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Renewable Systems Interconnection Study:

Utility Models, Analysis, and Simulation Tools

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Abstract

To facilitate more extensive adoption of renewable distributed electric generation, the U.S. Department of Energy launched the Renewable Systems Interconnection (RSI) study during the spring of 2007. The study addressed the technical and analytical challenges that must be addressed to enable high penetration levels of distributed renewable energy technologies. This RSI report focuses on the need for advanced distribution engineering analytical tools. High-penetration PV will change the way that distribution systems perform and provide both new capabilities and challenges for reliable, quality performance. The most fundamental change is the presence of generation on a system designed strictly to serve loads.

Preface

Now is the time to plan for the integration of significant quantities of distributed renewable energy into the electricity grid. Concerns about climate change, the adoption of state-level renewable portfolio standards and incentives, and accelerated cost reductions are driving steep growth in U.S. renewable energy technologies. The number of distributed solar photovoltaic (PV) installations, in particular, is growing rapidly. As distributed PV and other renewable energy technologies mature, they can provide a significant share of our nation's electricity demand. However, as their market share grows, concerns about potential impacts on the stability and operation of the electricity grid may create barriers to their future expansion.

To facilitate more extensive adoption of renewable distributed electric generation, the U.S. Department of Energy launched the Renewable Systems Interconnection (RSI) study during the spring of 2007. This study addresses the technical and analytical challenges that must be addressed to enable high penetration levels of distributed renewable energy technologies. Because integration-related issues at the distribution system are likely to emerge first for PV technology, the RSI study focuses on this area. A key goal of the RSI study is to identify the research and development needed to build the foundation for a high-penetration renewable energy future while enhancing the operation of the electricity grid.

The RSI study consists of 15 reports that address a variety of issues related to distributed systems technology development; advanced distribution systems integration; system-level tests and demonstrations; technical and market analysis; resource assessment; and codes, standards, and regulatory implementation. The RSI reports are:

- *Renewable Systems Interconnection: Executive Summary*
- *Distributed Photovoltaic Systems Design and Technology Requirements*
- *Advanced Grid Planning and Operation*
- *Utility Models, Analysis, and Simulation Tools*
- *Cyber Security Analysis*
- *Power System Planning: Emerging Practices Suitable for Evaluating the Impact of High-Penetration Photovoltaics*
- *Distribution System Voltage Performance Analysis for High-Penetration Photovoltaics*
- *Enhanced Reliability of Photovoltaic Systems with Energy Storage and Controls*
- *Transmission System Performance Analysis for High-Penetration Photovoltaics*
- *Solar Resource Assessment*
- *Test and Demonstration Program Definition*
- *Photovoltaics Value Analysis*
- *Photovoltaics Business Models*

- *Production Cost Modeling for High Levels of Photovoltaic Penetration*
- *Rooftop Photovoltaics Market Penetration Scenarios*.

Addressing grid-integration issues is a necessary prerequisite for the long-term viability of the distributed renewable energy industry, in general, and the distributed PV industry, in particular. The RSI study is one step on this path. The Department of Energy is also working with stakeholders to develop a research and development plan aimed at making this vision a reality.

List of Acronyms

CAD	computer-aided design
CAP	computer-aided planning
CHP	Combined Heat and Power
CIM	Common Information Model
DER	distributed energy resources
DEW	Distribution Engineering Workstation
DG	distributed generation
DRIA	Distributed Resource Integration Assistant
DSS	Distribution System Simulator
EEN	energy exceeding normal
EMTP	Electromagnetic Transients Program
EUE	expected unserved energy
EPRI	Electric Power Research Institute
GIS	Geographical Information System
GVA	gigavolt-amperes
IEEE	Institute of Electrical and Electronic Engineers
LTC	load tap changer
PWM	pulse-width modulation
PV	photovoltaics
TCC	time-current coordination
TOC	time-overcurrent
UE	unserved energy
UL	Underwriter’s Laboratories
VAR	volt-amperes reactive

Executive Summary

This is the second report in a series documenting the U.S. Department of Energy's Renewable Systems Interconnection (RSI) research and analysis activities to date. It covers the status of, and need for, analytical tools to integrate high levels of distributed photovoltaic (PV) power systems into the electricity grid. And it describes the analytical challenges and simulation tools needed to understand and enable high penetration levels of solar, wind, and other renewable energy technologies. These distributed generation (DG) technologies are expected to change the fundamental design and operating requirements of the electric distribution system. A number of hurdles to understanding and analyzing this issue have been identified; they can be grouped in the following categories:

- The need for current analysis tools to evolve and address a new, more interactive distribution system of the future, as discussed in the RSI study report on advanced grid planning and operations
- Changes and upgrades to distribution engineering tools to simplify their use and more efficiently handle distributed and renewable-generation-related issues
- The challenge to develop new analytical methods and related tools to determine the effects of high-penetration distributed generation on capacity limits
- The need to develop cost and benefit evaluation tools that better define the relationship of distributed resources to power system operations and dispatching
- The need to identify and document modeling and specification requirements for DG interconnection equipment
- Related training and best practices for utilities' technical staff.

The development of the concept of "DG-ready" distribution systems, as discussed in detail in another report in this series, is viewed as an important step in removing hurdles to the high-penetration deployment of PV systems. Research is needed to address several basic issues, such as whether or not DG inverters should regulate voltage. The successful development of DG-ready distribution is expected to lead the way to simplified and more streamlined tools that can be widely applied in distributed system integration analysis and in obtaining interconnection approvals.

Analytical Tool Needs

The primary distribution engineering tools are load-flow and fault-current calculation. Several commercial software packages are available and used widely by distribution system planners and designers for these tasks. These tools generally include a data-management system that is often integrated with a geographic information system, or GIS, that is used in operations and restoration. Some vendors have begun updating their products so that systems can handle multiple distributed energy sources. These are not always modeled in the same way, and results are not always the same. Furthermore, full evaluation of distributed PV integration requires additional functions not normally associated with current distribution packages.

Table ES-1 shows a set of requirements for load-flow packages for distribution systems with significant penetration of distributed generation. These functions are needed to determine capacity limits, assess voltage regulation, and develop a voltage-regulation plan. They are also used to assess system losses and reliability.

Table ES-1. List of Needs of Load-Flow Packages for DG Distribution Systems

Requirement	Discussion
Able to model transmission/subtransmission system	Needs to assess subtransmission loss and capacity limits, plus cases where the substation transformer load tap changer (LTC) reaches its limits
Able to model voltage control equipment—transformer LTC, voltage regulator, and capacitor switching	Needs to model the regulator function of LTC and regulators as well as the line drop compensator. Should accommodate capacitor switching based on both time of day and electrical quantities (voltage, current, kVAR, etc.)
Able to model unbalanced systems, single-phase loads, single- and two-phase lines, and the specific transformer connection	Existing software for the distribution market will generally do this, but many transmission-level load flow packages do not
Efficiently handle load and generation profiles	Must handle daily/weekly/annual load and generation cycles, plus interruption rates
Optimization routine	Sensitivity studies for loss, voltage profile, capacity, feeder reconfiguration, and capacitor placement/size
Includes or accommodates accurate and flexible DG models	Negative load, synchronous or induction generator, and so on

Commercial distribution engineering software-based packages also include the calculation of fault current. These can be modified to include significant distributed generation in a variety of different ways. In general, distributed resources will be modeled differently in a fault-current analysis, and this is less of an issue in load-flow analysis. There is a need for expanded benchmark systems to be used in assessing the capabilities of the various packages.

High-penetration PV will also create a need for other new analyses not normally included in distribution engineering studies. A case in point is the need for a dynamic analysis to analyze the interactions among many distributed generators clustered on a feeder, including the ability of these groups of generators to satisfy anti-islanding requirements.

This report includes a description of the range of engineering analysis tools needed for the modern distribution system and the capabilities that will be needed for high-penetration PV, and it includes a needs assessment. These are separated into near-term and long-term needs and classified by priority and level of developmental effort. Near-term needs loosely correspond to needs with feeder penetration levels of about 15%. Mid-term needs are consistent with feeder-level penetrations of about 30%, and long-term needs address higher feeder penetration levels, and intentional islanding could be considered.

A summary of these needs are presented in Tables ES-2, ES-3, and ES-4. In the near term, four high-impact needs will accommodate the next level of DG penetration. Load-flow and screening tool needs are critical to the planning function to ensure that capacity, voltage, and reliability criteria are met. In addition, load-flow upgrades will identify the peak-load and loss-reduction benefits of the resource.

Table ES-2. Near-Term Needs Assessment

Need	Impact	Development Effort	Description
Distribution load flow	High	High—expand to include capacity/reliability capability, year-long load cycles.	Existing benchmarks need to be expanded to assess the new capability
DG screening tool	High—needs to meet mandated response dates	High—needs to evolve in order to incorporate the routine analysis	Currently available software dated
DG database manager	High	Medium—effort needed to coordinate DG needs with the common information language (CIL) effort	Needed for planning, design, and operation—must integrate with existing tools in all three areas; needs capability to pull in the real-time data flow
Fault current calculation/TCC relay coordination	High	Medium—inverter fault performance not documented; models are limited; there is need for coordination research	Fault-current software must account for DG contribution; TCC packages must use contributions in drawing the coordination curves

In the case of fault-current and protection software, research and design procedures are needed before software tools are developed. An example of this is protective relaying, in which distributed generators can impact the settings requirements for traditional time overcurrent protection systems. In addition, in high-penetration scenarios both with and without intentional islanding, time overcurrent relaying may not be sufficient, and directional or distance schemes could be required. As penetration levels rise on individual feeders into the 30% range, concerns emerge regarding the dynamic performance of DG. A need will develop for dynamic analysis tools used to study generator oscillations, damping, and anti-islanding controls for large numbers of generators. Existing tools must be upgraded, advanced system models for PV and other distributed generators must be developed, and these must be improved to accommodate a wider range of users.

Table ES-3. Mid-Term Needs Assessment

Need	Impact	Development Effort	Description
Dynamic analysis—medium term	High	Medium—DG dynamic model development, need for unbalanced analysis	Must analyze multiple DG devices/technologies to determine potential for oscillations, damping, and effectiveness of anti-islanding controls
PV flicker	Medium	Low—research needed	Need for data and methods to assess flicker from distributed PV
Load-flow planning	Medium	Medium	Includes research on determining capacity benefits of PV—continuing evolution of methods to quantify capacity and reliability needs

At some point, increasing penetration levels will lead to questions on the feasibility of developing microgrid capability for improved reliability. Research is currently under way to develop and demonstrate the technical capability to establish and operate these microgrids. Future advances are expected to create an additional need for analytical tools and software. These needs are described in Table ES-4.

Table ES-4. High Penetration Level and Microgrid Needs Assessment

Need	Impact	Development Effort	Description
Dynamic analysis—long term	High	High	Assess islanding capability of multiple DG devices/technologies; propose and assess islanding control strategies; support PQ study issues
Fault current/protection	High	Medium—need for research	Beyond TCC—and ensure minimum fault levels
Power quality/ reliability—long term	Medium	Medium	Quantify the benefits of intentional islanding on customer service; determine weak source PQ impacts
DG screening tool	High	Medium—build on near-term model	Screen intentional islanding scenarios, both technically and from a business perspective
Distribution state estimator	High	Could evolve from database tool	Incorporate this operations tool into planning and design functions

Inverter Performance Standards

As the penetration levels increase for distributed photovoltaics, there is a need to discuss the inverter design. Specifically, allowing inverters to regulate voltage may become the preferred option at high penetration levels. The fault performance of inverters must be considered from both fault-duty and protective-relaying viewpoints—potentially both for grid-connected and intentionally islanded systems.

To successfully meet the distribution designers' needs as penetration levels increase, significant upgrades are needed in the analytical tools that are available to distribution planners and designers. The ability of software tools to accurately model the PV inverters is as important as the upgrade of the analytical capabilities of this software. Finally, there is a need to develop a consensus on how these inverters can best perform during both normal and abnormal conditions.

DG-Ready Distribution

The concept of DG-ready distribution is proposed to bring focus to the diverse issues involved in upgrading an existing system to prepare it for the installation of PV and other distributed generation at high penetration levels. This concept would synthesize the results of ongoing research and demonstration packages and identify a preferred set of options for appropriate distribution designs. The resulting analytical and screening tools will then be simplified, and the engineering time will be reduced for distribution systems that are experiencing significant increases in the penetration of distributed PV. These methods will also provide accurate information about the benefits that the DG resources provide to the system—such as peak load reduction and associated capacity benefits and loss reductions.

This report includes an assessment of the current state of the art and research (Section 2) and an assessment of research needs (Section 4). Section 5 is a gap analysis, and the research plan presented in Section 6 identifies needs that are ranked with respect to benefit, effort, and urgency. The conclusions and recommendations in Section 7 put research and development needs in context and identify high-level issues that will be addressed by this work.

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1.0 Introduction

Successfully integrating large numbers of distributed photovoltaic (PV) generation technologies into the electric power distribution system presents new challenges to distribution company engineers. This report, therefore, focuses on the need for advanced distribution engineering analytical tools. High-penetration PV will change the way that distribution systems perform and provide both new capabilities and challenges for reliable, quality performance. The most fundamental change is the presence of generation on a system designed strictly to serve loads. This raises many issues, such as reverse power flow through switching and regulating devices, the need for high-speed communication with the distributed controller device, and the possibilities for these devices to regulate voltage and frequency.

There is no doubt that complexity increases for distribution systems with high levels of distributed generation (DG). The analytical methods and software tools that distribution engineers use in planning and designing these systems will need to evolve to address this added complexity effectively and efficiently. Distribution companies have an obligation to provide safe and secure systems that deliver reliable, high-quality electric power to their customers. Therefore, distribution companies must work to deliver power economically and recover their costs fairly. In the public interest, distribution companies must be financially sound and have an opportunity to maintain and upgrade their systems in response to market and technology forces. This report addresses the need for analytical and software tools that will allow distribution engineers to design and develop safe and secure DG-ready distribution systems, as well as identify the benefits that distributed PV can provide.

By nature, every distribution system is "one of a kind." A single distribution company will have multiple individual distribution systems—here, a distribution system is considered to be a set of feeders fed from a common bus. Distribution systems vary by type of load (residential, commercial, industrial), load density (urban, rural), type of construction (radial, networked, three-wire, four-wire), voltage level, and other parameters. In most cases, the systems have evolved over many years and include a variety of equipment vintages and technologies. Many systems include special loads—e.g., high-priority loads such as hospitals and "high-maintenance" loads, such as those that feature large motors, welders, and arc furnaces and have the potential to adversely impact neighboring loads.

Distribution systems are constantly growing. This growth is the result of new customers, new loads installed by existing customers, or changing usage patterns in existing loads. Distribution companies are aware of new customers and assess their needs and usage. They are generally not aware of new loads installed by current customers. Over the years, distribution system planners have evolved a set of analytical tools and techniques that monitor load growth and provide an orderly means of evaluating and upgrading the system to maintain required service levels at a reasonable cost, addressing the uniqueness of each system without undue expense.

Today's planner is faced with a number of challenges and opportunities, including deregulation, distribution automation, and increasing expectations regarding reliability and quality. Among them are increasing opportunities for distributed energy resources (DER) to be applied on the system. DER includes distributed generation, energy storage, and dispatchable loads. DG technologies include renewable resources, such as photovoltaics and wind, plus internal-combustion and turbine-driven generators, which have been installed for some time by consumers who require high levels of reliability. When DG is installed by customers for reliability purposes, distribution companies usually conduct studies and set connection requirements. Customers typically pay for both the engineering studies and any system upgrades needed.

The current interest in installing large amounts of renewable DG on distribution systems is causing the entire process to be reevaluated. The presence of numerous renewable DG installations on the system changes the nature of the engineering studies needed to ensure that the system operates properly. The successful integration of renewable DG requires the development of DG-friendly distribution systems that involve technologies and techniques that can be readily deployed over a range of distribution systems. There is also a strong need for analytical and software tools to aid distribution system planners and designers in identifying necessary system upgrades and justifying those needs to their company, regulators, the public, and new DG owners. There also must be a mutually agreeable way to recover the costs of any upgrades needed, whether from DG owners, distribution companies' customers, distribution company owners, or the public.

Section 2 describes distribution system analytical and software tools in current use and identifies issues that planners and designers will face in addressing the upcoming expansion of DG. Section 4 identifies the research and development needed for upgrading these tools and ranks these needs with respect to their impact and the amount of effort required. The gap analysis for this study is presented in Section 5, and Section 6 provides a list of near-, medium-, and long-term needs, ranked according to priorities.

2.0 Current Status of the Research

The needs of the energy market are creating a strong interest in rapidly developing distributed energy resources for the electric power system. These resources will normally include small-scale generation, energy storage, and dispatchable loads that are located on electric power distribution systems. The resources include renewable distributed generation technologies such as photovoltaics and wind (apart from large, central-station developments) as well as microturbines, combustion turbines, reciprocating engines, fuel cells, and other diverse generators. Controlled and interruptible loads can also benefit system performance; these are consumer loads that may be enrolled for utility control in mutually beneficial rate structures.

At present, it is widely accepted that well-designed DG installations can be successfully applied to the grid at low penetration levels with little need for engineering studies or distribution system upgrades. The implementation of Institute of Electrical and Electronics Engineers (IEEE) Standard 1547-2003, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems [1], has led to the development of interface equipment (particularly inverters through UL 1741 [2]) that can often qualify easily for installation.

There are indications that DG penetration levels on individual distribution systems will increase and be widely applied in the near future. There is a significant body of work on the effects of higher penetration levels; general planning and design impacts have been identified. A number of challenges will arise as penetration levels increase, and choices will have to be made as to how best to deploy these resources.

