (CVR) is one of the VVO strategies that reduce overall system voltage while staying within the ANSI voltage limits (Singh et al. 2011). The CVR philosophy is to reduce the overall energy consumption on each feeder, thus reducing overall generation requirements. Many utilities have embraced CVR and many other utilities are looking into adopting CVR strategies. However, higher levels of DER have created significant challenges, because DERs tend to raise voltage levels on a feeder when capacity penetration levels increase.

During the past few years, as DER penetration levels have increased, many utilities have been evaluating and sometimes requiring inverters to absorb reactive power for mitigating high voltage situations, or to provide reactive power when voltage levels are too low (Smith et al. 2011). The capability of absorbing or providing reactive power has been available for several years in larger, three-phase inverters. It is now a required function for all “smart inverters” (UL 1741 2016), although the use of such functionalities in actual installations is not currently predominant in the industry.

- **Maturity Level**

Currently, it is estimated that more than half of U.S. utilities conduct some forms of volt/var studies. Sensors can be installed in feeders to help analyze voltage changes under volt/var control schemes. Volt/var studies often consider boundary cases of both peak load and minimum load to investigate whether existing devices, such as LTCs, capacitors, or voltage regulators, can be used to properly maintain voltage. In more-detailed analyses, volt/var studies use time-series analysis with time-varying loads, as long as sufficient data is available for the study.

Over 60% of the commercial DSA tools, and all the open-source DSA tools considered in this report, have volt/var analysis functions to analyze capacitor and voltage regulator operations, and usually to optimize capacitor sizes and locations. One of the commercially available DSA tools has incorporated advanced inverter control functions that assist in volt/var studies, whereas the open-source DSA tools that are reviewed have this functionality.

2.2.10 Real-Time Performance Analysis

- **Summary**

Real-time performance analysis is the combination of computerized circuit modeling and continuous analysis, based on measured real-time consumption and generation, to determine the voltages and currents of all elements on the distribution grid (See et al. 2008). The computation results represent the near-term and future feeder states. This information is used by system operators, analysts, and management to facilitate generation dispatch, switching procedures, location and settings for reclosers and capacitors, and demand-side management needs. Power system state estimation is a data processing algorithm for converting redundant meter measurement into an estimation of the power system state (Primadianto and Lu 2016), and is essential for real-time studies. State estimation has been widely used by transmission and generation control centers, due to the very limited number of generators, transmission lines, in-line equipment and devices, and limited technical and economic feasibility to measure and communicate data from circuit elements. Redundant measurements can make the system mathematically observable to enable a state estimator to work. In contrast, distribution systems have a much larger number of nodes and feeder elements and low measurement redundancy. Thus, with an increasing number of DERs, it is extremely challenging to conduct state estimation studies on distribution systems due to the limited availability of input information and the large number of devices. Several different distribution-system state estimation (DSSE) methodologies have been proposed by researchers (Primadianto and Lu 2016), such as the weighted-least-squares–based DSSE method and the dynamic DSSE method. However, only a few utilities have implemented DSSE. New techniques, as well as a sufficient amount of continuously measured and communicated data, would be required in distribution systems to effectively demonstrate state estimation methods.

Currently, in most cases, we find that utilities monitor distribution-system supervisory control and data acquisition (SCADA) alarms rather than conducting real-time performance monitoring. However, integrating DSA tools into utilities' various applications, including the distribution management system (DMS), outage management system (OMS), energy management system (EMS), SCADA, and geographic information system (GIS), would allow system operators to perform simulations in real time and quickly respond to changing network conditions.

- **Maturity Level**

Forty percent of the commercial DSA tools reviewed for this report, and all the open-source DSA tools, are capable of being integrated into utilities' applications to incorporate real-time monitoring. This capability may appear first in a distribution state estimator. Some utilities have been adding sensors to feeders beyond the substation, although these feeders are still not fully instrumented. Thus, the ability to perform DSSE is limited.

2.3 Power Quality Analysis

Power quality is defined as the electrical system's ability to maintain the sinusoidal waveforms of voltages and currents at rated magnitude and frequency in the system. Marginal or poor power quality contributes to a number of negative effects on both the operation of the transmission and distribution system equipment, and particularly affects the utility customer devices. Electrical disturbances include oscillations, voltage variations, flicker, harmonics, fast disturbances (transients), fault-induced voltage sags, and phase imbalance. Many power quality disturbances are localized, especially voltage and current harmonics and ANSI rating levels.

Fewer power quality problems are seen system wide, such as frequency variability, some harmonics, and occasionally high, low, or imbalanced voltage levels.

A comprehensive power quality assessment is helpful to detect the operating practices that cause power quality disturbances, in order to determine the devices affected by the power quality disturbances, and to mitigate the effects and eradicate the causes more efficiently. Harmonic level is a commonly investigated attribute in power quality studies.

2.3.1 Voltage Sag and Swell Studies

- **Summary**

Short duration voltage variations are typically caused by fault conditions or energization of large loads that require high starting current (e.g., a very large motor starting, often resulting in a voltage sag). Voltage disturbances are generally temporary in nature and can either be temporary voltage reductions (denoted voltage sags), or increases in voltage (denoted voltage swells). Based on IEEE Standard 1159 (IEEE 2009), a voltage sag occurs when the root mean square voltage decreases to between 0.1 and 0.9 per unit of the nominal voltage level for a duration of 0.5 cycle to 1 minute. A voltage swell is defined as an increase in the root mean square voltage level to 1.1 to 1.8 per unit of the nominal voltage level for a duration of 0.5 cycle to 1 minute. The short voltage variations can disrupt or damage sensitive equipment, and thus have economic impacts on utility customers, and sometimes the utility itself. Power quality is not often examined by a utility unless there is a customer complaint. When a voltage sag and swell study is performed, it is often performed as an add-on to a protection or fault analysis study. Voltage sag and swell studies are usually conducted by reviewing results of power flow or fault analysis from a power quality perspective (see Section 2.4 for more discussion on fault analysis). During an interconnection study for DERs, voltage sag studies look at the step change in output of DERs from 100% to 0%. The step change in voltage will indicate the risk of sags or flicker. A true voltage sag study requires dynamics.