To realize the full potential of DG, its benefits must be readily assessable. At the same time, DG installations need to be planned, designed, and installed to manage impacts on the distribution system. As system numbers and penetration levels increase, analytical techniques and computer aided planning (CAP) and design (CAD) software must mature to allow efficient, effective installations. Widespread installation requires analysis and software tools that can be used readily by distribution system planners, designers, and operations staff with limited time to investigate options or conduct studies. Figure 1 shows a typical structure for the tasks and responsibilities of these groups in a large utility. The process is increasingly driven by outside inputs from regulatory and public perspectives, as well as by reliability requirements and technology changes.

Ideally, a new distribution technology is evaluated and approved by a standards group, and designs are based on these standards. The benefit of this approach is that evaluation is centralized and designers do not perform the assessment individually. For smaller utilities, these functions are likely to be handled by the same people, and available industry best practices are applied. Actual design work is performed by engineers and engineering assistants whose expertise is focused on the structure and performance of their respective systems. Most have little background in power generation systems, power electronics, system dynamics, or electromagnetic transients.

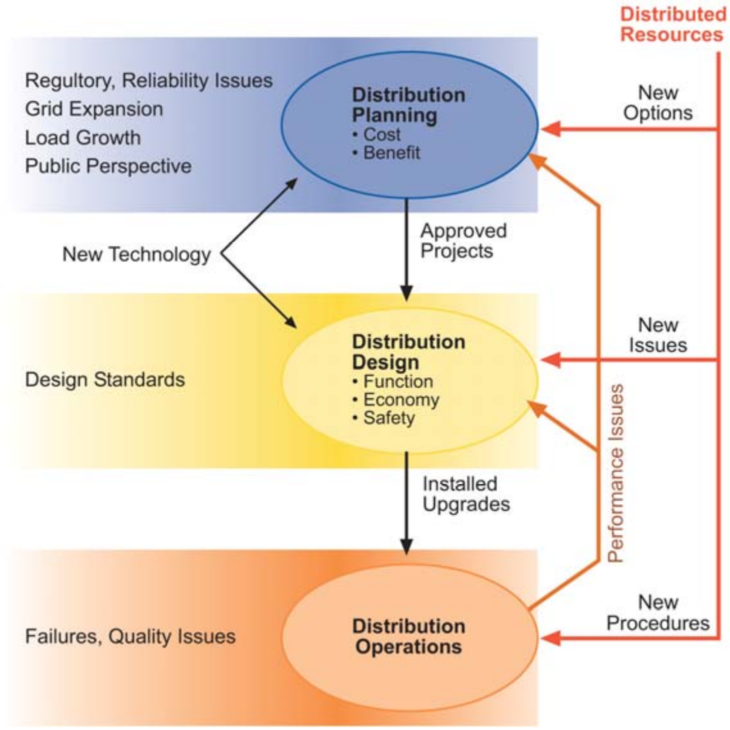

Figure 1. Flow chart of the distribution system planning and design process

As PV penetration levels become widespread on many distribution systems, distribution companies will move beyond the point where a small number of DG experts will suffice, and there will be a strong need to provide training for a full range of distribution system designers. A three-pronged approach is needed to successfully integrate DG in the distribution system:

- Development of DG-ready distribution system concepts
- Development of DG-capable analytical methods and software tools
- Training of distribution system designers in these new needs and methods.

Each of these three tasks is critical to the success of this effort. DER expertise must be placed in every design group of a distribution company and not centralized in a single location. Failure to do this will result in a long transition period in which the same issues are addressed repeatedly on a regional basis, and DG-ready concepts are not regularly employed for upgrades except in cases in which DG projects are expected.

Adding increased levels of distributed resources on a distribution system will bring both challenges and opportunities to the process. Opportunities will be available primarily to a distribution system planner when distributed resources have the potential to improve reliability and mitigate the need for system upgrades but also impact the voltage regulation and reactive power needs of the system.

Distributed energy resources will add new challenges to the distribution system design process in the areas of safety, fault sensing, and protection, among others. These issues are a function of the nature of the DG resources, the structure of the distribution system, the DG penetration level, and the strength of the system at the point of DG connection. As DG penetration levels increase, design standards that are regularly applied to distribution systems will no longer work, and new standards will be needed to avoid costly, one-of-a-kind installations.

In order for DG to be successful at high penetration levels, buy-in must be achieved from a wide range of parties, including these:

- Distribution system customers with distributed generation
- Distribution system customers without distributed generation
- Distribution system owners/operators
- Merchant distributed generators
- Merchant bulk generators
- Grid customers
- The public
- Policy makers

Customers with Distributed Generation. We anticipate that a wide range of customers will install DG, in response to a wide range of opportunities. These will include, for example, those who are willing to pay extra for renewable energy, those interested in improving the reliability of their energy, and those wanting to reduce their energy costs through participating in load-interruption options. Different objectives will lead to different installations, and we expect that there will be a variety of DG installations in most areas. All the installations must be compatible with each other, with the distribution system, and with system loads.

Customers without Distributed Generation. Customers who elect not to install DG will expect to receive electric power service with no impact on its price or quality. It is important that these customers have a good impression of neighbors who do participate, so that they will be more likely to select DG options in the future.

Distribution System Owner/Operator. The distribution system owner is the glue that holds these various groups together. The distribution system provides a valuable service to customers both with and without DG. Of course, some electric power consumers will elect not to participate in the grid. High-penetration DG owners who elect to stay grid-connected do so to realize the benefits of being system-connected. The primary benefits are cost, convenience, and quality.

The distribution system will have to evolve both to accommodate DG and to meet customers' requirements. These needs will increase as penetration levels increase. At high penetration levels, system designs will be able to tap into DG to provide new, perhaps more affordable, expansion options, as well as improved reliability through islanding. DG penetration is also one of a number of driving forces for advanced distribution automation, which provides additional benefits to the system.

These changes will require investment in the distribution system. The distribution system owner will not make the investments without expecting a return on them. Because most distribution companies are regulated monopolies, the rules for returns on investment are formulated at the state level and implemented through state public service commissions.

At present, when customers install large distributed generation on the distribution system (usually for reliability purposes), these customers are generally expected to pay for any needed upgrades of the distribution system. This allows the customer to implement this upgrade without impacting the quality or cost of the other system customers. It is expected that this strategy will not work for the numerous small, sustainable DG installations that are expected and being encouraged. A new method of encouraging these necessary system changes is needed in order to realize the high penetration level of photovoltaic systems that are being envisioned.

Merchant Distributed Generation. Entrepreneurs and new entrants to the market will probably step forward and propose DG installations on distribution systems for which they are not customers. This will occur when there is a good business case for it and profits to be made.

Merchant Bulk Generators. Bulk power generators will be sensitive to two issues in particular. The first is the level of subsidy for the renewable DG. This is not expected to be a significant issue in the near term, when renewable penetration levels are relatively small and particularly while there is significant sentiment in their favor. The second issue for bulk generators regards the varying and limited predictability of both wind and photovoltaic generation. Large system penetration levels of these nondispatchable resources could change the level of baseload generation needed, for example, or could increase the ramping rates required of bulk generation. These issues must be appropriately recognized and addressed as penetration levels increase.

Grid Customers. Grid customers (including those not served by a distribution system with high DG penetration) will be similar to distribution system customers without DG, but may not participate in improvements and/or changes in quality provided by the DG. They likely will participate in the economics of the DG installations through the rates they pay. There also will be some benefit realized by these customers due to the development of sustainable energy alternatives in their general neighborhood.

The Public and Policy Makers. Sustainable distributed resources provide a public benefit even to those who are not customers of a DG distribution company and are not in the same neighborhood in which the distribution company operates. Clearly, however, the public is cost-conscious as well as interested in sustainability and the environment. These objectives can at times compete, particularly in the short term. Policies will be needed (and are being developed) to implement plans for increasing DG penetration levels in ways that the public supports. The political and regulatory process is an expression of the public and, ideally, acts in its interest.

Clearly, increased DG penetration levels will call for significant changes in distribution system planning, design, and operating procedures. These changes will create a need for greater sophistication in all three areas. In particular, new analytical techniques will be needed for successful planning and design of the systems, and this analysis will be conducted largely by using specialized distribution planning and design software. The following sections of this report include a needs assessment for CAP/CAD software tools, a discussion of the impact of penetration level on tool needs, an appraisal of the limitations of current tools, and plans for research and development needs for CAP/CAD software to avoid limitations in the development of DG.

Electric power distribution systems exist in many forms, and there is interest in connecting DG over the full range of system types. The discussion that follows pertains to all the various types of distribution while focusing on radial distribution systems.

3.0 Project Approach

The main objective of this task was to provide an update on available software tools and relevant experiences and, from this background, to pinpoint future gaps, needs, and requirements for modeling and simulation tools to address increased penetration. In this approach, we apply the premise that today's tools must evolve to address the new requirements and opportunities that will come from the increasing use of distributed resources. Future elements to be considered include advanced distribution automation and the application of advanced metering infrastructure with real-time price signals and demand response capabilities. All these technologies rely on an adequate communication infrastructure that must be defined and developed.

The research agenda is based on the premise that we will need all available energy resources, both central and distributed, to meet future electricity demand effectively. At the same time, a wide range of analysis tools will be needed to assist in placing, sizing, integrating, and optimizing the use of distributed PV, storage, and related resources in the larger electric power system.

Specific experiences illustrate both the state of the art and the need for additional research. We also draw on the penetration scenario experience and results from studies by other team members, including any results from a penetration analysis that are available during this project. Single-feeder demonstrations are included, as well as definitions of future scenarios that will help define the issues and research needed for greater penetration. In each example, we define how distributed renewable energy is integrated into models and what software is used to determine the impacts of distributed energy systems on the grid. We also identify any gaps that need closing to accommodate the introduction of more renewable generation.

The result is an overview of current simulation models that utilities use to plan the dispatch and receipt of power and to understand how these tools impact renewable energy systems on the transmission and distribution system. We define renewable energy models that will be needed (consistent with utility studies) to evaluate steady-state and transient conditions for PV penetration studies. And we define additional data that need to be collected on field tests and demonstration systems to provide input and validation for modeling and analysis work in this area. Existing case studies and experiences are reviewed, as well as the need for additional case studies or demonstration projects to provide realistic operations of large-scale PV deployment. We also determine the tools and data needed to identify optimal locations for PV in the distribution system.

In this report, we use examples of existing and recommended future cases to illustrate the need for and application of modeling and simulation tools, including development requirements. We assume that the tools must evolve as penetration levels and our reliance on distributed resources increase.

4.0 Project Results

4.1 Description of Issue

In general, distribution system engineering tasks can be divided into planning and design stages. The planning function is to identify system needs and limitations, to propose projects to resolve the issue(s), and to gain approval for projects. The design function takes a project from concept to realization in a safe, efficient, cost-effective manner.

Primary planning functions are as follows:

- Load flow, to establish power flow and voltage regulation limits
- Reliability assessment
- DG distribution impacts screening
- DG installation database management
- Assessment of grid-level impacts

The first two topics are traditional planning tools that will be impacted by increasing DG penetration levels. Reliability assessment is an evolving issue of increasing importance, as a result of deregulation and the implementation of performance-based rate structures. DG screening and DG database management are new distribution planning functions that make use of new tools to address the issues that arise with the advent of DG technologies and operating regimes. Finally, the need to assess the impact of DG on grid-level issues—including generator dispatch, unit commitment, and transmission congestion—goes beyond distribution planning and will be a new function for the system planners as system-wide DG penetration levels increase.

The primary design functions considered are as follows:

- Load flow
- Fault current analysis
- Protective relay coordination
- Power quality and reliability
- Dynamic analysis
- Ferroresonance
- Transient analysis
- Grounding design

Each of these functions is part of the design process for all distribution systems. However, the presence of DG on these systems impacts both the design process and the level of analysis needed. As penetration levels rise, DG will also have an impact on the nature of the design. For example, the transformer connection and the protective system philosophy will be a function of the size of an individual DG device as well as the penetration level of DG on a particular feeder segment.

By nature, distribution system design is an ongoing process in most utilities, where systems are continually evolving. Often, some functions (such as protective relay coordination or ferroresonance) are performed by outside specialists. There are also times in which the planning, design, and operations functions overlap—for example, when a flicker complaint involves an unplanned addition of a new load by an existing customer.

In some cases, such as rural electric cooperatives and small municipal power companies, the number of in-house staff who can deal with analyses of distributed generation will be very limited. This is likely to be an important gap in achieving high penetration levels of distributed renewable generation. Often, utility planners, designers, and field engineers barely have time to handle the basics and would find it difficult to include any time-consuming and difficult studies. To be useful, tools must be user-friendly and cost effective, as well as backed up by industry best practices.

4.2 Individual Tool Capabilities and Needs

4.2.1 Load-Flow Software

Load-flow programs are used widely, and commercial packages for distribution system load-flow analysis are readily available. An analysis of several of these packages can be found in reference [3]. In addition to being the basis for loading and voltage studies, load-flow programs are also the foundation of reliability, flicker, and other analyses.

Load-flow studies are used to determine the basic capacity and voltage regulation issues associated with DG interconnection, as well as the impact of the DG on system losses. Adding significant levels of nondispatchable DG, such as photovoltaics, to the distribution system significantly increases the complexity of the analysis. The complex time- and location-dependent relationships between feeder segment loads and PV output create a need to run many additional studies to determine the range of operating conditions that the new system will experience. A single load value and a generator output value do not suffice for determining the impact of DG.

Figure 2 illustrates the impact of PV generation on building load over a single 24-hour period. In this case, an extended load characteristic means that the midday peak reduction does not extend into the evening load period of this particular load. This figure demonstrates the need for detailed knowledge of both load and generation profiles. In addition, planning studies will be required to use predictive methods to analyze the range of loads and generation created by time of day, day of week, seasonal, weather, and other impacts. In most cases, distribution planners will need to perform hourly studies for a full year in order to fully assess system impacts.

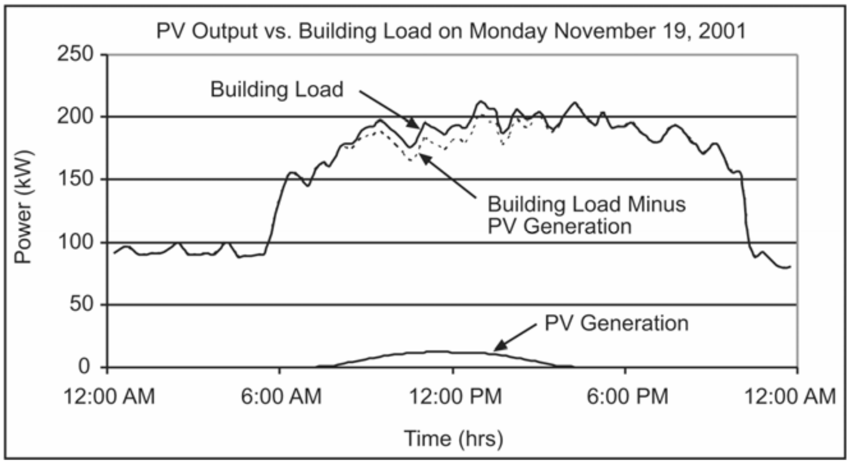

Figure 2. Measured building load, PV generation, and load-reduction effects for a small PV installation [4]

Distributed generation provides several challenges to standard distribution system load-flow software. The primary issues are shown in Table 1. Though in most cases we can expect that DG will alleviate both loading and voltage drop issues on the distribution system, planners must provide for a full range of reasonably expected operating modes.

Table 1. Summary of Load-Flow Capabilities Needed for High-Penetration DG Studies

Requirement	Discussion
Able to model a portion of the transmission/subtransmission system	Subtransmission loss and capacity limits are often more restrictive than distribution limits; also, cases in which the substation transformer LTC reaches its limits must be identified.
Able to model voltage-control equipment	Needs to model the regulator function of LTC and regulators as well as the line drop compensator; should accommodate both time of day and voltage-based capacitor switching
Able to model unbalanced systems, single-phase loads, single- and two-phase lines, and the specific transformer connection	Existing software for the distribution market will do this, but most transmission-level load-flow packages will not
Efficiently handle load and generation profiles	Must handle daily/weekly/annual load and generation cycles, plus interruption rates
Optimization routine	Sensitivity studies for loss, voltage profile, capacity, feeder reconfiguration, and capacitor placement/size
Includes or accommodates accurate DG models	Negative load, synchronous or induction generator, and so on

Though it is not practical or desirable to run a full load-flow study for every small DG addition, system models must include all DG resources when studies are indicated. It is also important to make a clear distinction between penetration levels composed of numerous small PV installations and similar penetration levels consisting of a single turbine-driven synchronous generator. At higher penetration levels, DG can be expected to play an increasingly significant role in the system voltage profile as well as provide an alternative to capacity expansion on the system.

Vendors of commercially distributed load-flow software are continually updating and upgrading their products. Table 1, however, indicates a number of areas in which basic upgrades are needed to accommodate design needs for increased DG penetration levels. The Electric Power Research Institute (EPRI) has been investigating advanced methods for distribution load flow analysis with its Distribution System Simulator (DSS) [5]. The DSS has been under development since the mid-1990s and has broad modeling flexibility. At the same time, it is not a commercial product and at present is being used only in research environments.

The DSS provides a platform that allows investigations of DG planning issues as continuing research identifies new types of studies needed to facilitate the integration process. For example, several approaches have been investigated to better quantify the capacity benefit of small DG installations.

To date, the DSS has been used for the following studies:

- Reliability assessment
- Neutral-to-earth, or stray, voltage simulations; this requires extensive modeling of the neutral and ground paths at the triplen harmonics of power frequency
- Evaluations of losses due to unbalanced loading
- Development of DG models for IEEE radial test feeders
- High-frequency harmonic and interharmonic interference
- Losses, impedance, and circulating currents in unusual transformer bank configurations
- Transformer frequency response analysis
- Distribution automation control algorithm assessment
- Impact of tankless water heaters on flicker and distribution transformers
- Wind farm collector simulation
- Wind farm impact on local transmission
- Wind generation and other DG impacts on switched capacitors and voltage regulators
- Open-conductor fault conditions with a variety of single-phase and three-phase transformer connections.

The primary needs for DG-ready distribution system load-flow software are to assess voltage profile, losses, and capacity issues for arbitrary distributed resource studies, as well as to support the reliability analysis described in the next section. The DSS was developed with distribution system topologies in mind and performs a distribution-style power flow in which the bulk power system is the primary source of energy and is represented by a system equivalent a few buses back into the transmission system. It can model the nearby subtransmission system and the substation transformer with its load tap changer (LTC) and line drop compensator; this is often necessary in DG evaluations. It can perform both per-phase and three-phase solutions.

The DSS has other features for supporting the analysis of DG interconnected with the distribution system. In addition to performing single load-flow solutions, DSS can efficiently execute multiple solution studies to analyze the effects of changing load and DG levels. These include daily, yearly, duty-cycle, and Monte Carlo modes and other modes in which the load varies as a function of time. Yearly load growth can be modeled readily for multiyear studies.

The analysis can be over an arbitrary time period. Although a 1-hour step size is common for distribution planning studies, the duty-cycle model can be used for modeling such things as wind generation, in which the step size might be as small as 1 second. The DSS results provide losses and other information for the total system, each component, and certain defined areas. For each instant in time, kilowatt losses are reported. Over a given time interval, losses can also be reported as energy losses (in kilowatt-hours). Power flow can be computed for both radial distribution circuits and network systems. The DSS provides excellent flexibility because it can be driven by its native scripting language, as well as by other programs such as Matlab, C++, or Visual Basic (including VBA for Excel). It readily accepts user-written models for new equipment or study modes, which is essential for the development of new DG component models and the investigation of alternate DG control strategies.

The DSS has been used as a tool to develop analytical methods for assessing DG installations on the distribution system. Reports on these developmental issues can be found in references [5] and [6]. Tools continue to be developed, and other techniques are also being investigated. This brief discussion provides an example of the innovative types of analysis needed to investigate and document DG additions to existing distribution systems. Current methods are often too coarse to recognize any value in DG. Existing engineering tools for distribution planners are designed primarily to model power flow from the bulk power system (transmission system) through the distribution substation to the end user. Also, these tools are designed for analyzing large capacity additions. Any practical tool must also be able to efficiently manage and display the large amounts of data that result from these analyses.

4.2.2 Assessing the Contribution of DG to Distribution Capacity

This section illustrates a method researched using the EPRI DSS [5] for determining the capacity contribution of DG to the power distribution system. The question of impact of DG on distribution system capacity boils down to this:

> *How much more load can be served on the system with a given amount and type of generation?*

If this were only a matter of serving a given load at a given time with available generation, it would be a straightforward exercise to determine the answer. The distribution system, however, must also operate reliably. To do so, it must maintain the capacity and flexibility to serve the load under adverse conditions. Historically, engineering judgment and standard design practices were used in developing these designs. Heuristic methods were used to reach a suitable balance between reliability and economy. In this age of increased oversight and deregulation, however, heuristic methods are being called into question as not providing sufficient justification for decision making.

At the same time, DER technologies are coming of age and providing new opportunities and challenges that are beyond the capability of existing tools. Today, distribution companies are often criticized for having unused capacity at the same time that they are penalized for having low reliability. The relationship between capacity and reliability is not often apparent to nonspecialists, and specialists often do not present convincing quantitative information on the issue. The next generation of distribution planning tools will be required to fill this gap.

The answer to the capacity question depends on at least two fundamental issues:

1. How is “system” defined?

2. What measure of “capacity” is used?

If the focus is on a single feeder, the increase in load served can be closely related to the size of the DG technology, depending on its location and type. In some cases, the increase in load-serving capability can be greater than DG size, if it is an appropriate generation technology in a particularly good location. At other locations, the benefit can be a small fraction of the DG capacity. If we define the system as consisting of more than one feeder and/or substation, the net gain is often much less than the DG size even if it is in a good location for one feeder. A specific generator provides capacity to only one of those feeders and to the substation to which the feeder is connected. However, if the DG is sited so that it displaces load on a feeder in the proper location, it is theoretically possible to transfer loads from another feeder, if tie switches are placed properly, and achieve an apparent capacity increase.

Consider these cases (referring to Figure 3Figure 3. Affect of DG on Distribution Reliability [5]):

- If the transmission system goes down, the only load that can be served is the load with microgrid capability.
- If a fault occurs on either feeder A or feeder B, the load theoretically can be shifted to feeder C by opening some normally closed tie switches and closing some normally open ties. This feeder is now more capable of serving the load because part, or all, of its load has been supplied by the DG shown. The ability of DG to serve the load in the immediate period following restoration must be assessed here.
- If a fault occurs on feeder C, the DG may or may not help, depending on where the fault is located. If the fault is in the section closer to the source, the tie to B can be closed, and the DG helps support the remaining load on C while being fed in the opposite direction from B. If the fault is between the DG and the tie, the DG is likely to be of no assistance.

One way of dealing with the reconfiguration problem is to leave sufficient capacity in one backup feeder to serve the entire load of each feeder. Thus, any time the load exceeds 50% of maximum capacity, there is a risk of an outage that cannot be covered by a simple reconfiguration. This is a conservative approach found more frequently in urban areas where feeders are short—which both lowers costs and simplifies the necessary switching.

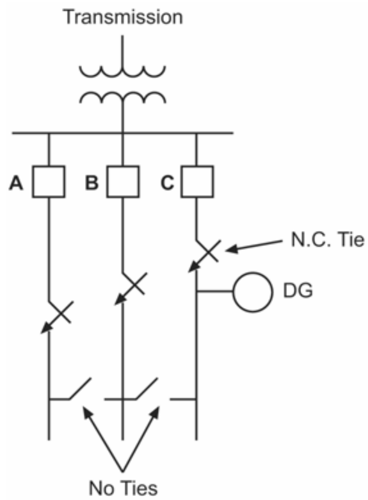

Figure 3. Affect of DG on Distribution Reliability [5]

A wide variety of approaches are currently in use that result from varying factors such as load density and service expectations. Some utilities permit the load to grow to 70% to 80% of maximum capacity. This approach can be taken when price concerns outweigh reliability issues, and it might be the case in areas where outage times are historically short. In general, this philosophy results in lower investment at the expense of reliability. Consider a case in which the 50% philosophy will be used—that is, the normal feeder rating is set at 50% of the maximum rating. Any time that the loading exceeds this level under standard operating conditions, it is assumed that the reliability of the system is compromised. The amount of energy served above this level (EEN = energy exceeding normal rating) will be considered the energy at risk. EEN is a surrogate for more direct assessments of the reliability of a design. This surrogate has been determined to be useful in the past and will continue to be used until more detailed reliability prediction tools evolve to supersede this approach.

In theoretical terms, using a normal rating of 50% is related to the “N-1” planning criteria used on the bulk power system. Because of the nature of the distribution system, coupled with the different short-term service expectations, bulk power system methods do not translate directly to the distribution system. The EEN method does allow for comparisons of various investment options and provides better resolution for comparisons of the alternatives, which is important when there are very small differences such as those found in evaluating solar generation. Thus, the capacity basis for answering the planning question posed above is the amount of energy served above the normal rating. Two alternatives that yield the same value would be considered to have equal reliability risk.

Basic Concepts Underlying the Analysis. Often, there are numerous simultaneous constraints in any given distribution planning area. It is obvious that we need to look beyond single points in time to incorporate a measure of risk that incorporates time dependency.

Figure 4 illustrates the EEN evaluation method. It is flexible and can be adapted to a wide variety of problems, including both dispatchable and nondispatchable DG. Two ratings are defined for key elements of the system, such as transformers and lines:

1. Maximum rating
2. Normal rating that is considerably lower than maximum rating.

The daily load and DG profiles are then simulated—typically, hourly for each day of an entire year. This is repeated for each year of the planning study. When the power exceeds the maximum rating of a piece of equipment, some load must be curtailed. This is called *unserved energy* (UE). Applying a probability to this value yields a more familiar term: *expected unserved energy,* commonly abbreviated EUE. The energy under the power curve when the power is above the normal rating is referred to as *energy exceeding normal,* or EEN, as noted above. This is the energy that is at risk of being interrupted if a key element fails and capacity for backing up the load is insufficient.

Simulating a daily load shape and computing the energy associated with certain criteria automatically includes the element of time dependence compared with methods that simply look at the power at a specific point in time. Also, because energy is the quantity that is sold, it is often easier to convert energy to a cost that can be used in the economic evaluation of alternatives.

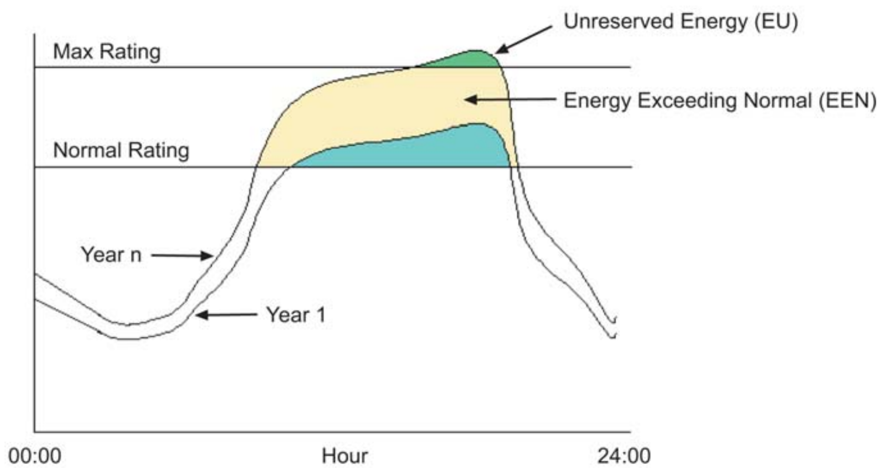

Figure 4. Daily load curve for a line segment showing the UE and EEN for a daily load curve in years 1 and N [5]

Keeping track of the energy above planning limits for every component in the system automatically includes the element of location dependence. Both time- and location-dependent values are very important in determining the value to a distribution system of incremental capacity solutions such as DG.

The results of this study will be EEN values (and UE values, if any) for each piece of equipment on the distribution system. This analysis also provides data on system losses and can include data on load profiles, reliability, and so on, with an accompanying increase in complexity and data flow. This method provides consistent results when the same approach is used to analyze multiple options. The results are turned into costs over a planning horizon through which the planner ranks alternatives and seeks the lowest life-cycle cost solution (not necessarily the lowest first-cost solution).

Traditional utility planning methods, which are often based on designing for peak load, are an alternative (and simpler) planning process. Only the peak load condition is considered, and when the load in some future year exceeds the planning limits, a range of system upgrades is considered. Typically, the planners have chosen from a smaller menu of solution alternatives—mainly substations and feeders. A least-cost solution is selected from the alternatives. This approach generally favors large-capacity additions and obscures the potential value of incremental solutions such as DG—which has been fine in previous eras with low computing power and limited DG options. It is clear that more powerful tools are needed now.

Computing EEN. Energy exceeding normal has become an effective way to compare risks in assessing the capacity limits of distribution systems. It can be computed straightforwardly by simulating the normal system configuration.

While the *maximum* rating of elements is reasonably well defined from engineering limits, the *normal* rating is a better indicator to use in assessing the trade-off between cost and reliability, particularly when distributed generation is an option on the system. It can also be adjusted to conform to specific planning philosophies.

The concepts described above can be applied in a number of ways to compute EEN. Figure 5 illustrates two different ways of computing the quantity, depending on operating philosophy and, sometimes, specific constraints. The usual way to compute EEN is to estimate the excess energy served over the normal limit. This reflects an operating philosophy of shifting the excess load or, in an emergency, curtailing just enough load to keep the system operational. This method applies generally to evaluations concerning substations where the excess load can be shifted to other substations by switching feeder sections. This is the method employed more commonly in this analysis.

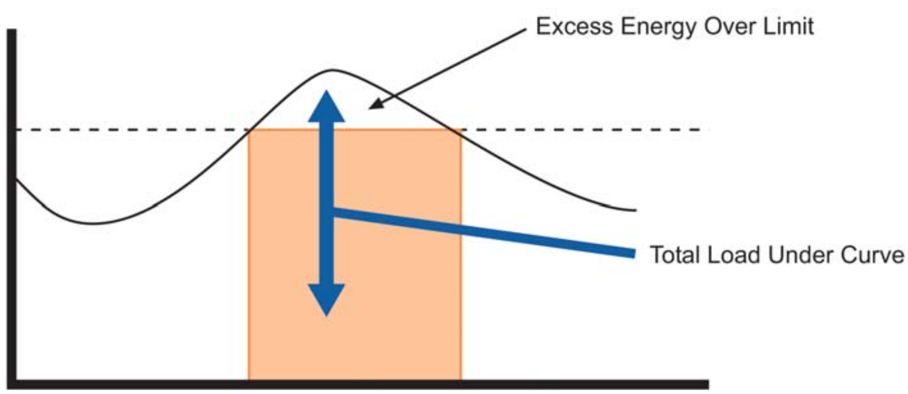

Figure 5. EEN computed as excess energy over the limit and total excess energy during the limit [5]

Another way, which generates a larger EEN value, is to count all the energy beneath the power curve when the power is above the limit. This implies that the power must be turned off to all downstream customers until the demand returns to an acceptable value. It applies more typically to a feeder that cannot be restored easily; for this, the normal rating of the feeder would be set to the maximum load that can be picked up on the main designated backup feeder.

Annual Simulations. The ideal way to compute the annual EEN is to perform an annual 8760-hour simulation over the entire load shape (see Figure 6). This has a number of advantages:

- The EEN calculation captures all the peak demand hours that might be scattered over several months.
- It captures the loss benefits (or lack thereof) simultaneously.
- The result can be used to create annual 3-D plots that communicate well to both planners and the public.
- It better captures the true benefit of nondispatchable DG, such as renewable resources, that are not necessarily coincident with the demand. It also represents noncoincident demand better.
- Voltage and volt-amperes reactive (VAR) control devices are properly sequenced on and off during the simulation; this is also true of any daily simulation procedure.

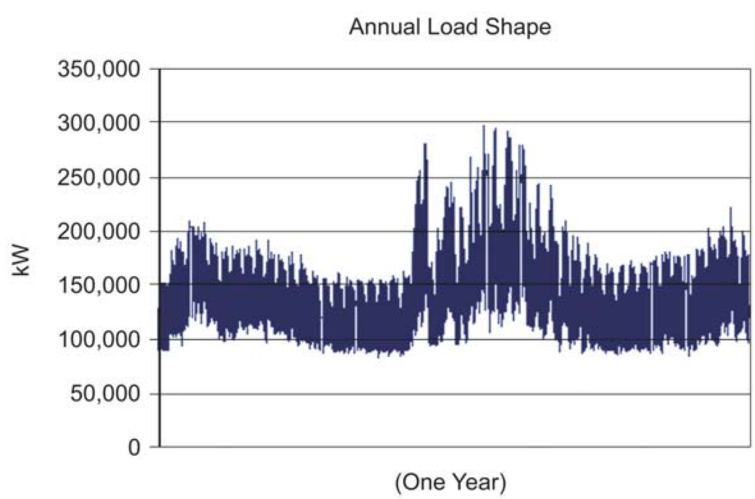

Figure 6. Typical output for an 8760-hour (1 year) analysis, showing hourly, daily, and seasonal variations of the load [5]

For a large planning area, computing 87,600 power flows over a 10-year planning horizon can take a significant amount of computer time. These are off-line calculations, however, and are readily completed on a dedicated computer. This is not viewed as a major concern, particularly with continuing advances in computer power. Greater issues include the set-up time, the ability of the set-up to follow ongoing system changes, the ability of software to automate many multiples of input data, and the ability of the software to display large amounts of data effectively and efficiently. Significant advances in each of these areas are needed before this method becomes a widely used planning tool.

Figure 7, Figure 8, and Figure 9 illustrate an effective method of displaying study results for a given system component. Figure 7 shows the total kilowatt flow on the segment over the course of a year. This plot clearly shows both daily and seasonal variations in the demand. When a DG option is being considered, this curve can be used to quickly identify the kilowatt rating required of the machine. It also identifies the hours per day that operation would be needed, as well as the duration of the year during which it would be used.

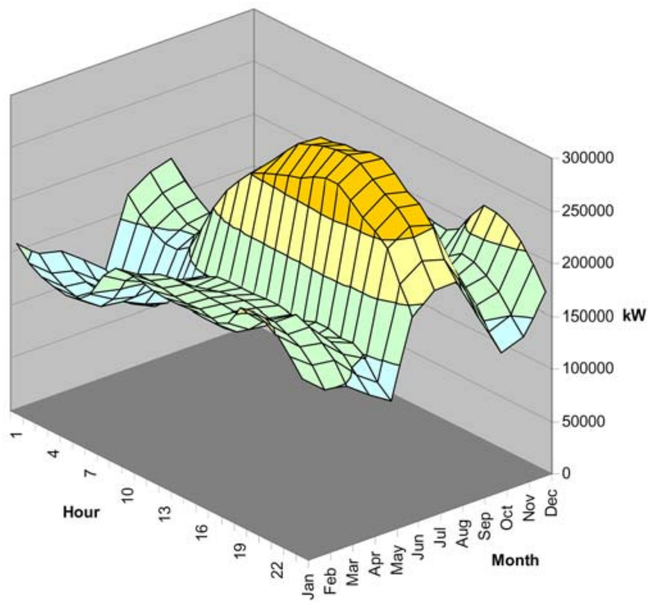

Figure 7. The hourly kilowatt flow on a system component, plotted versus hour of the day and day of the week [5]

Figure 8 shows the EEN results for the same case. The normal limit of the piece of equipment is exceeded for relatively few hours per day during summer months. The sharpness of this peak can be expected to favor a DG solution—the much broader EEN results often indicate that a more costly substation/line upgrade would have lower overall life-cycle costs. Each case, however, must be decided individually.