- **Maturity Level**

Voltage calculations are provided by all DSA tools as part of the power flow and fault analysis. However, in most cases, post-processing of the voltage data is necessary for all DSA tools in order to conduct the voltage sag and swell studies, based on the duration of overvoltage and/or undervoltage conditions. Most of the commercial DSA tools have power quality analyzers of some variety, but these are somewhat limited due to the complexity of the topic of power quality. Generally, existing commercial tools cover the critical aspects of voltage and current levels satisfactorily.

2.3.2 Harmonics Study

- **Summary**

When multiples of the supply frequency (e.g., the fifth harmonic would be 300 Hz if the supply frequency is 60 Hz) are added to the supplied voltage or current waveform, distortion occurs, which may cause malfunctions or overheating of the power system devices and customer loads. Harmonics can be caused by nonlinear elements or electronic equipment that draws current in short pulses that are non-sinusoidal in nature. Harmonics can result in power system inefficiencies, such as the overheating of transformers, capacitors, and generators, and false tripping of fuses and other protective devices (Square D 1994). A harmonics analysis is necessary for filter design, ripple-control signal simulation or for determination of the network resonance frequencies. Harmonics analysis is also required when a PV site happens to be near an arc furnace or something similar. Modern harmonic mitigation techniques (Schwanz et al. 2016) include classical approaches (e.g., line reactors, phase-shifting transformers, and tuned harmonic filters), active solutions (e.g., shunt or series active filters), and hybrid filters that combine passive and active filters.

Harmonics generated by DERs, including electric vehicle chargers, could cause distortion in power system voltages and currents (Arghandeh et al. 2013). Therefore, in areas with high penetrations of DERs, harmonic studies become increasingly important. Ideally, all DERs installed on distribution systems in the United States should be tested and listed under UL 1741 (UL 1741 2016), and be IEEE 1547 compliant. Thus the harmonics generation allowance should be very low (IEEE 2014). However, when large numbers of different DERs are combined with high harmonics from loads, the impact on the distribution system may exceed allowed levels of harmonics which a utility may need to mitigate to avoid potential problems. This type of situation is exceptionally difficult to model with modern computer simulators in most cases due to the general lack of accurate harmonic content models of DERs and the loads that constitute a distribution system.

Industrial facilities have been major producers of harmonic current; these industries are often asked to conduct harmonic studies and, if necessary, implement mitigations. Harmonics studies are also required as part of interconnection studies if someone is connecting a PV system near industrial facilities. Utilities seldom conduct distribution-system harmonics studies unless they receive customer complaints. Utilities determine the customer harmonics injection by field measurements when needed. With the integration of DERs, possibilities of high-harmonics currents increase, even though DERs are listed and tested to make sure they contribute very low levels of harmonics.

- **Maturity Level**

Harmonics analysis is offered by 90% of commercial DSA tools, and is usually an add-on function. Half of the open-source DSA tools include this function.

2.4 Fault Analysis

Power system faults and outages occur due to lightning, animals, trees, vehicles striking poles, switching surges that cause overvoltage, insulation contamination, or other mechanical or natural causes. Protective equipment may be installed on the system to quickly restore power after a fault, or to isolate a line section to minimize the number of utility customers affected by a fault. Fault analyses are conducted to help design the settings and locations of the protective devices, based on calculated fault current, feeder topology, and a variety of factors that are unique to each feeder. This fault-current calculation is very similar to power flow analysis, except that loads are either ignored or linearized. Several applications of fault protection analysis are listed below.

2.4.1 Arc Flash Hazard Analysis

- **Summary**

According to National Fire Protection Association Standard 70E (NFPA 2015), arc flash is a “dangerous condition associated with the release of energy caused by an electrical arc”

(ABB 2010). The arc flash can be initiated through accidental contact, equipment experiencing a higher than rated amount of short-circuit current, contamination that leads to tracking over the surface of insulators, and corrosion of equipment (Clark 2000). An arc flash event is most likely to occur in a region near electrical equipment with high short-circuit power levels, such as transformers, service-entrance switchgear, generators, switching equipment, and protective equipment (ABB 2010).

Arc flash hazard studies are needed to define the hazard level to people working on or near live equipment. Arc flash models, based on IEEE Standard 1584 (IEEE 2002), are used to estimate the incident heat energies that a person near an arc fault would be exposed to (Bradt et al. 2010). An arc flash hazard assessment characterizes the risk level and defines the appropriate personal protective equipment (PPE) required for a person working near the equipment. Equipment with potential arc flash hazard must be affixed with warning labels, including information such as the arc flash hazard boundary, hazard category class, and PPE required, so that the risks of burns and injuries are significantly mitigated.

With the rapidly expanding DER market (including battery energy storage systems), there is a significant level of interest in direct current (DC) arc flash calculations (Ammerman et al. 2010). DC arc flash situations are generally considered far more dangerous than alternating current (AC) arc flash, because AC systems have a “zero crossing” in the sinusoidal waveform, thus allowing the energy to drop to zero. DC arc flash studies are more complicated than AC studies, and mitigation of high arc flash can be difficult. DSA tools are not able to calculate these DC fault current levels because they are designed for AC systems.