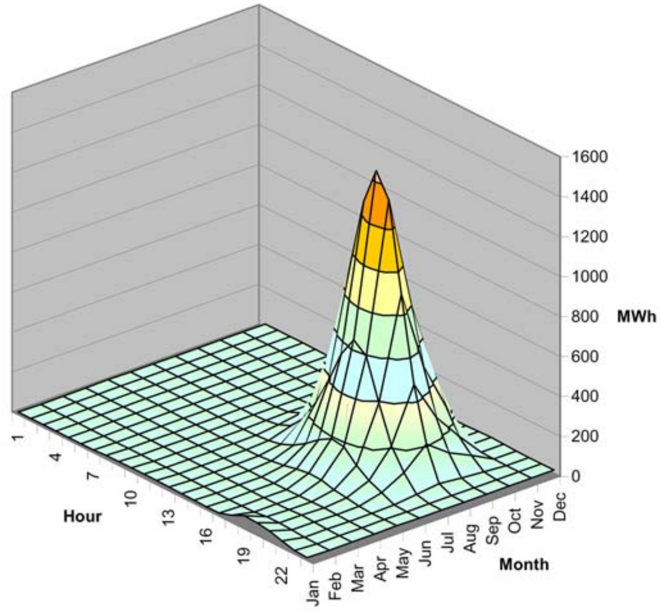

Figure 8. EEN plotted for the case shown in Figure 7 [5]

Ultimately, the distribution system grows and develops each year, and a single-year result is not sufficient. Figure 9 shows the results of a multiyear planning study showing the expected growth of EEN over a 5-year period. In traditional planning practices, we could expect that an upgrade would serve the load for this entire period. With the advent of high-penetration DG deployment, however, there could be situations in which DG growth and load growth develop in similar proportions.

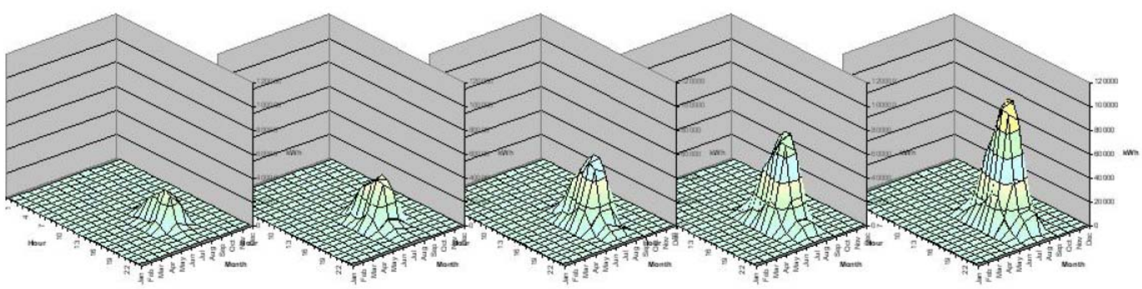

Figure 9. Example of multiyear growth of EEN [5]

To be attractive, proposed options must be capable of offsetting power demand at the levels and times indicated on these charts. Ideally, a traditional large-capacity solution to the problem depicted would take the EEN characteristic down to zero for several years. Incremental solutions will allow the EEN to reappear more quickly if the load continues to grow in subsequent years. Thus, DG solutions frequently look very good in built-out areas with low-to-moderate load growth.

The capacity gain for a proposed solution can be quantified by comparing the total annual EEN for the solution case to an alternate case—either the "do nothing" case or a base upgrade. This is done by plotting both total EEN values as a function of the total load in the planning area (Figure 10). For a specific EEN value, the capacity gain is the horizontal distance between the two options. This curve answers the question: How much can the load grow in the planning area until the EEN (risk of unserved energy) is the same as for the base case? The figure shows the incremental capacity gain for a distribution planning area blanketed with 4 MW of photovoltaic generation. Based on equal EEN, the gain is approximately 40% of the power rating of the solar generation, which is a good value for this type of generation.

In summary, the evaluation of EEN can be used as a planning tool in identifying the need for distribution system upgrades and to evaluate the effectiveness of various options to provide the upgrade. While EEN is not a direct measure of system reliability, it is a surrogate for reliability that can be used effectively for planning purposes. Direct methods for evaluating system reliability are discussed in the next section.

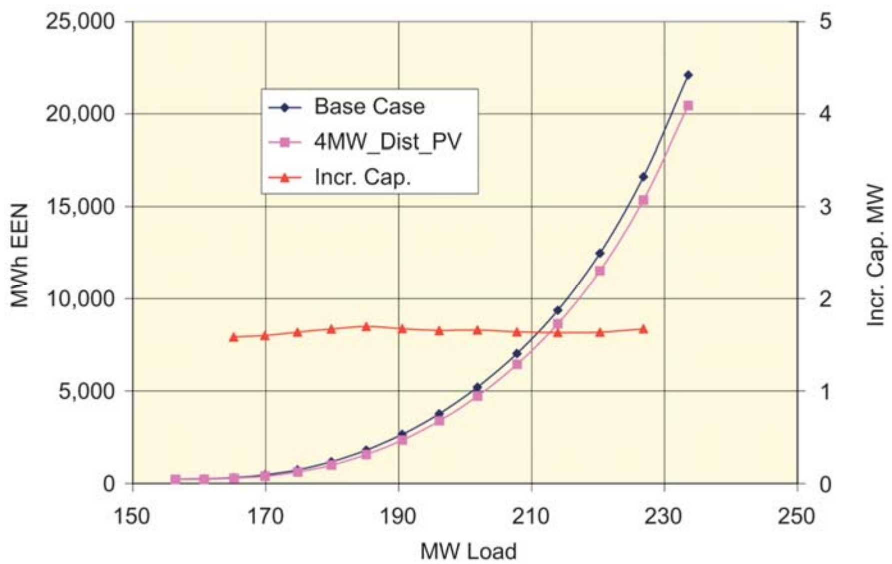

Figure 10. Example case of EEN plot of base case and proposed cases showing capacity gain achieved by proposed case [5]

Tools for assessing DG capacity credit are generally limited to use by experts. This is more complicated to calculate for some renewable generation, such as rooftop solar systems, where systems are more distributed and available solar resources are less certain.

4.2.3 Reliability Analysis

The need for a distribution system reliability assessment is both expanding and evolving. Because of the implementation of performance-based rates and the increasing costs some customers incur from outages, there is significant interest in incorporating reliability issues in the distribution engineering process. Reference [5] provides a comprehensive review of the need for software tools and current software capabilities in the reliability area. The report describes some concerns with current reliability tools as follows:

- *"Reliability analysis* does not yet have a clear definition. Although such standards as IEEE Std. 1366-1998 have defined some aspects of distribution reliability, the components of that analysis can vary quite significantly from one utility to another and from one tool to another. Reliability tools are designed based on the problems the vendors' customers are presently experiencing and are often too inflexible to be adapted to other problems.
- "Many utilities are purchasing the reliability analysis modules, but finding it difficult to put them into practice. It is not entirely clear why this is happening, but the likely reasons stem from insufficient time for engineers to use the tools properly. Tool vendors are attempting to address this by making the interface more seamless" [5].

At present, many different reliability indices have been proposed and are being used. These can be divided into four main categories:

1. Indices that measure frequency of sustained interruptions
2. Indices that measure duration of sustained interruptions
3. Indices that measure frequency of momentary interruptions
4. Indices that measure frequency and depth of voltage sags.

The first two categories have traditionally been considered "reliability" issues, while the last two have been considered "power quality" issues. Although there are historical reasons to make the distinction between reliability and power quality, modern loads are increasingly dictating that sustained interruptions, momentary interruptions, and voltages be treated as one. The need for this is reinforced by recent research documenting that the majority of monetary losses are commonly incurred because of momentary interruptions and voltage sags rather than sustained outages [7].

There is a significant need for maturation in this area. In particular, there is a need to address all four categories of concern consistently and in an economically consistent manner. There are some very basic issues that need to be resolved before this can be done:

- Should indices be based on a per-customer basis or a per-kilowatt-hour basis?
- Should indices reflect the range of losses incurred by various customers due to sustained interruptions, momentary interruptions, or voltage sags?
- What consistent method can be used to evaluate trade-offs between interruptions and voltage sags?
- Should geographic and/or load density issues be considered in determining reliability goals for a system?

Though there is a significant amount of interest in these issues, it will take some time to resolve them.

Meanwhile, researchers are investigating distribution reliability predictions and the development of reliability software tools. Brown et al. [8] describe four different reliability modeling approaches:

1. Network modeling: Analytically, this is a straightforward approach, but it cannot always capture the complexity of a distribution system.

2. Markov modeling: Markov modeling is a powerful method of reliability analysis. However, matrix inversion is required, and the number of states in a realistic distribution system can be enormous. It can also be difficult to identify accurate device models.

3. State enumeration: This method generates states for the system by some means and then determines the impact of each state on system reliability. The method works best for systems that are in their normal operating condition nearly all the time, which is often the case for U.S. distribution systems.

4. Monte Carlo simulation: Monte Carlo simulation represents possible events with probability density functions and generates sequences of events randomly. This method is computationally intensive but fairly straightforward to model, and it can represent complex system behavior. Improvements in computational efficiency are making this simulation more popular.

Note that reliability analysis is stochastic and predictive in nature. The goal of a distribution system reliability tool must be to provide consistent, accurate comparisons between competing design options. The following steps [5] are proposed to attain this goal:

1. Create a reliability model of the distribution system. This needs to be an exhaustive model of the distribution system with accurate topology and device models. An efficient database tool and interface will greatly ease the topology issues, although many existing databases do not include certain items (such as cable splices) that are important from a reliability standpoint.

2. Calibrate the system to historical performance. Historical records provide reliability rates and some level of failure data. In some cases, default values must be used for some equipment. Some software will be able to update failure data as operating experience accumulates, after the original reliability model is built for a system.

3. Perform a root cause performance analysis. Effective root-cause analysis will require utilities to improve their fault analysis and recordkeeping as faults occur on the system. Modern fault-location equipment will be helpful. As state estimators gain credence in the field, they could aid in this cause.

4. Perform a sensitivity analysis. This step is the primary result of the reliability analysis—prediction of the various reliability/power quality indices in response to a proposed system upgrade. Users will need to have a clear vision of the relationships among various indices to make this effective. For example, eliminating fuse-saving may reduce voltage sag indices for some customers while raising sustained interruption indices for others. At present, there is no widely accepted method for assessing this trade-off.

5. Perform an economic analysis. Ideally, the economic analysis would provide the designer with an exact and identifiable cost-benefit ratio. Though the costs of system upgrades are readily predictable, the benefits are not. Even if the exact monetary benefits could be identified at a given time for a full range of customers, they would change as soon as loads are switched, tasks change, and so on. Performance-based rates and incentives that are negotiated between a distribution company and its regulating body are an attempt to address this issue. They have the potential to provide clear signals for the designer's economic analysis. Rates must be designed very carefully to avoid inefficiencies in outcomes.

At present, there are two simultaneous challenges regarding reliability analysis tools. The first challenge is to meet the need for research into unifying the wide range of performance indices currently in use, along with understanding the relative impacts of sustained interruptions, momentary interruptions, and voltage sags. The second challenge is to meet the need for significant improvements in the ability of today's commercial packages to accurately and effectively generate a distribution system model that accommodates both system upgrades and changes in system operating configurations.

There is no question that DG has the fundamental ability to mitigate voltage sags on the distribution system. This service has the potential to provide a significant benefit to distribution system customers. However, this benefit is largely unrealized today because of factors like these:

- DG operating strategies that do not support voltage during faults
- The current distinction between power quality and reliability events
- The focus of many performance-based rates on interruptions
- Analytical models that can limit the ability to accurately compare the impact of voltage sags vs. sustained interruptions.

Developing accurate, usable distribution system reliability software is very important to improving the operation of distribution systems, and they are particularly important for systems with increasing DG levels. Accurate DG reliability models are, of course, a basic requirement for success, but they are not always a top priority for researchers or software developers. There is thus a need for targeted research into DG reliability models and into the effects of DG on system reliability. This research must consider the impact of various DG operating strategies on reliability—for example, the prescribed delay in DG coming back on line following a fault must be considered from a reliability point of view in determining the appropriate response of the unit to system restoration following an interruption.

4.2.4 DG Screening Tool

Reference [9] calls for the development of a screening tool that would assist in the review of proposed DG installations to determine if they can be installed with a simplified interconnection design and without the need for detailed system-impact studies. The industry greatly needs this type of software tool to significantly reduce the current "impact study cost barrier" for small to mid-sized DG. This would be the DG equivalent of the process that occurs when new loads come onto the system, allowing for the fact that injecting power into the system raises issues that generally do not arise with loads.

EPRI has developed a Distributed Resource Integration Assistant (DRIA) software package that implements a set of screening tools along with some basic analytical capability. The tool was developed to address the interconnection of single DG units onto a feeder and does not address high-penetration situations. Also, the developers of the Distribution Engineering Workstation (DEW) have a screening tool in preparation. The screening tools currently available are based largely on heuristics, with some analytical capability. The DRIA tool uses DG penetration levels and system strength metrics to identify areas in which voltage regulation, flicker, or other issues could arise. DRIA uses both flowcharts and software to present this material to designers.

A modern screening tool has to go beyond simple flowcharts to include basic standard analysis of specific cases. This is important because a fast response time is often required once a DG application is submitted to the distribution system planner.

Common screening tests include the following:

- Voltage change upon sudden loss of generation. The DG is required to disconnect from the grid during a transient system disturbance. The change should be less than 5%.
- Increase in fault current contribution. Certain DG technologies can contribute sufficient currents into fault to disrupt the normal protection. At present, PV systems are not expected to be major contributors, and this test may be waived.
- Open conductor fault screening. This condition happens when line fuses blow, switches fail, or conductors break. DG run-on can generate high overvoltages.
- Islanding evaluation. Results vary, depending on the size of the DG unit and transformer winding connection.

A tool for evaluating these four criteria is being developed and built on top of the EPRI DSS.

A recent report examines the application of DG on grid or spot networks and concludes that the state of the art in this area is not sufficiently advanced at present to allow the development of screening tools for these applications [10]. Spot networks are considered to be more accessible to DG installations than grid networks are. Therefore a gap exists and tools are needed to help evaluate high penetration of DG on spot and grid networks.

Increases in DG penetration levels will create a need for DG-ready distribution systems. The next generation of screening tools will need to assess the distribution system as well as the DG resource. This screening must go beyond penetration levels and system strength to include details on voltage regulation, fault performance, and grounding.

Modern screening tools also need to evaluate the DG equipment that is already installed or approved for installation on a given system. The current tools were developed primarily with relatively large single installations in mind. Currently available tools do not easily accommodate the continuing incremental additions of small units.

The next generation of screening tools should be upgraded to include the following new characteristics:

- Access characteristics of a distribution system from the existing database(s)
- Access database of present or proposed DG installations on the system
- Assess the impact of proposed DG on the system as a function of existing DG penetration levels, system strength, and so on
- Assess the "DG readiness" of the system and use this to determine allowable penetration levels
- Identify potential system upgrades that would lead to higher allowable penetration levels.

Ideally, the tool will be employed on systems as they surpass nominal penetration levels and will be continually updated as projects develop. Tools will not be expected to perform detailed planning or design studies but rather identify particular studies that need to be done.

4.2.5 Fault-Current Analysis

Most commercial distribution system software packages will include a fault-current package that is generally driven from the same database used for the load-flow analysis. To be appropriate for use as DG penetration levels increase, fault-current software should have the following capabilities:

- Include accurate, flexible DG models for inverter, synchronous machine, and induction machine systems
- Provide full details on line, transformer, and source flows
- Be able to model fault resistance
- Be able to model unbalanced systems, single-phase/two-phase lines, and the full range of transformer connections
- Be able to interface with protection and reliability software

- Readily assess fault current flow under numerous switching states
- Determine system voltages during faults and identify overvoltages.

The need to involve accurate models of both the DG and the distribution system components seems obvious. However, many fault studies have been performed for radial systems with no DG that rely on the fact that the vast majority of loads do not provide fault currents. This often means that distribution transformers are not modeled, even when the software can do so.

The fault contributions provided by synchronous and induction generators will have a significant impact on both the fault withstand requirements of the equipment as well as the protective relaying design. There are well-accepted standard models for both synchronous generators and induction generators, although it can be difficult to obtain accurate parameters for smaller machines.

Accurate fault models are not generally available for inverters, however. In fact, active discussions are now under way on the appropriate performance characteristics for inverters during faults. One school of thought is that the inverter should not provide fault current so that the time-current curve coordination of the distribution system relays will not be affected. Another school of thought is that the inverter should mimic a similarly sized synchronous generator during faults, in order to maintain sufficient current to operated relays, reclosers, and fuses for faults under all system configurations. The second school of thought concerns the need for and desirability of rapid separation of the DG during system faults. There is increasing recognition that the unnecessary dropping of DG resources during a fault-induced voltage sag will have undesirable and unnecessary consequences for systems with high DG penetration.

Depending on the type and size, distributed generators can cause significant increases in fault-current levels, so that the withstand and interrupting capabilities of devices need to be evaluated. In islanding situations, however, it must be verified that DG will provide sufficient fault-current levels for reliable protective system operation.

There are two primary research needs in this area. The first is to develop accurate inverter models and reach a consensus on how inverters should respond to faults. This is discussed further in the next section on protection. The second is the need for appropriate benchmarks for fault studies on systems with high DG penetration. Commercial providers of distribution system CAD tools will have to upgrade their products to be DG-compliant. To facilitate and encourage this process, benchmark systems are needed that will signal the requirements for DG-integrated fault studies and allow distribution company planners and designers to evaluate competing tools.

In sum, a fault-current analysis provides the information necessary to design the fault-protection system. The use of the resulting data in protection design is discussed in the next section.

4.2.6 Protection System Design

Today's radial distribution systems are almost exclusively protected by time overcurrent schemes involving time overcurrent elements for circuit breakers and reclosers, fuses, and sectionalizers. These schemes rely on the fact that the fault current flows from the substation transformer toward the fault, with little if any fault contribution from the load. Radial distribution systems are not directly redundant, and reliability is achieved through a combination of low fault rates and selective coordination of the protective scheme. Selective coordination is designed so that a permanent fault is cleared by the closest upstream device, thereby interrupting the smallest number of customers.

Temporary faults are dealt with in similar fashion, with one of two basic approaches: fuse-saving, which minimizes or eliminates interruptions on temporary faults while exposing customers to more voltage sags and momentary interruptions, or breaker-saving, which minimizes the number of sags and momentaries across the system while intentionally interrupting service to a small number of customers. Coordination among devices is achieved through variable time delays in each protective device, and downstream devices operate more quickly than upstream devices at any given current. Reliability is enhanced on these systems through restoring unfaulted feeder segments by switching those segments to adjacent feeders following an interruption.

Many commercial distribution engineering software packages include time-overcurrent coordination (TOC) capability, along with a library of curves for fuses, relays, and reclosers. These rely on having the fault current flow from the substation source to the fault, and they need to be recoordinated or redesigned in situations in which DG generates significant fault currents.

Perhaps more problematic is that this protective approach will fail or be degraded under some conditions. There is thus a need for research into alternate protection strategies for two particular situations:

1. Where synchronous generators (and possibly some inverters) supply fault current levels that can cause misoperation of the TOC feeder protection

2. In intentionally islanded systems, where fault currents can be small and vary widely.

A near-term need is to develop design procedures that will include infeed effects in the time-current coordination (TCC) process. This process should also establish a set of general guidelines addressing the trade-off between fault detection/duration and DG.

As described in the previous section, the fault performance of inverters is not well documented, and there are several competing ideas on how inverters should be designed to operate during faults. One school of thought is that inverters should not contribute current to faults—they should either continue to draw load current during a fault or shut down. This strategy would provide minimal impact on existing TOC protection schemes.

This strategy would not work well in situations where intentional islanding is permitted, however; it would lead to shutdown of the entire islanded system during any system fault. It also would be difficult to identify the fault location in this scenario. While this performance might be acceptable for small, single customer islands, it is unlikely to be workable for the larger islands envisioned. To achieve selective coordination of fault clearing, there must be a significant level of fault current available from the island's generation. This could be supplied either by synchronous generators or by inverters designed to deliver fault current.

TOC Coordination Issues. For low- to mid-level DG penetration, time overcurrent (TOC) protection will remain the preferred protection strategy. Fault current supplied by DG will have the effect of increasing the total fault current flow while reducing the fault contribution from the utility source. The effect of increased flow on equipment ratings is discussed elsewhere.

The three most important issues generally identified as coordination issues with DG are as follows [11-13]:

1. Loss of fast trip coordination

2. Unnecessary tripping of circuit breakers or reclosers

3. Protection from equipment damage.

Figure 11 shows a typical situation that could lead to loss of fast trip to sectionalizing fuse coordination. The effect of DG is to speed up fuse-melting while slowing down the recloser fast trip.

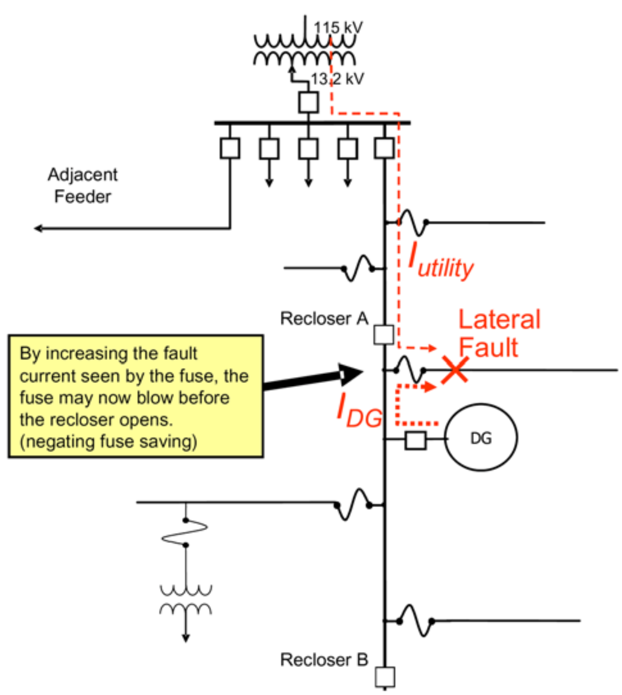

Figure 11. Situation in which DG fault current can lead to loss of recloser fast trip to fuse coordination

Figure 12. Situation in which DG fault currents could cause misoperation of feeder head circuit breaker shows a scenario in which the unnecessary tripping of a circuit breaker can occur. In this diagram, the fault current supplied by the DG flows from one feeder toward a fault on another feeder. The fault current flowing from the bus toward the fault will generally be significantly higher than that supplied by the DG unit, so it could be expected that this miscoordination would be unusual. Still, when this scenario does occur, it can result in the unnecessary interruption of service to all the customers on the unfaulted feeder.

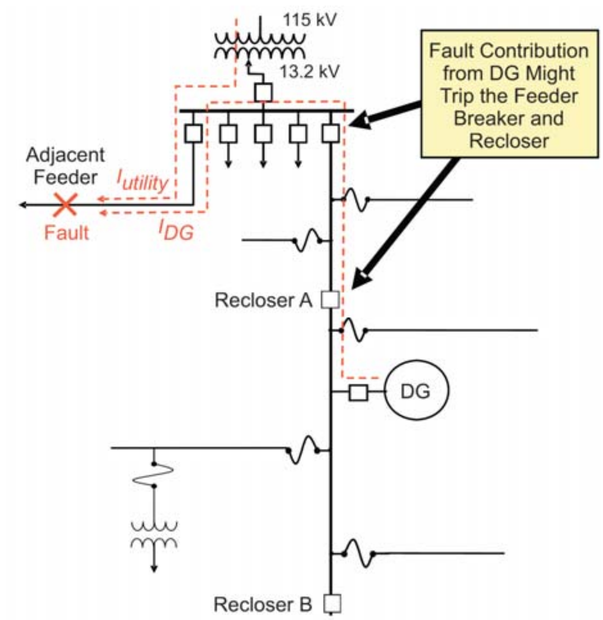

Figure 12. Situation in which DG fault currents could cause misoperation of feeder head circuit breaker

The third scenario of concern is the potential that delays in clearing time could lead to equipment damage. Figure 13 shows a case in which a DG installation is being added to an existing feeder at point P. Before the installation of the DG, the feeder head relay will see the total fault current for faults anywhere on the feeder. For a three-phase fault under this scenario, the bolted fault-current flows are shown in Table 2. The table also shows relay sensing times plus margin for faults at P, Q, and R, and conductor damage times for the same three points. Protective relays set on this basis would prevent damage in this case.

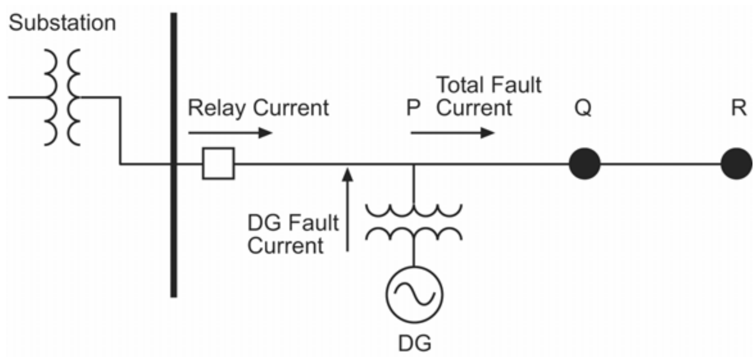

Figure 13. One-line diagram showing the fault-current study case

Table 2. Fault Current Sensing Time and Damage Time with No DG

Point of Fault	Total Fault Current	Relay Sensing Time plus Tolerance	Conductor Damage Time
P	4647 A	0.83 sec.	1.4 sec.
Q	2705 A	1.7 sec.	4.6 sec.
R	1907 A	3.2 sec.	9.2 sec.

Table 3 shows the values of the effect of DG being on line. The total fault current will increase significantly, while the relay current will decline. The increase in total fault current significantly reduces damage time. At the same time, the reduced relay current during the fault increases the fault-clearing time in all cases except when the fault is near the point of interconnection. Table 3 shows a case in which adding DG provides a risk of damage for faults at P, Q, and R when the relay setting is unchanged.

Table 3. Fault and Relay Currents, Relay, and Damage Times with DG

Point of Fault	Total Fault Current	Relay Current	Relay Sensing Time plus Tolerance	Conductor Damage Time
P	8137 A	4647 A	0.83 sec.	0.52 sec.
Q	3602 A	2057 A	2.45 sec.	2.3 sec.
R	2311 A	1319 A	8.0 sec.	6.2 sec.

When significant DG is present on a distribution line, the protection system designer will need to consider all of these cases. TOC protection software will be used for this analysis and will have to include the effect of fault-current infeed from the DG.

At present, most of the available time-current curve software present the “no-DG” case as shown in Figure 14. This type of curve is based on the assumption that the same current will be flowing in the relay and the susceptible equipment, which would be true when the utility source is the only source of current. The presentation of the data in this format is very useful to the protection engineer, and at a glance it shows the relationship between the two curves over the range of possible fault-current levels. It shows a single protective device curve and a single damage curve; however, in most cases there will be multiple protective device curves that must coordinate and at the same time protect their respective pieces of equipment. It is common to display multiple curves on a single plot and use a number of plots to design the coordination for an entire feeder.

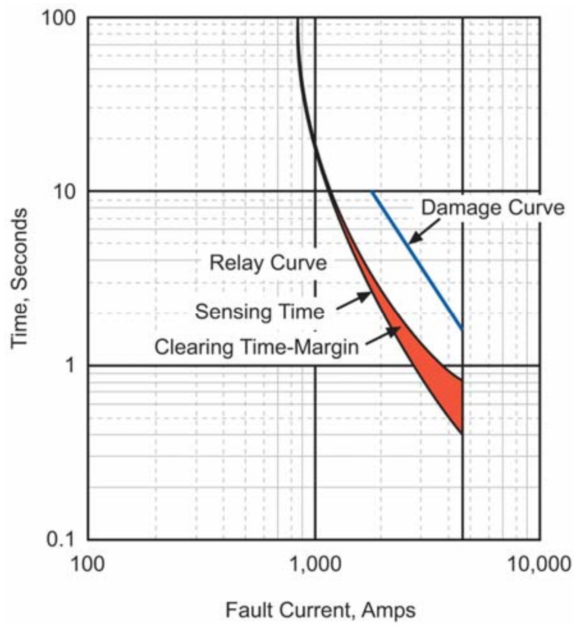

Figure 14. Plot of time-current curve for No-DG case

It is highly desirable to continue to display the coordination information on this type of time-current curve. To do this, the software must recognize the increase in the magnitude of the fault current caused by the DG installation, as well as the fact that the protected equipment and the various protective devices will now see different fault currents. In situations in which multiple DG installations provide fault current, the challenge of doing this increases significantly.

Research is needed into developing coordination techniques that address the issues raised by the installation of DG on the feeder protection systems. It is clear that there are potential conflicts between existing TOC protection and the fault-current infeed from DG installations. When this occurs, a range of actions must be considered:

- DG infeed current effect is within accepted margins and requires no changes in protection design
- TOC protective settings must be adjusted to compensate for DG infeed
- Advanced protective functions/relays are necessary to provide protection because of the DG infeed.

To effectively assess a given protective system, software tools will be required that clearly present the impact of DG infeed current on the standard time-current curves. Research is needed into methods of doing this, and a consensus is needed on how it should be done. At the same time, case studies are needed to demonstrate the methods involved and to begin building a knowledge base on the transition points between the three cases discussed above.

When this research is completed, these methods will need to be incorporated into commercial time-current curve protective packages. Ideally, a consensus on how to display the infeed effect on time-current curves will result in consistency among various software products. This in turn will aid in the implementation of these methods. The results of this research are expected to be adopted by commercial software providers in response to market forces. There will also be a significant need to train protection engineers in the use of these upgraded tools to obtain the benefits of this work.

Overall issues concerning the protection of islanded systems are discussed in Reference [14]. There are a number of issues to resolve before standard protection methods will be determined. The protection scheme chosen for a microgrid will be influenced by the microgrid's structure, the design of the microgrid grounding system, the nature of the interface between the microgrid and the grid, and the philosophy behind the microgrid. Furthermore, in most cases, minimal levels of fault current will be required in order that faults within the isolated microgrid can be safely sensed and interrupted. This is further discussed in the section of this report on microgrids.

4.2.7 DG Database Manager

The data needs and requirements for DG are significantly greater than those for standard loads of a similar size. These data will be needed in planning, design, and operation activities. Examples of data needs include fault current for protection studies, reactive power control for voltage-regulation studies, and restoration and reconfiguration information. In the case of renewable generation, historical data on available resources are needed, as well as a current forecast of expected output.

The increasing use of GIS systems in distribution engineering and operations is providing a new option for DG data management. Also, the proposed development of the distribution state estimator will both require and use this same information. The potential application of distribution state estimators in operations as well as in planning and design increases the need for accurate and thorough data for DG resources.

One component of the Intelligrid effort to implement distribution automation is to develop a Common Information Model (CIM) for the power system. CIM is an information model for power system components that includes organizational and ownership aspects along with technical aspects. CIM was initially developed under the aegis of EPRI research project RP-3654-1. It is currently under development by International Electrotechnical Commission (IEC) TC57 WG13, with the intent of developing a set of standards, IEC-61970. There is a definite need to develop appropriate CIMs for DG resources. While the CIM development effort is ongoing, there is a need for an effort targeted at developing CIM protocols for DG resources.

4.2.8 Dynamic and Transient Analysis

Traditionally, the need for dynamic analysis of distribution systems has been limited, and as a result, products available for this purpose are also limited. EPRI's DSS has dynamic analysis capability but is not currently a commercial software product. More general products, such as the electromagnetic transient program (EMTP) in its various forms and the Matlab Power System Blockset, can be used for distribution system dynamic analysis. These products are somewhat specialized and would involve a steep learning curve for many distribution system engineers. High levels of DG penetration raise two basic issues that need to be addressed through dynamic analysis:

1. Will multiple DG devices located close to one another interact in a negative way?

2. Will single or multiple DG devices support an intentional island? Alternatively, will anti-islanding schemes work when large numbers of DG units are present on a weak segment?

At present, these are research or development issues, rather than issues of software being available to distribution engineers. Depending on how the research evolves, at some point a designer might need to assess the dynamic properties of a group of specific devices; at that time, a commercial grade software package will be required that is appropriate for distribution system designers to use.

A dynamic study of facility microgrids is presented in reference [15]. The study involved balanced system conditions and the ability of the system to tolerate balanced faults. It examines the performance of both synchronous generator and inverter-connected DG. It also considers the impacts of system controls and of allowing the DG unit to regulate voltage and frequency.

Figure 15 shows results of a representative anti-islanding study done on a single facility system with two DG units. The five cases represent five different anti-islanding controls simulated on an otherwise identical system, illustrating the range of responses that can be expected as a result of changes in the DG controllers. Figure 16 shows results of a microgrid study featuring a single DG unit. The speed response of an induction motor is shown following a voltage sag that did not lead to islanding. The two cases that lead to motor stalling are the no-DG case and the inverter-DG case with no regulation in place. The other three cases—both synchronous generator cases and the inverter-DG case with regulation—predict that the motor will recover from the sag without stalling. The controls in this study involved both voltage and frequency regulation with droop. Full details are reported in [15].