- **Maturity Level**

The AC arc flash hazard analysis function is provided by 75% of the commercial DSA tools, and is usually an add-on. The AC arc flash hazard evaluations are mostly based on IEEE 1584 (IEEE 2002) and NFPA 70E (NFPA 2015). There are also specific tools for arc flash studies.

None of the open-source DSA tools include an AC or DC arc flash hazard analysis function.

2.4.2 Protection Coordination Studies

- **Summary**

Protection coordination studies are performed in order to determine the optimum characteristics, ratings, and locations of the power system protective devices. In a protection coordination study, a short-circuit study is conducted primarily to obtain the fault-current values in the systems. These are checked against the interrupting capabilities of the circuit breakers, reclosers, and fuses that isolate faults. Then, based on the feeder topology and the manufacturer’s data on the protective devices (e.g., time-current curve settings), the optimal relay and recloser settings that will provide the most comprehensive and cost-effective protection for the system are determined. Study results typically include fuse sizes, breaker settings, and overall ratings for each protective device.

- **Maturity Level**

Protection coordination studies are one of the most common studies conducted by electric utility distribution planning engineers. All of the commercially available DSA tools evaluated include protection coordination capabilities as an add-on function. A comprehensive protective device library that stores several thousand device characteristics is helpful for a protection coordination study. However, most utilities choose a handful of fuse sizes as their standard, while substation breakers and reclosers may have a far greater array of set points. Open-source DSA tools are capable of conducting these studies as long as there is a user-defined script and a library of protective devices included.

2.4.3 Fault Location Identification

- **Summary**

When a fault occurs, the fast detection of the fault and the identification of the fault location are helpful to reduce outage durations. Detection and location require microprocessor-based relays that usually reside at the substation breaker. Fault location analysis assists in quickly troubleshooting outages by accurately predicting the locations of equipment to repair. Accurate and fast fault location identification can help utilities improve their standard reliability metrics such as SAIDI. Fault location identification is a function for system operation. The protection coordination study (Section 2.4.2) addresses the same function in the planning stage.

The most common method for utilities to learn about system faults, and thus dispatch line crews to repair the faults, is though their customer service centers that receive customer calls. When a fault occurs, utilities will dispatch “trouble crews” to the locations near customers that reported the power outage. Crews will search for blown fuse(s) and locked out recloser(s), and patrol the line to locate the fault location. The line crew will then restore power by switching lines, clearing tree branches or animals, or by repairing or replacing any damaged devices. It may be necessary to reconfigure the line segment through switching; line reconfiguration is executed by manual switching operations in the field, or automatic switching by a dispatcher, to temporarily restore service from possible alternative power sources after the fault location is identified. Reconfiguration occurs during system operation. The contingency and restoration study (Section 2.2.4) addresses the same function in the planning stage.

Substation relays may be capable of identifying fault locations based on current and voltage values measured during events, which require modern microprocessor-based relays and detailed modeling inputs for the location calculations. Due to various topologies of distribution systems, the integration of DERs and their varying sources of current, and underground distribution cables and equipment, fault location identification by this method may be significantly more complicated in distribution systems than in transmission systems.

Fault location, isolation, and service restoration (FLISR) is one of the key distribution automation applications and is increasingly being deployed. FLISR is an automated or semiautomated system that attempts to keep as many customers energized as possible following a fault in the distribution system. FLISR involves automated feeder switches and reclosers, distribution management systems, outage management systems, SCADA, and other technologies (DOE 2014). FLISR systems are likely to reduce outage time significantly and improve overall reliability. A typical FLISR system process includes four steps (Parikh et al. 2013):

1. identification of the fault location after a fault occurs
2. isolation of both sides of the fault after the fault location is identified
3. estimation of the capability to restore power from an alternative line section or power source
4. restoration of power based on capability estimation results.

Projects using FLISR technologies have been deployed by several utilities, and the results reveal that FLISR has reduced the number of customers interrupted by up to 45%, and reduced the customer minutes of interruption by up to 51% for one outage event (DOE 2014). Some of the challenges that remain in FLISR applications include the requirement of greater resilience in communication networks, firmware and software upgrades, and utility operations training.

- **Maturity Level**

One-quarter of the commercial DSA tools that are reviewed include fault location identification functionality for operations. One open-source DSA tool is capable of conducting the analysis using user-defined scripts.

2.5 Dynamic Analysis

In dynamic analysis, a time-dependent response to some trigger or stimulus is simulated. Dynamic simulation estimates the oscillatory response, namely, how long it takes to return to a stable operating state after a system perturbation, the frequency of oscillation, and how large the oscillation is. Dynamic studies are of primary importance in microgrids, planned-island systems, or “weak” grids. In larger systems or in distribution systems connected to the bulk system, the dynamics of the bulk system overwhelm any potential dynamic response of the distribution system if viewed as a separate entity. Thus, the interconnection of the distribution system to the bulk system is typically viewed as very “stiff,” meaning that it is highly unlikely that isolated actions in the distribution system will affect the interconnection frequency. Dynamic analysis includes long-term dynamics, electromechanical dynamics, and electromagnetic dynamics, based on time scales needed for the simulation.

2.5.1 Long-Term Dynamics

- **Summary**

In a large-scale interconnected power system, the system response to disturbances may develop over times from tens of seconds to tens of minutes. Such a long-term frequency or voltage dynamic can provoke cascading failures. A long-term dynamics simulation is needed to analyze the effects of large excursions of voltage, frequency, and power flow that may invoke potential problems. The differential-algebraic equations of the entire power system are solved in the simulation, requiring appropriate techniques to mitigate large computational efforts. Some tools offer capabilities that are called dynamics; however, in reality, they are often time-series analysis.