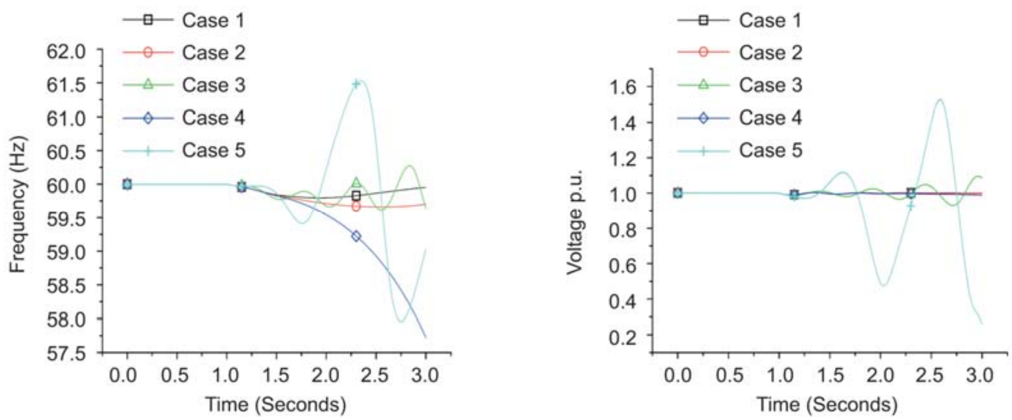

Figure 15. Representative post-separation islanding study, with two DG units and a variety of anti-islanding controls [15]

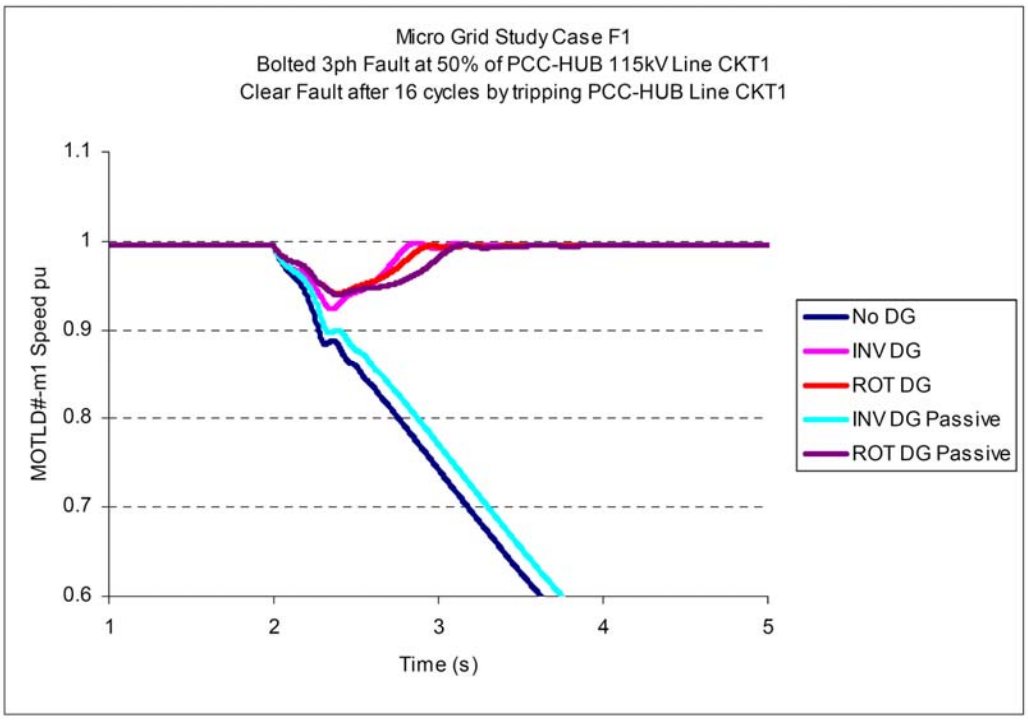

Figure 16. Microgrid simulation study showing the effect of DG and DG regulation on motor stalling following a voltage sag that did not cause islanding [15]

This study and similar ones leave the impression that distribution system dynamic simulations will be necessary to achieve high DG penetration levels. This is particularly the case as DG control issues remain under discussion, and there is no consensus as to the best control strategies for DG assets. The development of a DG-ready distribution system will include a study of this issue and examine trade-offs between system investment and DG control. As this discussion progresses, there could be less need for dynamic analysis on a case-by-case basis.

The model requirements for an effective dynamic study remain an open question. Reference [15], for example, assumes balanced system conditions and faults throughout the study. Other tools are capable of modeling unbalanced system performance. The extent of the system modeling required for an effective study is also not fully known. It is generally not practical to model a distribution system in the detail needed for load-flow studies of large systems. Accurate system equivalents are needed to construct accurate and efficient dynamic models. It will also be necessary to better understand the dynamic performance of system loads, because these loads will be much closer to the generation sources than is the case with bulk power system generators.

Transient Overvoltages. Three types of short-duration or transient overvoltage conditions can occur on a system with DG or be exacerbated by DG. These conditions include the following:

- Ground-fault overvoltage
- Ferroresonance
- Load-rejection overvoltage.

The conditions above may occur individually or in various combinations depending on the design characteristics of the power system. Under some conditions, these voltages can become severe enough to damage power system equipment and customer loads. Figure **17** illustrates a simulated case in which significant overvoltage is predicted to occur from line to ground on a 13.2-kV distribution line as a result of the formation of a sudden generation island during a ground fault.

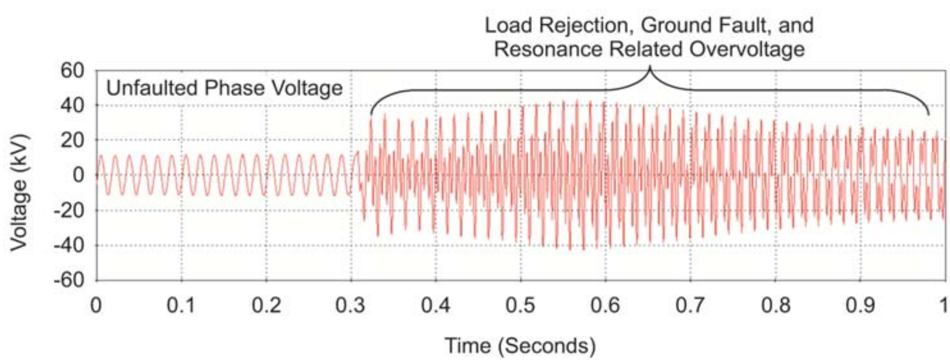

Figure 17. Example of simulation of combined ground fault overvoltage, load rejection, and resonance-related overvoltage

(occurring when synchronous generator was suddenly isolated on island with capacitor and minimal load)

Ground Fault Overvoltage. Overvoltages can occur on three-phase systems during ground faults. The presence and extent of the overvoltage depends on the system grounding; effectively grounded systems limit the level of overvoltage. Effectively grounded systems are those in which the zero-sequence reactance is less than three times the positive-sequence reactance. Most primary distribution systems are four-wire, multigrounded systems designed to be effectively grounded. When effective grounding is not maintained, the 60-Hz line-to-ground voltages can rise as high as 1.73 times the prefault voltage. Most effectively grounded systems rely on a substation transformer to provide this level of grounding. When the substation transformer is isolated from a distribution system, DG remaining on line can lead to these overvoltages if effective grounding is not maintained.

Ferroresonance. Ferroresonance is a nonlinear resonance that involves the magnetizing reactance of a transformer and system capacitance. The most common form of distribution system ferroresonance occurs when a single phase is open on a three-phase distribution transformer [9]. It also can occur with two open phases and one closed phase. Cable-fed transformers are particularly susceptible because of the high capacitance of the cables. The transformer connection is also a determining factor for ferroresonance, and ungrounded primary connections are the most susceptible. It typically takes little resistance to damp a ferroresonant condition, which makes standard transformers less prone to ferroresonance than high-efficiency transformers are.
A second type of ferroresonance is possible when DG sources are operating in an islanding situation—either intentionally or unintentionally [16]. This mode involves DG employing synchronous or induction generators; transformer connections and system capacitance are primary influencers. This type of ferroresonance will not occur when there is sufficient load on the system, and it is also influenced by the transformer connection. EMTP or other transient simulators are required to analyze ferroresonant situations.

Load-Rejection Overvoltage. Load-rejection overvoltage occurs as a result of the sudden loss of load on a synchronous generator. The generator exciter voltage is high to compensate for the armature reaction, and the loss of load causes the generator to become overexcited, leading to an overvoltage situation.

In most cases, transient overvoltage studies will require a full transient analysis package that accounts for the stator and line transients. Many dynamic analysis programs do not include these effects. As in other distribution studies, the transient analysis program should be able to model unbalanced systems. Ideally, this program will interface with the distribution system database to each model implementation. Without this, a transient's expert would be required to create the system model. Another issue is that most transient studies involve reduced models of the system. Many distribution designers would need guidance in identifying the components to model in detail and providing accurate reduced models, as appropriate. The ideal transient model would interact with the database and designer to develop a suitable model for a given study.

4.2.9 Grounding and Transformer Connections

A variety of grounding philosophies are used in modern distribution systems, ranging from four-wire multigrounded systems to three-wire ungrounded systems. For each type of system, a preferred set of transformer connections has evolved to serve systems in which power is fed from the bulk power grid and flows to loads on the distribution system.

DG installations can have different needs, and they often make standard transformer connections less than desirable. One example is a distributed synchronous generator large enough to warrant a separate transformer. To protect the generator against ground faults on the primary system, a grounded wye-delta transformer could be used. This type of transformer, however, provides a new source of ground-current flow to primary faults, which in turn can affect the integrity of the protection system. This connection does serve to maintain the effectively grounded status of the primary system when the substation transformer is disconnected.

These conflicting objectives between the protective relaying needs and grounding needs must be resolved for effective system operation. The delta-grounded wye transformer configuration that commonly serves loads provides the generator with similar isolation from primary faults, but it can lead to generator damage issues during secondary faults in some configurations. It also can lead to temporary overvoltages during faults on the primary system, as described below. With significant DG levels on a distribution system, fault performance becomes very important, and fault current levels, overvoltages, and protective device functions must be considered carefully for all possible operating configurations [14, 17].

The class of four-wire, multigrounded distribution lines depends on the distribution system being effectively grounded, as discussed in the previous section. During unbalanced faults on the system, effective grounding limits the voltage rise on the unfaulted phases. Insulation coordination and overvoltage protection of these systems are based on the premise that the system is effectively grounded.

In traditional distribution systems, effective grounding is provided by the substation transformer having a grounded wye configuration. In islanding situations in which a distribution feeder circuit breaker or recloser opens while DG installations remain connected to the system, effective grounding can be lost, and damaging overvoltages could occur. In these cases, there can be damage even when this situation lasts only for a few cycles. There is a definite need to develop CAD software tools that analyze the effectiveness of grounding on four-wire, multigrounded systems when isolated from the substation transformer.

Subtransmission Effects. Barker [18] has shown that effective grounding can also be lost on subtransmission systems. The source transformers for subtransmission are also a primary means of providing effective grounding for these systems. Figure 18 illustrates a situation in which DG installations on the distribution system can cause damaging overvoltages on the subtransmission system, when the subtransmission source operates before the DG in the event of a fault.

Even short-term overvoltages can be damaging. It is unlikely that this issue would be addressed through changes in either of the delta-grounded wye transformers shown in the figure. The problem is worst at light loads, and often this condition is not a problem during full-load conditions. Currently, the preferred way of analyzing this effect is through dynamic analysis. There is a need to develop streamlined techniques or screening tools for this issue.

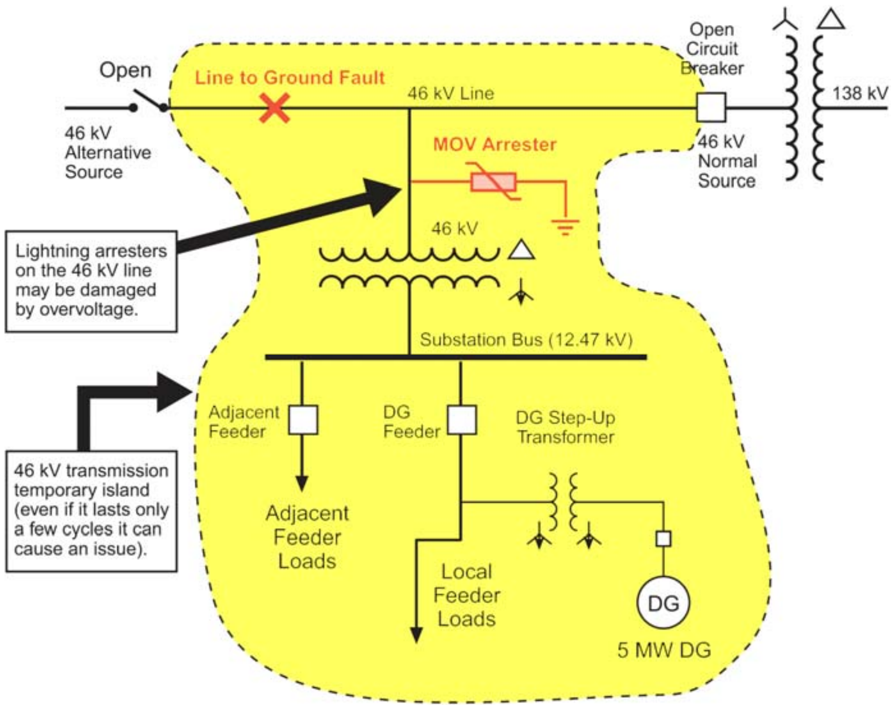

Figure 18. Illustration of events that can lead to arrester failures on the subtransmission system

4.2.10 Power Quality

In general, power quality is considered to cover voltage sags, momentary interruptions, voltage and current waveforms, and flicker. Sustained interruptions are usually classified as reliability issues.

Historically, reliability has been determined strictly on the basis of sustained interruptions, and momentary events have been considered power quality issues. A trend is emerging to merge these issues and provide a consistent way of assessing trade-offs between sustained interruptions and momentaries. This trend is ongoing and is independent of (and somewhat complementary to) the increasing penetration of DG. We assume that momentary interruption and voltage sag issues will eventually be merged with the sustained interruption studies involved in reliability analysis and will be dealt with in a consistent manner.

Power quality also involves power system harmonics and voltage flicker. Commercial software is available for both harmonics and flicker analysis. The performance of the inverters and synchronous and induction machines of DG is similar to that of significant load groups in both the harmonics and flicker realms, so further software development in these two areas should not be needed.

There will be a need, however, to monitor the development of models and standards for DG inverter performance and to include appropriate models for these inverters in harmonics and flicker analysis routines. For example, fault-current contributions and ramp rates of inverters may evolve so that DG inverter performance is somewhat different from that of inverters serving loads.

Modern pulse-width-modulated (PWM) inverters switch at high frequencies and inject little current below the 50^{th} harmonic—the traditional upper range of harmonic consideration. Substantial levels of higher frequency voltages can be created at the inverter input terminals, however, which in some cases can create objectionable interactions with other equipment. Different inverter manufacturers address these issues differently; some, for example, note qualification with FCC standards while others do not.

A knowledge base is needed on the impact of DG inverters at frequencies above 3 kHz. There are documented instances where multiple PWM converters have interacted and increased background-noise levels in their neighborhoods. A solution to these issues is to install electromagnetic interference (EMI) filtering on the system—ideally between the PWM device(s) and the system. From a distribution company's perspective, this need is most apparent in situations in which multiple customers are fed from a common distribution transformer.

Flicker from Photovoltaic Installations. There is very little information in the literature documenting flicker caused by photovoltaic installations. In contrast, there are numerous papers on flicker that results from wind installations. There is thus some question as to the significance of the flicker issue in PV installations.

Figure 19 shows the measured output of a nominal 100-kVA PV installation. Conditions for 9/17/98 through 9/20/98 show a classic shape for clear-sky conditions. The week before, however, there was significant cloudiness each day. The figure shows that PV output can go from near zero to full load rapidly during partly cloudy conditions. In fact, several instances can be observed in which the load goes above the normal daily peak, which is likely a result of cloud magnification. This and similar plots provide sufficient data for flicker studies for large, single-installation PV arrays.

There are little or no data on flicker effects of multiple, small PV installations spread across a neighborhood or town. As a result, the only option currently available for determining the potential of PV installations to cause objectionable flicker is to make a worst-case assumption that all PV installations on a distribution system will experience full-load to no-load power output transitions simultaneously. Although this model is appropriate for large, single PV installations, it could lead to overly conservative designs in PV neighborhoods where flicker is a concern.

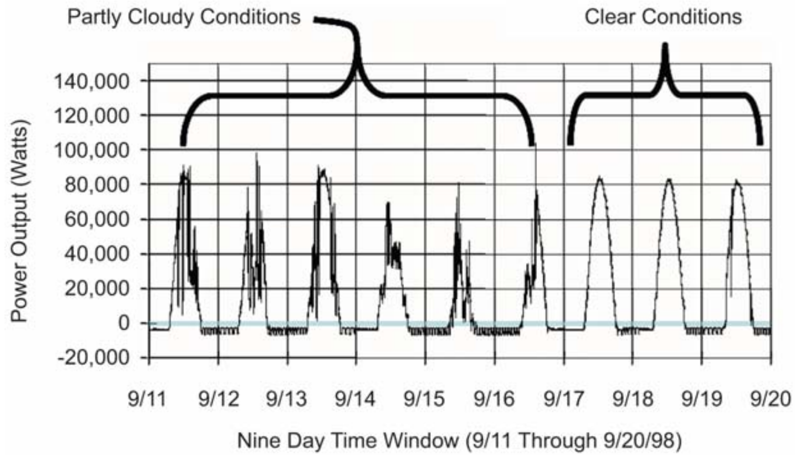

Figure 19. Photovoltaic power fluctuations at a 100-kW PV site Near Albany, NY, from 9/11/98 through 9/20/98

Katiraei et al. [19] discuss operating experiences of high-penetration PV neighborhoods in Japan, Germany, Australia, and the Netherlands, noting that flicker has not been an issue in these installations. Coppye et al. [20] describe a study in Belgium that showed a lack of correlation for short-term PV output across that nation. The result was a much lower level of fluctuation in power output for a group of installations than was observed for a single installation. Note, however, that this effect was observed over a relatively long (2-minute) time interval and considered installations over a wide geographic area. There is a need to gather comparative short-term data for numerous PV installations on a single distribution system. If research were to provide a less conservative model for PV flicker, it would reduce the need for system upgrades on installations in which flicker is a limiting factor.