Long-term dynamics analysis is very common in transmission systems but seldom used for distribution system studies and analysis. However, these studies will become increasingly important in microgrid designs that would include electric distribution system components.

- **Maturity Level**

One-quarter of the commercial DSA tools that are reviewed have long-term dynamics analysis functionality, while none of the open-source DSA tools are capable of endogenously conducting the analysis.

2.5.2 Electromechanical Dynamics

- **Summary**

Electromechanical dynamic analysis examines the rotor angle swings and power system responses to voltage and frequency oscillations for synchronous machines and other non-power electronic based DERs. The smallest time step in electromechanical dynamic simulations is around one millisecond. The main difference between long-term dynamic analysis and electromechanical dynamic analysis is the time step. The electromechanical dynamics is faster with time steps between one millisecond and one second, compared to at least several seconds with long-term dynamics. An electrical system with low inertia (e.g., an island grid such as Hawaii), will see more rapid changes of system frequency following sudden generation changes. Therefore, similar to long-term dynamics, electromechanical dynamics studies have been used in transmission systems more than in distribution systems because most distribution systems have the high inertia of the bulk system behind them.

Electromechanical dynamics is important for microgrids to investigate whether automatic control systems can maintain voltages and frequency under various disturbances (Lopes et al. 2006; Katiraei and Iravani 2006; Pogaku et al. 2007). This includes large industrial facilities and utility power plants that can operate in island mode with local generation. Currently, distribution system dynamics is studied in research activities, rather than used by utilities for distribution planning or system planning.

- **Maturity Level**

Half of the commercial DSA tools that are reviewed contain electromechanical dynamic analysis capabilities, and all the open-source DSA tools are capable of conducting the analysis. While some DSA tools are capable of the analysis, there is considerable difficulty in accurately modeling DERs' electromechanical dynamics and specific difficulty modeling DERs with no mechanical interface (e.g., PV systems), in the electromechanical dynamic timeframe.

2.5.3 Electromagnetic Dynamics

- **Summary**

Electromagnetic dynamics analysis is used to analyze electromagnetic responses to sudden, microsecond-level conditions, such as faults, switching transients, and overvoltage caused by lightning. The time step in electromagnetic dynamics simulation ranges from nanoseconds to milliseconds. Utilities may conduct electromagnetic dynamics studies for relay and sensor performance. In FLISR systems, electromagnetic dynamics analysis is usually applied to analyze fault events and switching transients.

Electromagnetic dynamics analysis can also be used for power systems with DERs. A fault is applied to the modeled system and control schemes with feedback loops are studied. Unintentional islanding of the DERs may result in power quality issues or even personnel safety hazards. An anti-islanding study for grid-connected inverters is one of the essential transient analyses. Voltage and frequency positive-feedback controls are implemented in inverters to help detect and trip inverters during an outage within a specified time frame, as specified in IEEE 1547 (Ye et al. 2004). We estimate that, due to the specialized tools and training required, more than half of utilities rely on consultants and researchers to conduct electromagnetic dynamics analysis when needed. It should be noted that the IEEE 1547 Full Revision, due to be published in late 2017 or early 2018, will have expanded parameters surrounding voltage ride-through and frequency ride-through in order to address bulk system reliability concerns. Those provisions for ride-through will further complicate future electromagnetic dynamic analysis and require new DER model development. Electromagnetic Transients Program (EMTP) and Power System Computer Aided Design (PSCAD) are used for electromagnetic dynamics analysis in transmission systems, including unbalanced phases and separate grounded conductors. This is not typically done in distribution systems, and not many DSA tools are capable of conducting this type of analysis. With the increasing focus on DER studies, more electromagnetic dynamics simulations in distribution systems may be required.

- **Maturity Level**

Twenty percent of the commercial DSA tools that are reviewed provide electromagnetic dynamic analysis capabilities, and none of the open-source DSA tools are capable of conducting this type of analysis. However, separate from traditional DSA tools, at least four vendors are providing commercial electromagnetic transient programs that are applicable to distribution systems.

2.6 Summary of Maturity Levels

The percentage of analysis tools reviewed for this report that offer each analysis type identified in Sections 2.2 through 2.5 are shown in Table 1. Based on the percentages of DSA tools that provide each type of analysis, a maturity level score, ranging from 0 to 3, is listed. At level 0, none of the DSA tools offer the corresponding function. Level 1 means that only a small number of DSA tools provide the function. Level 2 means that more than half of the DSA tools are capable of conducting the function. At level 3, the function is mature enough that almost all the DSA tools offer it.

Table 1. Summary of Maturity Levels

Distribution System Analysis Types and Applications	Percentage of DSA tools	Maturity Level
Power Flow Analysis		
Peak Capacity Planning Study	100%	3
Voltage Drop Study	100%	3
Ampacity Study	100%	3*
Contingency and Restoration Study	100%	3
Reliability Study	100%	3
Load Profile Study	90%	3
Stochastic Power Flow Study	60%	2
Volt/Var Study	70%	2
Real-Time Performance	50%	2
Power Quality Analysis		
Voltage Sag and Swell Study	100%	3
Harmonics Study	80%	2
Fault Analysis		

Arc Flash Hazard Analysis	60%	2
Protection Coordination Study	100%	3
Fault Location Identification	30%	1
Dynamic Analysis		
Long-Term Dynamics	20%	1
Electromechanical Dynamics	60%	2
Electromagnetic Dynamics	20%	3**

* Ampacity studies include overhead conductor ampacity and underground cable ampacity studies. All of the DSA tools reviewed include the capability to perform overhead conductor ampacity studies, and 50% of the DSA tools include the capacity to perform underground cable ampacity studies.

** Although only 20% of the reviewed DSA tools include this function, electromagnetic dynamics analysis is widely applied by utilities in other settings, and if needed for distribution systems, could be accomplished using certain DSA tools or other tools such as EMTP or PSCAD.