4.3 Distribution System Capacity Benefits

Photovoltaic and wind energy installations provide a clear benefit in displacing energy that would otherwise have to be generated from conventional sources. Another known benefit is loss reduction, when resources are installed close to the loads they supply. Both PV and wind, however, are nondispatchable. They do not necessarily lead to reductions in the need for power system capacity, in the form of either conventional generation and transmission or distribution facilities. Photovoltaics could provide a capacity benefit, however, which could add substantially to the monetary benefit of a PV installation.

The impact of high-penetration PV installations on power system capacity requirements remains an open question. Power system capacity issues are divided into grid (generation and bulk power transmission) and distribution levels. Grid-level capacity studies are both planning and operational, and operational issues include both the day ahead and real-time markets. Distribution capacity issues, on the other hand, are primarily planning in nature. While the feed for specific distribution system segments is changed to improve performance, balance the load, and/or minimize losses, this is generally done on a short-term planning basis. Distribution system real-time operations concentrate primarily on response to interruptions and equipment failures.

*Grid Capacity***.** Denholm and Margolis [21] report a study of 10% to 15% PV penetrations at the grid level. The primary focus of the study was the ERCOT (Texas) system, using measured loads of this system and projected PV generation with an installed capacity of 16 GW. This level represents a system-wide PV penetration of 11% on an energy basis. The study shows that a PV installation provides a definite benefit on typical summer days, where this level of penetration can reduce the daily peak load from 48 GVA to 43 GVA. In contrast, this level of PV penetratin has less benefit in the spring, when there is virtually no impact on the daily peak load and a significant reduction in the daily minimum load that could have an impact on baseload generators. This study proposes using a PV system capacity factor to assess the capacity benefits of high PV penetration levels. Proven capacity from PV has the potential to influence the spinning reserve requirement as well as the need for new generation. Depending on the location of the PV within the system, it could also be used to alleviate transmission congestion. In a deregulated market, the PV owner would receive the benefits of these impacts through the marketplace**.**

Another study [22] predicts the capacity factor of PV for regions across the United States. This study predicts that PV installations can have an impact on capacity ranging from less than 10% to more than 80% of the installed capacity, depending on the local conditions of the installation.

*Distribution System Capacity***.** Watt et al. [23] report a study of distribution system capacity impacts for several Australian systems. This study documents the differences between commercial and residential loads in the study area and notes that the commercial load had a stronger correlation to PV output than the residential load did. This is because the residential load peaks later in the day than the commercial load does. The primary study period was a summer week. A New South Wales feeder serving residential load experienced a daily peak of 18 to 20 MW during the study week. The study projects that 6 MW peak of installed PV on this system would have no impact on the daily peak for 4 of the 5 days reported, and would result in a 10% reduction in peak on the 5th day. A South Australia commercial load, however, showed a significant peak-load reduction each day of the study. The study also discusses regional effects and cloud cover impacts.

There are anecdotal reports that PV correlates more closely to commercial loads than to residential ones, and the Australian report is one of the few that provides documentary evidence. Publication in the literature of studies involving a broad range of situations is needed before general conclusions can be drawn on this issue.

The capacity benefits of PV installations result from both from the generation-transmission system and the distribution system. Both need to be determined accurately to evaluate the benefit of PV installations. Today, it appears that PV can provide a significant capacity benefit to the generation-transmission system. The capacity benefit to a distribution system needs further clarification, although it appears that there would be such a benefit for systems that experience load constraints, particularly in the presence of significant commercial loads.

The primary tool for identifying the capacity benefits to a distribution system will be a load-flow planning study, such as the EEN assessment technique. When the planning method indicates the need for a capacity expansion, DG options can be considered to defer or avoid the need for investment in the distribution system infrastructure. Any cost savings provided by this deferral would be a benefit provided by DG. In instances where PV or other DG resources are integrated into the grid for other purposes, this distribution capacity benefit can be identified by evaluating capacity limits with and without DG. Savings can be calculated by identifying the value of the capacity upgrade that would be required if DG were not present.

There may be some limits to this approach created by limitations on the DG resource. For example, when inverters are programmed to wait 5 minutes before reconnecting to the system after an interruption, the capacity benefit is reduced because an overload condition could exist in the period before DG is restored. This situation coincides with cold load pickup after an extended outage and can extend restoration times. Research is needed to investigate the possibility of reducing this delay time without compromising equipment or personnel safety or interfering with the recloser trip sequence.

4.4 Inverter Performance and Modeling

Photovoltaics and other distributed generation resources will be connected to the AC distribution system through PWM inverters. These inverters have fast response times and are highly flexible when compared with the synchronous generators that other DG sources use. Inverters, however, have shorter thermal time constants than synchronous generators do, and this reduces their overload capability.

The inverter itself can respond to control signals in less than a millisecond; in fact, most inverters respond to reduce overcurrents much more quickly than this. The design of the inverter controller will define how the inverter responds to fault situations, changing voltage, waveform and frequency of the system, and changing conditions of the energy source (see Figure 20). It can respond (though probably more slowly) to signals from the distribution system defining real and reactive power flow, status of the substation and/or other DG, for example.

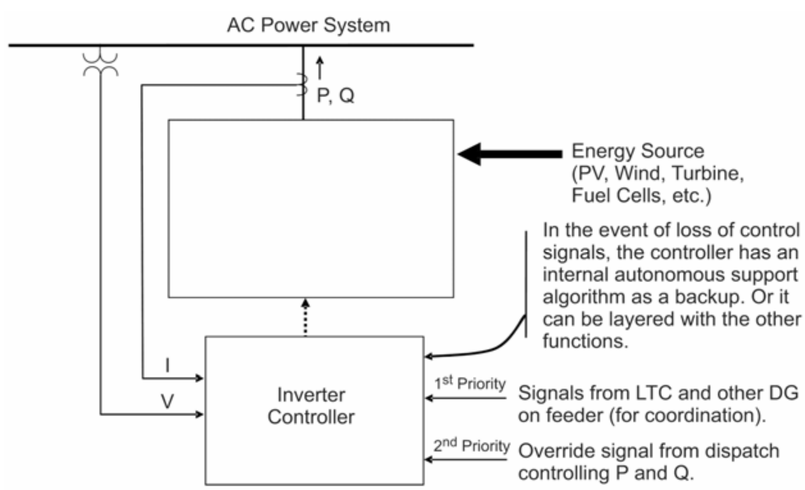

Figure 20. Inverter controller interconnection between the grid and DG

The resulting inverter controller will in turn impact the required power rating of the inverter bridge. Certain functions, such as voltage support, will require additional current to flow for a given real generated power flow. This voltage support, however, can provide benefit both to the distribution system and to the inverter.

The inverter's response during faults is of particular importance. In many cases, small fault-current contributions from the inverter are preferable to minimize the impact on the TOC protective relaying system of the distribution feeder, as described earlier. This situation changes dramatically, however, in inverter-fed microgrids that rely on sufficient levels of fault current to allow selective coordination of the distribution system, as well as safe clearing of faults by reclosers, fuses, and high- and low-voltage circuit breakers. Although it is thought that a microgrid could shut down completely in the event of a fault while operating disconnected from the grid, this would seem to defeat many of the advantages of installing this type of system. Therefore, a microgrid will need to ensure that sufficient levels of fault current are maintained in all possible operating configurations.

The second aspect of inverter fault performance is the fault withstand and interrupting capabilities of system components. The inverter fault current contribution must be determined before system designers can assess the withstand and clearing requirements of circuit breakers, reclosers, fuses, and other equipment. In order to be consistent with other generation equipment on the power system, these fault-current levels should be identified in the inverter specification as to magnitude and time duration.

IEEE Std. 1547-2003 currently mandates that a DG may not actively regulate voltage at the point of common coupling. Installations that comply with this standard are therefore limited in the range of operations that they are able to do. This provision is in the standard to avoid conflicts between DG voltage regulation and distribution system voltage regulation controls. As DG penetration levels increase, there is a significant need for research into the voltage regulation aspects of distribution system design to identify the best approaches to voltage control in high-penetration DG situations.

Clearly, a set of DG resources will be required to regulate voltage in a coordinated way in microgrids. Research into the benefits of drawbacks of inverter voltage regulation in a variety of distribution system topologies is a near-term need. This research will provide answers as to the best solutions for inverter control in high-penetration DG. This understanding is needed before a DG-ready distribution system philosophy can be finalized.

Ideally, the operating flexibility of the inverter would benefit system performance. Appropriate voltage regulation controls could reduce the need for mechanical voltage regulators or reduce the number of operations that these regulators experience. In some situations, defining a fault current of set magnitude and duration could reduce the withstand requirements of equipment. It is important to develop this coordinated approach of inverter control design and system characteristics before these inverters are implemented widely on the grid. An example of this would be the response of the inverter during a voltage sag. One possible control scenario is illustrated in Figure 21. The figure shows a schedule of inverter output current during the sag. This response would be designed to support adjacent loads to aid them in riding through a sag while protecting the inverter from overcurrents during deep and extended sags.

Duration (Cycles)	Voltage at Inverter Terminals During Sag (%) (Current is Shown in Per Unit of RMS Rated Output)									
	0	10	20	30	40	50	60	70	80	90
½	2.8	2.5	2.0	1.9	1.8	1.5	1.3	1.3	1.2	1.1
1	0	0	0	1.8	1.7	1.5	1.3	1.3	1.2	1.1
2	0	0	0	0	1.7	1.5	1.3	1.3	1.2	1.1
4	0	0	0	0	0	1.5	1.3	1.3	1.2	1.1
8	0	0	0	0	0	0	1.3	1.3	1.2	1.1
16	0	0	0	0	0	0	1.3	1.3	1.2	1.1
32	0	0	0	0	0	0	1.3	1.2	1.1	1.1
64	0	0	0	0	0	0	1.3	1.1	1.1	1.1

Inverter Trip-Out Zone

Figure 21. Possible operating sequence for an inverter during voltage sag conditions

Another very important consideration is that the inverter operate properly in islanding situations. Inverters will be required to respond correctly to avoid inadvertent islands. Current IEEE Std. 1547-2003-compliant inverters have anti-islanding controls shown during tests to identify islanding situations and to shut down within the specified time when islanding occurs. To date, tests have been limited to the operation of one or two units, although there have been some simulations of larger installations. The ability of anti-islanding controls is still considered to be unproven for large numbers of inverters operating in parallel.

The inverters will be required to operate together and to maintain frequency and voltage in microgrid situations, in which the microgrid is intentionally islanded at times. Multiple inverters (and synchronous generators when present) must work together to supply the load and respond to events such as motor starting. It is clear that this operating mode is different from the anti-islanding performance, but it is likely that a single inverter will be required to be able to operate in both modes in the near future. Ongoing microgrid research and demonstration projects will answer many questions concerning inverter control in this mode. Then, there will be a strong need to develop a new set of standards for DG inverter performance that will satisfy both the distribution system designer and DG equipment designers. It is reasonable to expect that all DG inverters will respond in a known and similar manner to the range of system events.

4.5 Investing in DG-Ready Distribution

Integrating high penetration levels of DG into the distribution system will trigger a need to invest in many of the systems in question. This investment could take the form of upgrades in voltage regulation strategies for the system, changes in protective relaying devices, or upgrades in the interrupting capability of circuit breakers, for example. There are two basic issues associated with making needed upgrades. The first is providing appropriate data to justify the need for the upgrade to a wide audience, and second is determining who will bear the cost of the upgrade.

Noteworthy among current efforts to identify DG-compliant distribution structures [24] is Southern California Edison's distribution circuit of the future. These and similar efforts will determine effective strategies for accommodating high penetration levels of DG. The DG-ready concept will take this a step further and define a standard approach to assess and upgrade existing distribution systems to allow them to accommodate DG penetrations in the 30% range.

Engineering tools can provide information in forms that are of limited use to nonspecialists. This is not always the case; for example, when a new DG installation raises the fault current level above the interrupting capability of a circuit breaker, this concept is relatively easy to convey to a broad audience. At the other end of the scale, the need to provide capacity upgrades on systems that will experience overloads only under contingency conditions can be a very difficult concept to convey to nonspecialists. The DG-ready concept provides a single framework through which to address voltage regulation, fault current capability and system protection, grounding and safety, and power quality issues.

Developing this concept would provide an understanding of the relative trade-offs between voltage regulators, switched capacitors, static VAR compensators, and inverter regulation, for example. Developing concepts and standard analytical tools to support the DG-ready concept would minimize the engineering time involved in assessing individual installations onto the DG-ready system. This development would also provide a basis for disseminating these concepts and tools to a broad range of distribution system designers in the field.

4.6 Microgrids

There is a significant amount of interest in microgrids and there has been considerable research. The demonstration projects that are currently active will provide significant contributions to our knowledge of the design and operation of the various types of microgrids under consideration.

The full development of the microgrid concept will answer many of the planning and design issues currently under consideration. The routine development of microgrids will present significant engineering challenges that go beyond those required by high-penetration DG on DG-ready distribution systems, however. The software tools that will be needed to support microgrid planning and design can be divided into two categories: the upgrades to existing tools needed to support microgrid design and the new tools required for this technology.

Two examples of increasing needs for existing tools are dynamic analysis and protection. Microgrid dynamic analysis needs will be more demanding than those for high-penetration DG with anti-islanding controls. This is so because the microgrid will be required to sustain operation for long periods when not connected to the stabilizing grid source. For example, a study of across-the-line starting of medium-size motors will move from being a routine steady-state analysis to a detailed dynamic analysis. Similarly, it is likely that microgrid protection will be required to move away from typical TOC protection to some type of directional protection approach. Though the research will show which protection schemes are viable, a new set of protection software tools will be needed to support the design and setting of these relay schemes. Needs of this type have been discussed in previous sections of this report.

In the next two sections, we identify current software development projects that are accompanying the Consortium for Electric Reliability Solutions (CERTS) microgrid research and demonstration project. In the third section that follows, we discuss a significant need to develop analytical methods to approach the business and regulatory needs that will occur with broad implementation of microgrid technology.

4.6.1 CERTS DER-CAM Software Tool

The Distributed Energy Resources Customer Adoption Model (DER-CAM) is a technology-neutral optimizing model for economic DER adoption. DER-CAM is designed to choose the optimal combination of DER components to minimize the operating costs of the microgrid. The software examines available equipment and its associated capital costs, operation and maintenance costs, customer load profiles, energy tariffs, and fuel prices. The DER components can include PV, solar thermal, energy storage, any thermal prime mover, heat-recovery devices, and combined heat and power (CHP) units, including absorption chillers. The model accounts for trade-offs in equipment sizing, such as a reduced generator size providing less absorption chilling benefit. In addition to choosing the optimal combination of DER components, the software also produces an idealized operating schedule showing grid electricity and fuel purchases.

4.6.2 CERTS µGrid Analysis Tool

A unique microgrid simulation tool being developed at the Georgia Institute of Technology is µGrid. Microgrids can present unique modeling challenges owing to the wide variety of equipment and electrical infrastructure configurations that can be present within the system. µGrid can accommodate three-phase, single-phase, and two-circuit secondary circuits while addressing many issues relevant to microgrid operation, such as imbalances, asymmetries, equipment derating, stray voltages, and ground potential rise. µGrid also examines the dynamic interaction of microgrid components and their effect on system stability, generation-load control, and occurrences of stray voltage and neutral potential rise.

4.6.3 Microgrid Business Case Analysis

There is sufficient knowledge of the technical aspects surrounding microgrid architecture to begin deploying microgrids in a wide range of applications. However, just because a microgrid can be built does not make it financially viable, and there are still many questions to be answered. In particular, the business case for microgrid development is not clear. Further research needs to be conducted to better understand the costs and value streams that come from microgrid operation. Are certain microgrid configurations more likely to be financially viable? What is the optimal method for identifying customers who are willing to pay a premium rate for premium power?

Many issues associated with building successful microgrid business cases need further study. The most pressing issues are described in the list below. These issues are critical to the microgrid business case, so they need to be well understood and incorporated into microgrid economic evaluation software.

- Stakeholder identification and roles: Who are the major stakeholders in microgrid development? What is the role of the government, regulators, wire companies, independent power producers, customers, and others? What are the benefits and detriments to each of these groups?
- Regulatory constraints: Some regulatory issues can significantly affect microgrid viability, such as the definition of "utility" and the issue that nonutility wires are often barred from crossing public roadways. Although microgrid operators generate and distribute power, they are generally not considered a utility and therefore cannot run wires across these roadways. This restraint can severely limit the reach of a microgrid. There can also be considerations regarding the "obligation to serve" that come with franchise rights. Will customers in a microgrid neighborhood have the option to opt out of this service, and, if they do, how would they then be served by the franchise owner? More consideration needs to be given to these issues to determine if they present a significant barrier to microgrid development and how to overcome a barrier if it is one.

  Other regulatory constraints include the availability of net metering or, in the case of a microgrid, how energy sales into the microgrid are governed and how microgrid participants are compensated for those sales. A discussion of the regulatory constraints surrounding microgrid development should also examine the overall regulatory environment. What type of regulatory environment is the most favorable for microgrid development? Once the components of such an environment are understood, then public policy can be modified to achieve it.
- How environmental legislation will shape microgrids: There has been much discussion about enacting a carbon tariff or carbon-trading system in the United States. Implementing these types of carbon constraints can shape the makeup of future microgrids. If carbon emissions become too costly, then microgrids will take on a more renewable structure with an increased focus on photovoltaics, wind energy, and, possibly, biomass generation.
- Fuel price and volatility: The uncertainty surrounding fuel costs, especially of natural gas and diesel fuel, is a barrier to microgrid investments. Some microgrid developers are pursuing long-term contracts for biofuels to help offset this volatility. Fuel prices dramatically influence operating costs and play a significant role in the microgrid business case.
- High first costs: The capital costs for microgrid generation and storage technology can be a barrier to economic viability. As with most fledgling markets, there is a vicious circle of cost and demand; there has to be enough demand for initial higher cost units to support increased production. Increased production should then result in lower costs, further increasing demand and growing the market. More research is needed to determine the extent to which capital costs pose a barrier for various microgrid configurations and how to overcome this barrier. Solutions can range from simply letting the market naturally reduce costs to providing subsidies or other financing incentives.

4.6.4 Microgrid Economic Modeling Tools

The Galvin Electricity Initiative presented the results of a investigation of microgrid economics as part of a report titled *The Galvin Path to Perfect Power—A Technical Assessment* (Galvin Electricity Initiative 2007). The Galvin research team built economic evaluation models to examine the economic feasibility of several different microgrid configurations. The study focused on microgrids for perfect energy supply reliability and quality and the economic investigation was similarly targeted. The models developed by the Initiative use detailed input data, however, and can evaluate a variety of microgrid operating schemes. The models are publicly available from the Galvin Electricity Initiative (www.galvinpower.org).

4.6.5 Microgrid Economic Modeling Tool Development

The economic models of both the CERTS DER-CAM and the Galvin Electricity Initiatives are good starts for microgrid economic investigations. However, each is limited, and our knowledge of the factors influencing microgrid economics is continually expanding. The industry would benefit greatly if the capabilities of the two products could be combined and expanded upon in one software package. For example, DER-CAM is limited in its analysis of security, quality, reliability, and availability optimization, and the Galvin models do not perform as sophisticated a component optimization. Combining these capabilities would result in a very powerful design and optimization tool.

In summary, the development of microgrid technology is an exciting new option that will impact DG development. The deployment of DG in microgrids is widely viewed as being the most direct way for DG to provide a significant reliability benefit to consumers. When current microgrid technology issues are resolved, a variety of analytical and software tools will be needed to promote proper design and effective operation. The greatest new need is that for a utility business model with value proposition and related tool(s) that can quantify and justify the value of microgrids to utilities and stakeholders.

4.7 Summary

This section discussed the range of analytical and software tool issues that need to be resolved to facilitate the smooth integration of photovoltaics and other DG into the electric power distribution system. In several cases, there is a need for basic research into analytical methods before particular tools are developed. In other cases, there is a need for a consensus to emerge before the full development of design methods. A case in point is the fault-current contribution of PV inverters, for which there are several competing philosophies.

The concept of DG-ready distribution is offered as a method to unify this effort and address common issues that will arise on distribution systems with high levels of DG penetration. When fully developed, this concept will offer a set of design standards that will promote timely and effective application of DG resources.

The development of microgrids is the next step beyond DG-ready distribution. A near-term need is to develop a business planning tool for microgrids that will identify project costs and value as well as regulatory hurdles.

5.0 Gap Analysis: Analytical and Software Tools Needs Assessment

The previous section presented an overview of the analytical and software tools needed for distribution system planning and design to accommodate increasing DG penetration levels. In particular, we discussed CAP and CAD tools that are both available and needed for each major topic in the planning and design process.

Table 4 provides a summary of this analysis. Each topic included in the table is accompanied by a corresponding need for updated software tools and/or updated analytical procedures. One column in the table also indicates a perceived need in the design process that is beyond the scope of currently available CAD tools.

Table 4. Needs Assessment for the Major Distribution System CAP/CAD Analytical and Software Tools

CAP/CAD Category	Current Status	Gaps in Supporting High-Level DG Penetration	Comment
Load Flow	Commercial packages available	Need for an expanded capability to assess both DG benefits and DG system impact; need to bring grid-level tools to the distribution system	Research-grade methods largely available
Reliability Assessment	Commercial packages available recently	Need significant upgrade to model DG, address intentional islanding	Need to merge with power quality tools for both CAP and CAD
DG Screening Tool	Research-grade software in limited use	Need to move research-grade tool to the marketplace	Ongoing need to validate breakpoints in the tool
DG Database Manager	No known availability	Will have multiple uses, high need as DG penetration approaches 15%	Will need to interface with multiple CAP, CAD, and operating software
Fault Current Analysis	Variety of commercial packages available	Need accurate models for DG sources and transformer connections to be useful	Marketplace should provide any needed changes
Protective Relay Coordination	Commercial time-current curve (TCC) software available	a) TCC software needs to accommodate infeed from DG sources b) Coordination support for non-TCC protection needed as these come into use	Analytical methods to be identified, software needs may follow; need to include interfaces to power quality/reliability software
Power Quality and Reliability	Reliability packages available of varying capability; commercial software available for harmonics and flicker—both are suitable for DG applications	a) Need for predicting momentary outage rates and voltage sag depth, duration, and rate b) Need to develop DG models	a) Other issues creating a need for this upgrade, push from DG community could aid this b) Model development critical for moving to intentional islanding

CAP/CAD Category	Current Status	Gaps in Supporting High-Level DG Penetration	Comment
Dynamic Analysis	General tools available, none are tailored to distribution	Need to assess interactions among DG when grid-connected, ability to support the load when intentionally islanding	a) Little past need; grid-connected capability includes analysis of anti-islanding protection when multiple DG sources are present
Ferroresonance	Analytical methods available and used for the traditional distribution system	a) Nonstandard transformer connections for DG can lead to differing ferroresonance exposure b) DG with rotating machine can lead to different ferroresonance mode	The best approach may be to raise awareness to these issues; might be done with a suitable screening tool
Transient Analysis	Lightning protection practices successful and should not change; new sources of temporary overvoltage will be present	a) Large penetration of PWM inverters may create interference issues. Some applications will need a full transient analysis for an unbalanced system	Similar issues to industrial drives with PWM input converters; EMI filtering may be needed; may be gaps in practice for large DG installations in residences
Grounding Design	Secondary distribution solidly or low impedance grounded; distribution transformer typically blocks ground current flow between primary and secondary systems	Increased DG penetration levels can create significant trade-offs between DG equipment protection and primary distribution relay coordination	Software upgrades may be needed once connection methods are established
Distributed Resources Interaction Modeling	Under development	High-resolution modeling to show the interactions of loads, generators, plug-in hybrid vehicles, and controls at end-user level	Such as “Gridlab-D” simulator at Pacific Northwest National Lab; support by DER interaction testing such as by EPRI
Using Detailed Data from Substations and Distributed Generators	High-resolution time-synchronized data are increasingly available	Analysis tools need to be able to accept this level of data detail to improve analysis	Applies to stability, voltage management, and control status to enhance distribution grid operations
Voltage Control Interactions	Today distributed resources to not provide active control	Methods and tools to coordinate fast and slow voltage control in the distribution line, the DG and loads	High penetration will necessitate active control

Table 4 documents a number of needs. Some of these are near-term needs, and others are long-term. The long-term needs can be associated with higher DG penetration levels. In some cases, however, they are associated with changes or expected changes in design procedures. This report also documents additional needs that go beyond the basic analytical tool realm, such as the following:

- The need for retraining distribution system planners and designers
- The need for microgrid business planning tools to assist in project value assessment and regulatory hurdles
- Future distributed storage and plug-in hybrid electric vehicles will need to be addressed with probabilistic analysis and to establish a control optimization that addresses the issue of uncontrolled renewable resources.

These two needs are critical to the successful integration of high-penetration photovoltaics on large numbers of distribution systems.

6.0 Recommendations for Future Research: Analytical and Software Tools

As a result of cost reductions in alternative energy sources and increasing costs of traditional sources, an expectation is emerging that there will be a significant level of distributed generation installed on many distribution systems across the nation. To facilitate the rapid expansion of these resources, there must be significant changes in the way that the electric power infrastructure is designed and operated. This report provides recommendations as to the need for analytical and software tools that will support these changes.

Table 5 identifies and sets priorities among the near-term needs identified in Table 4. It also provides a qualitative assessment of the impact that the need will have on DG development, and predicts the level of effort it will take to develop software. In these cases, the issues are largely known; development is needed to streamline the process and make it accessible to a wider range of distribution system planners and designers.

Table 5. Priorities for Near-Term Needs for DG Software Tool Development

Need	Impact	Development Effort	Description
Distribution Load Flow	High	High—expand to include capacity/reliability capability, year-long load cycles	Existing benchmarks need to be expanded to assess the new capability
DG Screening Tool	High (need to meet mandated response dates)	High—needs to evolve to incorporate the routine analysis	Currently available software dated
DG Database Manager	High	Medium—DG needs are not a high priority for the common information modeling effort	Needed for planning, design, and operation—must integrate with existing tools in all three areas; needs capability to pull in the real-time data flow
Fault Current Calculation/TCC Relay Coordination	High	Medium— inverter fault performance not documented; there is some need for coordination research	Fault-current software must account for DG contribution; TCC packages must use these contributions in drawing the coordination curves

Table 6 shows similar priorities among medium- to long-term software needs. Medium-term needs should accommodate high DG penetration levels while not allowing intentional islanding. Long-term needs are for penetration levels in which it might make sense to allow some level of intentional islanding.

Table 6. Priorities for Medium- to Long-Term Needs for DG Software Tool Development

Need	Impact	Development Effort	Description
Dynamic Analysis – Medium Term	High	Medium—DG dynamic model development; need for unbalanced analysis	Must analyze multiple DG devices/technologies to determine potential for oscillations, damping, and effectiveness of anti-islanding controls
PV Flicker	Medium	Low (research needed)	Need data and methods to assess flicker from distributed PV
Load Low Planning	Medium	Medium	Includes research on determining capacity benefits of PV—continuing evolution of methods to quantify capacity and reliability needs
Dynamic Analysis – Long Term	High	High	Assess islanding capability of multiple DG devices/technologies; propose and assess islanding control strategies; support PQ study issues
Fault Current/Protection	High	Medium—need for research	Beyond TCC– and ensure minimum fault levels
Power Quality/Reliability – Long Term	Medium	Medium	Quantify the benefits of intentional islanding on customer service; determine weak source PQ impacts
DG Screening Tool	High	Medium (with expected development of complementary tools)	Screen intentional islanding scenarios, both technically and from a business perspective
Distribution State Estimator	High	Evolve from database tool?	Incorporate this operations tool into planning and design functions

The development effort in these medium- and long-term projects includes research into technology and design practice in addition to the software development effort.

Grounding and non-TCC protection are not listed in either Table 5 or Table 6. For these two topics, a significant research and development effort is needed before software needs can be identified. It is certainly possible that, as the technology advances, software needs will emerge in these areas.

The development and maturation of these analytical and software tools is an essential component of the transition to high penetration levels of distributed resources on the electric power distribution system. While they are not the entire solution, they are clearly necessary to this transition, which cannot be made without appropriate tools.

7.0 Conclusions and Recommendations

Today's society is facing unprecedented challenges in maintaining a safe, secure energy supply. At the same time, improvements in the cost and reliability of renewable energy sources offer attractive new options for providing large amounts of energy to the nation. As a result, it is likely that there will be very significant changes in the basic nature of our electric power supply in the foreseeable future.

This report addresses one aspect of this issue—the need for improved analytical and software tools to facilitate these changes. Section 4 of the report discusses these needs in detail, along with limitations of the current state of the art. The gap analysis of Section 5 and recommendations for future research made in Section 6 identify a broad range of needs for both analytical methods and software tools.

Just as important, this report identifies several overarching issues. These issues are interrelated and strategically important:

- The DG-ready distribution system
- The need for training of distribution system designers
- The need for microgrid business planning tools to assist in making the case for the technology's value and overcoming regulatory hurdles.

DG-Ready Distribution. A DG-ready distribution system is a key concept in preparing for wide-scale integration of photovoltaics and other DG resources into distribution systems. This would be in part an identification of best practices for current installations. It would by necessity address the different characteristics of distribution systems and provide concepts for high- and low-load-density installations, three- or four-wire distribution, and so on. It would also require an agreement about how PV inverters should interact with the system. The full development of this concept would allow planners and designers to rapidly and effectively identify the deficiencies of an existing system so they can plan and design the system upgrades needed.

Training Needs. The rapid and widespread installation of renewable DG will prompt a great need for training distribution system engineers and engineering assistants in the technical issues involving high-penetration DG and in the use of tools and design standards for addressing these needs. At present, many utilities rely on a small number of DG experts who are personally involved in each application proposed for the system. This structure will break down as the number of applications increases. The only viable solution will be to train the full contingent of distribution planners and designers in understanding the issues and using the tools to develop DG-ready distribution.

Microgrids. At high penetration levels for distributed generation, many owners and end-uses will expect to have the option of operating off grid when electric energy is expensive or not available. Research into the technologies needed to do this are currently being developed, as are several demonstration projects. While there has been some consideration of microgrid business models, cost assessment and benefit identification, and regulatory hurdles, there is a need for continued conceptual development of microgrid business concepts and planning tools. This should be in place before groups of customers approach distribution companies about forming a microgrid. The electric utility will be the driver for microgrids in the long term. But it is easy to see how a particular campus, such as a university hospital, might want to have the security that a microgrid could offer.

By themselves, the upgrades identified for analytical capabilities and software tools will have a significant impact on facilitating increases in DG penetration on power distribution systems. When coupled with the overarching issues of DG-ready distribution, training of distribution designers, and the development of microgrid business concepts and planning tools, the components would be in place to enable a strong collaboration among distribution companies, DG owners, DG equipment providers, and regulators. Such collaborations will facilitate the development of these strategic resources.

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Appendix: Commercial Distribution Engineering Software Products

This appendix presents a brief overview of distribution engineering software products that are on the market. There have been a number of assessments of these software products over the last 6 years, including those referenced in this appendix. Those assessments include two reports published in 2006 that are particularly important. Reference [A1] covers reliability modules that have recently emerged on the market, and Reference [A2] includes a survey of the usage and needs of Canadian utilities.

Software products are continually being updated in terms of base capability, new modules, improved libraries, and, in some cases, availability. These factors quickly date specific assessments. Noted also that various software products at times use different approaches in solving such basic functions as load-flow and fault calculations. These can affect the ability of the product to address specific DG issues. For example, products that do not have the capability to model a substation transformer or a portion of a subtransmission network may be limited in their ability to assess certain impacts of DG, as discussed earlier in this report.

To provide a common basis for comparison of the various software products, the IEEE Power Engineering Society's Distribution System Analysis Subcommittee has developed a set of benchmark cases for evaluation. These cases can be seen on the Web at http://ewh.ieee.org/soc/pes/dsacom/testfeeders.html. Some vendors have addressed one or more of these benchmark cases with their software. Benchmark solution results are often available from the vendors for their products.

The distribution engineering software vendors mentioned in References [A1] through [A5] include those listed in Table A-1. This is not an exhaustive list, but it is representative of products that are available at the present time. In general, these products should be able to address distribution system load flow cases, including unbalanced loads. They should also be able to conduct short-circuit analyses and provide support for time-current curve coordination studies.

For distributed generation applications, engineering software tools should of course be able to model a variety of DG sources, including synchronous and induction generators and power electronic inverters. They should also be able to perform voltage regulation studies, including modeling load tap changers and switched capacitors. The product should include reasonable libraries of components for studies that will be conducted.

Many of the vendors have added reliability modules in recent years. There are a variety of capabilities available in these modules, and the suitability of a specific product for a given study should be considered. Finally, it must be noted that dynamic and transient analysis has not been a traditional distribution engineering design step and that standard software packages do not necessarily include these capabilities.

Table A-1. A Representative List of Distribution Engineering Software Vendors

Vendor Name	Web Site	General Product Name
ABB	www.abb.com	Feederall, Relinet
Cyme	www.cyme.com	CymDist
DIgSilent GmbH	www.digsilent.de	PowerFactory
EDSA	www.edsa.com	EDSA
Milsoft, Inc.	www.milsoft.com	WindMill
NEPLAN	www.neplan.ch	NePlan Electricity
Siemans-PTI	www.pti-us.com	PSS
Stoner Associates	www.stoner.com	Advantica Synergee
SKM	www.skm.com	Power*Tools

In addition to these products, two pieces of software were mentioned in the body of this report—DSS (Distribution System Simulator) and DEW (Distribution Engineering Workstation). EPRI has developed DSS, and it is primarily an in-house tool used for both research and development projects. DEW was developed under a government contract. The stand-alone work station is available as licensed freeware and has the ability to model and analyze distributed resource installations. The developers of DEW are currently under contract to the U.S. Department of Energy to develop a module that assesses DG penetration limits.

Reference [A2] is of interest in that it includes the results of a questionnaire sent to Canadian distribution companies. Survey results were received from 18 companies serving 7 million customers. The responses provide insight into the software products used by these companies. In addition, the survey provides some level of insight into the distribution system design process and the techniques that these companies currently use. The practices of the Canadian companies are similar to those of their U.S. counterparts. Though a survey of U.S. companies could be conducted and would provide additional data, this apparently does not have high priority at present.

In summary, the commercial market is providing a number of products aimed at satisfying distribution system design needs. It is a competitive market, and commercial providers are continually updating their products. Each product is unique, and the range of products offers a variety of choices to designers. Most products have some level of DG modeling capability, and there are indications that providers will upgrade their products in response to identified needs of the DG community.

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Distribution

1	MS1104	Margie Tatro, 6200
1	MS1104	Rush Robinett, 6330
1	MS1033	Charlie Hanley, 6335
1	MS1110	Jeff Nelson, 6337
1	MS1124	Jose Zayas, 6333
1	MS1108	Juan Torres, 6332
1	MS1033	Doug Blankenship, 6331
1	MS0734	Ellen Stechel, 6338
1	MS1108	Jason Stamp, 6332
1	MS1108	David Wilson, 6332
1	MS1108	Jaci Hernandez, 6332
1	MS1108	Michael Baca, 6332
1	MS0455	Shannon Spires, 6332
1	MS1108	Steven Goldsmith, 6332
1	MS1108	Jeff Carlson, 6332
1	MS 0899	Technical Library, 9536 (electronic copy)