3.0 Distribution System Studies with DERs

Electric distribution modeling tools are under significant pressure to adapt to the new world of “high DER penetration,” where DERs include generation sources such as solar PV systems, battery electric storage systems, small wind generators, small hydro generation, small geothermal generators, natural gas and diesel generators, and in some cases demand response and energy efficiency systems. According to IEEE 1547 (IEEE 1547 2014), DER systems are generally 20 MVA and smaller, and are tied to distribution circuits that also serve loads. While some smaller DER units may receive “fast track interconnection” (FERC 2016b), DER systems that present potentially negative effects on the distribution circuits are required to undergo “detailed impact studies” (IEEE 1547 2014). In this section, the DER impact studies are described, which draw upon a combination of the studies and analysis types discussed in Section 2.0.

3.1 DERs and Net Load Projections

- **Summary**

In order to understand potential effects of DERs on a distribution system, multi-scenario forecasts for DER penetration and gross load are needed (ICF 2016). Based on the forecasting of the DER and gross load, multiple-scenario simulations can be performed and mitigation strategies provided when possible problems are identified. Results may indicate the need for potential operational changes to system configuration and for infrastructure replacement. Results can also inform decision makers about potential distribution system upgrades and modernization investments and the potential for non-wire alternatives. In addition, distribution investments to enhance the safety, reliability, and security may be identified. However, most DER related distribution system upgrades are based on detailed impact studies completed during the interconnection process and paid for by the DER developers. A few states have started considering options for placing distribution system upgrades necessary for DERs into the rate base, in order to effectively increase the “grid hosting capacity.” In these cases, the costs allowed in the rate base are borne by all consumers (even if they do not participate in the DER market directly). Several factors affect the forecasting of DER, including historical adoption, economic potential, data regarding utility DER procurement programs, typical size of generation facilities, and PV pricing trends.

A recent report describes four different approaches to DER adoption forecasting, through the lens of distributed PV, and recommends that a combination of forecasting methods described below be used in utility integrated resource planning (Mills et al. 2016). These include time-series based (i.e., historical trend), goal-based (stipulated forecast, program-based) and more involved bottom-up customer-adoption modeling (Mills et al. 2016). The first three approaches are commonly used, easy to implement, and rely on few or no quantifiable predictive factors—but may not be sufficiently robust for planning purposes. In contrast, the customer-adoption modeling approach explicitly models consumer decision-making based on economics, taking into consideration several predictive factors that include historical DER deployment, location-specific technical potential, various technology-specific economic considerations, and end-user behaviors. A key benefit of the customer adoption approach is the ability to generate internally self-consistent forecasts across multiple scenarios with varying assumptions. (Mills et al. 2016).

- **Maturity Level**

Traditional load growth projections are commonly included in DSA tools. These typically use a load forecast growth rate applied to actual loads. A limited number of tools include a more detailed approach that includes small-area load forecasting based on economic, environmental, and societal factors. However, while traditional load forecasting is a mature field, DER forecasting—as a precursor to forecasting *net-load profiles*—is a relatively immature field of study. For very near-term forecasts (e.g., ≤4 years) simple time series extrapolations may be sufficient, though for longer planning processes, more-detailed methods are needed. An open question in this field is how accurate DER forecasts are, and how accurate these forecasts must be to provide actionable insights for distribution system operations and planning.

Of the current DSA tools investigated in this study, most lack the capability to endogenously predict DER growth and net-load profiles. Some leading utilities are acquiring new tools that support development of hourly load profiles for individual distribution feeders that can be compared against representative DER hourly profiles to determine hourly effect on capacity. Results from these advanced net-load profile tools are being combined with traditional power system modeling software to model the effect of DERs on the distribution system under different scenarios. However, a truly integrated and public platform that can both forecast DER deployment at the feeder level *and* understand the operational impact on specific feeders is not yet commercially viable.

3.2 Basic Distribution Engineering with DERs

- **Summary**

Integration of DERs may result in overcurrent, overvoltage, and miscoordination between protective devices.

Traditionally, snapshot power flow simulation is performed for the peak-load condition. However, with the integration of DERs, analyses of cases with different DER outputs and load conditions become important. DER interconnection studies consisting of multiple snapshot power flow analyses have been proposed and used to estimate the effect that high penetration levels of DERs would have on the interconnected distribution systems. In addition to peak loading levels, as seen in typical peak-capacity planning studies, other loading/generation levels are investigated, such as maximum generation, maximum generation-to-load ratio, and minimum load during periods when generation may occur (Mather et al. 2014, Seguin et al. 2016). Snapshot power flow studies are conducted to investigate the increased current values in distribution system lines to compare with the line ampacity. Decisions can then be made regarding necessary conductor replacement. Feeder voltages are also calculated through snapshot simulation to investigate whether voltage limit violations occur under certain DER penetration and load conditions.

With the integration of DERs, distribution systems are transforming from simple radial systems into a more complex network of load and generation devices. Previously coordinated protective devices can be affected and problems may occur. A common interconnection impact study evaluates protection coordination as DERs (potential new sources of fault current) are added to a distribution system.

- **Maturity Level**

Table 2 lists the percentages of the DSA tools investigated that are capable of conducting each aspect of the DER basic distribution engineering study.

Table 2. Capability of DER Basic Distribution Engineering Tools

Capability of DER Basic Distribution Engineering Study	Percentage of DSA Tools
Snapshot Current Calculation and Ampacity Study	50%
Snapshot Voltage Calculation	100%
Protection Coordination	70%

3.3 Time-Series Power Flow Analysis (TSPFA) with DERs

- **Summary**

Compared to the single-point analysis from snapshot simulation, TSPFA has become increasingly important with more integration of DERs. TSPFA can help study the effect on voltage of irradiance variations with solar systems or of wind speed fluctuations on power system controls such as voltage regulators, LTCs, and switched capacitors, as long as sufficient data is available at appropriate time steps.

To study the effects of DERs on distribution circuits, DER outputs can be modeled as time-varying negative loads, or as generators with appropriate inputs and controls.

- **Maturity Level**

As mentioned in Section 2.2.6, TSPFA is provided in most commercial DSA tools as an add-on. Ninety percent of the commercial DSA tools, and all of the open-source DSA tools, offer the quasi-steady-state dynamic analysis function. Some DSA tools incorporate basic DER operational characteristics, allowing the consideration of some DER system parameters such as the DC/AC power ratio of PV systems, the minimum operating level of reciprocating engine-based DER, and the weather related operational availability of wind-and-solar-based DER.

3.4 Advanced Optimization with DERs

- **Summary**

In order to minimize investment and operation costs of DERs, optimal sizing and location of DERs can be evaluated. Due to the significant variability in the power generation profiles of solar PV and wind, energy storage is increasingly seen as a viable solution with fast response and flexible controls (Eyer and Corey 2010). Studies on energy storage usually focus on several categories, including operation, sizing, and siting. Few utilities have conducted advanced optimization studies for DERs and storage systems, because they generally study interconnection requests based on a customer's existing point of interconnection. As utilities have little ability to steer DER interconnection request size or location, most studies on this topic are currently conducted in the research arena.

While most of the DSA tools have the capability to conduct basic distribution engineering studies and time-series simulations with the integration of DERs, gaps exist for advanced optimization studies. The selection of the optimal sizes and locations of the DERs plays a key role in maintaining the voltage profiles along the feeder with minimized costs.

- **Maturity Level**

None of the DSA tools have the advanced optimization feature, although customized scripts can be added into the DSA tools to enhance the capability of the tools. Sixty percent of the commercial DSA tools and all the open-source DSA tools are capable of conducting the optimization study with user-defined scripts. One open-source DSA tool has an "auto-add" function for DERs; given a list of eligible locations, this function optimizes DER to reduce system losses and/or increase load-serving capacity.

3.5 Hosting Capacity and Interconnection

- **Summary**

Hosting capacity studies are used to investigate the amount of DERs that can be accommodated without affecting feeder power quality or reliability (EPRI 2015). An interconnection impact study covers the same technical issues, but for a single DER project. Hosting capacity analysis typically consists of a set of automated DSAs that are repeatedly completed for increasing amounts of interconnected DER until one or more of the analyses results in a distribution system impact level above a predetermined threshold.

These thresholds or evaluation criteria for hosting capacity studies mainly focus on four areas: voltage, power quality, protection, and thermal limits. DSA tools are generally capable of conducting these analyses for hosting capacity studies but often require the addition of external scripts in order to automate the often considerable amount of analysis undertaken in such studies. Hosting capacity studies can be of either the single snapshot, multiple snapshot or time-series power flow type depending on the scope of the study. The inclusion of TSPFA in a hosting capacity study allows a more accurate determination of the effect of additional DERs on the system, and thus potentially allows less-conservative, more realistic impact thresholds to be used for the final determination of a circuit's hosting capacity. More-basic analysis, such as single snapshot analysis, typically requires the application of more-conservative impact thresholds and thus typically results in lower hosting capacity determination, albeit with less study effort and more accommodation for modeling uncertainties. Time-series power flow can be used to determine whether both the instantaneous voltage and sustained voltage on the primary and secondary sides of the feeder would be kept within the ANSI limits. In order to represent all possible effects of different DER deployments, a stochastic analysis can be used that considers different DER penetration levels and DER placements on the feeder. For example, when thousands of potential PV deployment scenarios are evaluated in a stochastic analysis, effects on feeders under different scenarios can be used to project the maximum amount of PV that can be accommodated (EPRI 2012).

Power quality analysis can be conducted to study the total harmonic distortion and harmonics; however, this is generally not considered a limit to DERs.

Protection coordination analysis is needed to investigate fuse-saving scenarios and the reduction of reach caused by the integration of DERs (Walling et al. 2008). In fault studies, fault-current contributions for inverter-based DERs are modeled as no more than 200% of the full load current, based on the actual hardware testing of different inverters (EPRI 2012). Fault analysis is also needed to study the increased fault-current contribution impacts, overvoltage and grounding requirements, unintentional islanding, and sympathetic tripping in multiple connected feeders.

In addition to the four evaluation criteria of the hosting capacity study that the DER studies need to investigate, advanced optimization studies are also important (see Section 3.4). The beneficial effects of DERs are closely associated with the proper design of DER locations and sizes. The sizes and locations of DER systems will have a significant effect on issues such as losses and overall costs of generation, but optimizing the locations and sizes of DERs is often very challenging, because utilities often have little or no real input into the DER decision-making process other than identifying possible negative grid effects that arise during a detailed impact study. Although existing DSA tools do not normally have the advanced optimization study feature regularly available, with customized scripts incorporated into the DSA tools for selecting the optimal locations and sizes, gaps associated with this type of study can be reduced, and in fact, some utilities are publishing hosting capacity maps to help DER developers choose the best, or at least better, locations for their proposed systems.

Some of the DSA tool developers are working to automate hosting capacity calculations within the tool. An automation of the hosting capacity or project impact studies would allow for automated interconnection studies and reduce overall time spent by utilities processing DER applications. The present approach for DER impact study analysis is somewhat of a manual approach, and once an interconnection application “fails” technical screening criteria, the application goes through the detailed study process. Having predefined hosting capacity analysis or an automated interconnection study available could potentially reduce interconnection times from months to days (Coddington et al. 2012).

- **Maturity Level**

Table 3 lists the percentages of the investigated DSA tools that are capable of conducting different aspects of the hosting capacity or project impact study. Most of the DSA tools are capable of conducting several aspects of the hosting capacity or project impact study separately.

Table 3. Levels of Hosting Capacity Analysis Capability

Hosting Capacity Analysis Capability	Percentage of DSA Tools
Time-Series Voltage Analysis	90%
Power Quality Harmonic Analysis	90%
Fault Analysis	100%
Thermal Limits Analysis	30%
DER Advanced Optimization Study	70%

3.6 Dynamic Studies with DERs

- **Summary**

Dynamic analysis is seldom conducted by utilities on distribution systems. With increasing integration of DERs, especially the inverter-based DERs, the importance of dynamic modeling and analysis of the DERs has been increasing. In steady-state analysis, DERs can sometimes be modeled as negative loads that do not account for many of the DERs' protection, control, and other advanced capabilities. However, the modeling of the DER as a negative load cannot support dynamic and transient studies such as anti-islanding function, fault-current contribution, and microgrid operation. Nor does it really capture the influence of DER on volt/var control. For better results, the control and protection need to be modeled with the specific implementation of the inverter topologies and control characteristics for each vendor (Stewart et al. 2014). The complexity of the detailed modeling of the inverters also requires a validation process, in which the dynamics study results are compared with full electromagnetic solvers.

- **Maturity Level**

There are two commercial DSA tools capable of modeling and simulating inverters in a dynamic form. Another option for conducting dynamic studies is provided through integration with other packages, such as Simulink with Simscape Power Systems.

Two open-source DSA tools provide a user-defined model interface for electromechanical studies. Differential equations of inverters can be written into the user-defined models using any language that will compile to a shared object library (Linux) or dynamic link library (Windows and Mac OS X). An interface has been provided to connect the user-defined model to the network model and conduct the dynamic simulation.

3.7 Co-Simulation with Transmission Systems

- **Summary**

Traditionally, power system analysis is conducted separately for transmission and distribution systems. In DSA, the entire bulk power network is aggregated into a single connection point in the distribution model. In transmission system analysis, distribution systems are modeled as aggregated loads in the transmission system model. With the increasing penetration of DER into distribution systems, the net-load characteristics from the distribution systems affect the transmission systems. The wholesale energy services provided by DER can be delivered across the distribution system to the transmission system. Therefore, an integrated view of transmission, distribution, and DER is needed to examine the interaction of the systems.

Modeling and simulation of transmission systems are quite different from those for distribution systems. Because the two systems have different characteristics, several solver methods have been adopted in transmission system analysis tools and DSA tools.

There are different approaches for addressing transmission and distribution integration. Co-simulation allows for expansion of capabilities with minimal investment and allows for the reuse of existing software and models. It also enables multi-scale modeling and simulation. A co-simulation approach can support a potential Distribution System Operator's role in coordinating between bulk energy services and DERs. The co-simulation can support this by helping coordinate DERs (at scale) for efficient participation in the bulk energy and ancillary service markets and by facilitating cooperation with bulk entities in management plans for large-scale system failures.

In addition to co-simulation of transmission and distribution systems at the power flow and market levels, some initial efforts have been made to co-simulate the effect of DERs on the transmission system using an open-loop co-simulation of traditional transmission-level dynamic simulation tools (e.g., PSLF and PSS©E) and DSA tools capable of modeling the response of DERs to fast time-scale voltage changes (see Section 2.3.1). This type of co-simulation attempts to determine the voltage-related response of DERs on a non-dynamic time scale but still on a relatively fast time scale, as could be seen by many DERs experiencing abnormal voltage conditions in a region affected by a regional-scale transmission-level fault (Mather and Ding 2016, Boemer et al. 2016). Such modeling efforts potentially promise the determination of aggregated response models of individual distribution circuits or entire distribution areas' responses to bulk system abnormal conditions without the need for highly detailed electromechanical or electromagnetic modeling of each DER interconnected. Such models may prove accurate enough for transmission-system-level reliability studies for interconnects with high levels of DERs.

- **Maturity Level**

Among all the investigated DSA tools, there are two commercial DSA tools capable of solving both transmission and distribution systems. One open-source DSA tool is able to simulate small transmission systems together with the distribution systems. Another open-source DSA tool can be integrated with other transmission system analysis tools, such as PowerWorld and MATPOWER, to conduct the co-simulation study.

4.0 DSA that Supports Market Analyses

States such as New York are increasingly interested in markets, not just at the wholesale level, but also markets that involve customer and third-party assets and/or responsive demand at the distribution system level. DSA that can be used to support market activities on the distribution system are described in this section. In particular, the subsections below characterize opportunities to use DSA to support understanding the effects of DERs on net demand and utility revenues, and distribution system and revenue impacts of time-of-use (TOU) pricing, demand response, and transactive energy.

4.1 Effect of DERs on Power Flow, Utility Revenues, and Customer Billing

- **Summary**

The utility establishes, often with the oversight of a utility regulator, the revenue that the utility must collect to serve its customers, maintain its debt service obligations, invest in its system, etc. Different customer classes (i.e., tariff groups, such as residential, small commercial, etc.) are then identified with classified costs allocated. The forecasted electric system revenue under the proposed rate design is calculated to determine whether sufficient electric revenue can be generated to meet expenses and reserve requirements (Leidos 2014).

The integration of DERs adds significant complexity to the traditional revenue and customer billing analysis. "Value of DER" studies are increasingly common as a way to characterize effects of DERs on the utility system. Potential benefits of DERs include savings on fuel and transmission costs, value of line-loss savings, and energy savings. Potential costs of DERs include those associated with additional sensors and safety equipment and control responses, such as operation of capacitor banks and voltage regulating devices (Barbose 2017; Darghouth et al. 2017; Darghouth et al. 2016; Denholm et al. 2014).

Time-series simulations are helpful for determining the effects of DERs on distribution systems in terms of reverse power flow and the resulting changes in customer usage, changes in system losses, and peak-load shaving/shifting. These can all affect customer billing and utility revenue. Proposed tariffs can be coupled with time-series simulations to calculate effects on revenue and customer bills.

- **Maturity Level**

Ninety percent of the commercial DSA tools, and all the open-source DSA tools, are capable of conducting revenue and customer billing analysis through post-processing of power flow analysis results. However, this is a nascent area in practice.

4.2 Effects of Time-of-Use Pricing on Distribution Systems and Revenue

- **Summary**

TOU pricing for electricity customers refers to prices that vary over the day, which are set in advance to respond to expected effects of changing electricity conditions (Hogan 2014). With smart meters, utilities are capable of recording electricity usage on a more frequent basis, enabling the possibilities of TOU or real-time pricing (RTP) at the residential level. Historically, most TOU or RTP rates have been implemented for larger commercial/industrial customers. A properly designed TOU program can help reduce customer, feeder, and system peaks, while maximizing savings for customers. Some utilities have adopted TOU rate for residential customers, but the uptake among these customers has been modest.

A TOU pricing analysis can also be conducted using time-series simulations in order to ascertain the effects on the distribution system given projected changes to customer demand in response to changing prices. Results from these simulations can also be used to calculate the revenue over time.

- **Maturity Level**

Detailed TOU pricing analysis is not provided directly by DSA tools. However, most tools, with customized scripts and post-processing capabilities, can conduct TOU pricing analysis in a market study.

4.3 Effects of Demand Response on Distribution System and Utility Revenue

- **Summary**

Demand response is defined by the Federal Energy Regulatory Commission (FERC) as "changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time or to incentive payments designed to induce lower electricity use" (FERC 2016a). Traditionally, controlled loads have not actively participated in the process of maintaining a balance between generation and load plus losses. Demand response can help reduce peak loads and regulate services to smooth load fluctuations. Using DSA tools, effects on the power system of changing loads can be modeled. Loads can either change in response to a price signal or an event called by a utility as a part of a prearranged program to which the utility customer subscribes.

To conduct an analysis of the effect of demand response on the distribution system, loads participating in the power balancing process, detailed load models, and information on load controls are needed. In traditional DSA tools, loads are generally defined as static, time-invariant models consisting of constant-impedance, constant-current, and constant-power elements. Load allocation and estimation are based on customer consumption data (residential, commercial, and industrial), weather data, distribution transformer size, and monthly billing data. While this simple form of static load modeling is sufficient for a steady-state snapshot study, a more detailed dynamic load model with thermal cycles is needed for time-series and more-detailed studies of demand response. A load model of a residential house with thermal cycles includes heat exchangers, heating, ventilating, and air conditioning (HVAC) systems, and end-use models of the water heater, lights, refrigerator, washer, plug loads, microwave, oven, freezer, and dryer. By controlling the load model based on the price signals, the demand response study can be conducted.

- **Maturity Level**

Demand response studies are currently at the research stage. One of the open-source tools evaluated for this report has modeled end-use appliances in detail and is capable of conducting demand response studies directly and evaluating the effects of demand response on the state of the utility distribution system and utility revenues.

4.4 Transactive Energy (TE) Analysis

- **Summary**

A transactive energy market allows for communications and transactions between multiple levels of energy generation and consumption. In a transactive market, distributed controllers and a market clearing mechanism (e.g., a centralized auction) are used so that an interactive system is created that can provide energy services, including limiting demand to decrease congestion (Fuller et al. 2011). Analyzing the potential physical and financial effects of transactive energy on a distribution system requires detailed modeling of the distribution system loads and components. As with TOU pricing and demand response discussed in the previous sections, a transactive energy analysis requires detailed modeling of the distribution system loads and components.

- **Maturity Level**

Currently, transactive energy analysis is in the research phase. One of the open-source tools considered for this report is capable of conducting transactive energy analysis, with modules of weather, residential, auction, and controller agents implemented. One commercial DSA tool, paired with that open-source DSA tool, is also capable of conducting a transactive energy study.

5.0 Summary and Next Steps

This report summarizes the major DSAs along with their applications, and investigates the capabilities of commercial and open-source DSA tools to conduct many types of analyses.

In Section 2.0, four types of DSAs are reviewed: power flow analysis, power quality analysis, fault analysis, and dynamic analysis. Different applications associated with each are presented along with relative maturity. The impact of DERs on distribution system operations and planning are discussed in Section 3.0. DSAs that can be used to support market activities on the distribution system are described in in Section 4.0.

In this report, the current capabilities of the DSA tools are summarized from vendors' websites and manuals. To further verify these capabilities, as a next step, a survey will be sent to vendors of the DSA tools that are reviewed in this report. The summary of DSA tools and capabilities will be updated based on the surveys. A survey will also be sent to utilities to identify current practices in distribution systems analysis and planning. Utilities vary in types and maturity levels for conducting DSAs. Some analyses that are common in research, such as dynamics of DERs, are not widely performed by utilities. Utility practices also differ in distribution-system model generation and validation, communication systems, and sensor and control placements. Based on utility survey results and interviews, more-detailed characterizations will be provided of current utility practices, emerging needs, and key questions/concerns around DSA for distribution system planning with increased DERs and market activity. Gaps and areas for future research will also be identified.

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