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EVALUATION OF DISTRIBUTION ANALYSIS SOFTWARE FOR DER APPLICATIONS

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CONTENTS

List of Figures

List of Tables

1. INTRODUCTION

The term "Distributed energy resources" or DER refers to a variety of compact, mostly self-contained power-generating technologies that can be combined with energy management and storage systems and used to improve the operation of the electricity distribution system, whether or not those technologies are connected to an electricity grid. Implementing DER can be as simple as installing a small electric generator to provide backup power at an electricity consumer's site. Or it can be a more complex system, highly integrated with the electricity grid and consisting of electricity generation, energy storage, and power management systems. DER devices provide opportunities for greater local control of electricity delivery and consumption. They also enable more efficient utilization of waste heat in combined cooling, heating and power (CHP) applications — boosting efficiency and lowering emissions. CHP systems can provide electricity, heat and hot water for industrial processes, space heating and cooling, refrigeration, and humidity control to improve indoor air quality.

DER technologies are playing an increasingly important role in the nation's energy portfolio. They can be used to meet base load power, peaking power, backup power, remote power, power quality, as well as cooling and heating needs. DER systems, ranging in size and capacity from a few kilowatts up to 50 MW, can include a number of technologies (e.g., supply-side and demand-side) that can be located at or near the location where the energy is used. Information pertaining to DER technologies, application solutions, successful installations, etc., can be found at the U.S. Department of Energy's DER Internet site [1].

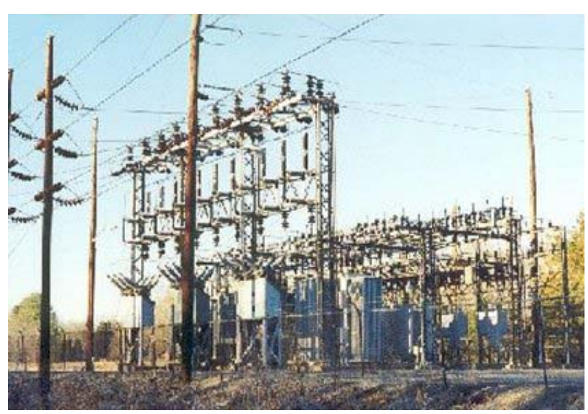
Market forces in the restructured electricity markets are making DER, both more *common* and more *active* in the distribution systems throughout the US [2]. If DER devices can be made even more competitive with central generation sources this trend will become unstoppable. In response, energy providers will be forced to both fully acknowledge the trend and plan for accommodating DER [3]. With bureaucratic barriers [4], lack of time/resources, tariffs, etc. still seen in certain regions of the country, changes still need to be made. Given continued technical advances in DER, the time is fast approaching when the industry, nation-wide, must not only accept DER freely but also provide or review in-depth technical assessments of how DER should be integrated into and managed *throughout* the distribution system.[1] Characterization studies are needed to fully understand how both the utility system and DER devices themselves will respond to all reasonable events (e.g., grid disturbances, faults, rapid growth, diverse and multiple DER systems, large reactive loads). Some of this

[1] This process has already begun in earnest. California is one of the first states to establish a standard practice for DER interconnection. In October 1999, the California Public Utilities Commission (CPUC) issued an order (99-10-025) addressing interconnection standards. Subsequent rulemaking has created specifications for standard interconnection, operating, and metering requirements for DER.

work has already begun as it relates to operation and control of DER [5] and microturbine performance characterization [6,7].

One of the most urgently needed tools that can provide these types of analyses is a distribution network analysis program in combination with models for various DER. Together, they can be used for (1) analyzing DER placement in distribution networks and (2) helping to ensure that adequate transmission reliability is maintained. Surveys of the market show products that represent a partial match to these needs; specifically, software that has been developed to plan electrical distribution systems and analyze reliability (in a near total absence of DER). The first part of this study (Sections 2 and 3 of the report) looks at a number of these software programs and provides both summary descriptions and comparisons. The second part of this study (Section 4 of the report) considers the suitability of these analysis tools for DER studies. It considers steady state modeling and assessment work performed by ORNL using one commercially available tool on feeder data provided by a southern utility. Appendix A provides a technical report on the results of this modeling effort.

A primary reason for performing the DER steady-state analysis study was to determine the adequacy of presently available software-based distribution system analysis tools for studying electric distribution systems with interconnected DER and the technical issues related to their operation. One selected tool was tested to see how well it could assess the benefits and impacts of introducing DER, in this case a distributed generator (DG) representing a microturbine, fuel cell, or some other small DG device, to the distribution network (see Section 4). The study lists several recommendations for enhancements that are needed to transform these distribution analysis tools into ones that can support a full scope of DER analyses. Such a tool would be able to provide analyses and system optimizations of dynamic distribution networks featuring high levels of diverse DER penetration. [Sources of DER shown in the Introduction are wind (right, previous page), solar (left, previous page), a 200 kW fuel cell (left), and 30 kW microturbine (right).]



2. VENDORS AND PRODUCTS

There are a number of vendors in the US producing high quality software tools for the planning and analysis of electric distribution systems. Table 2.1 lists four companies and their associated product names, Internet site URLs, and the software product's URLs. Consistent with the resource limitations of this project, no more than four of the more versatile and/or sophisticated products were selected for analysis. Additional information on the four companies, and several additional producers of distribution analysis software that were not selected for evaluation, is provided in Appendix B. The appendix provides URLs, addresses and phone numbers for contacts at each company.

PSS/ADEPT is a distribution system analysis program produced by Power Technologies, Inc. (PTI) for planning, designing, and analyzing distribution systems. It is the successor to PTI's widely used PSS/U program. PSS/ADEPT is built on PTI's PSS/Engines, a suite of computational engines for power system analysis. PSS/ADEPT provides the following analysis functions: power flow, short-circuit analysis, motor starting analysis, capacitor optimization, tie open point optimization, predictive reliability analysis, and more.

Table 2.1. Distribution system analysis software vendors and products including URLs

Company/*product names*	**Company site & product site**
PTI	http://www.pti-us.com/pti/ptihome_flash.htm
PSS/ADEPT	http://www.pssadept.com/
Milsoft	http://www.milsoft.com/
WindMil	http://www.milsoft.com/windmil.html
CYME Int'l	http://www.cyme.com/
CYMDIST	http://www.cyme.com/cymdist.shtml
EDSA	http://www.edsa.com/
Technical 2000	http://www.edsa.com/ACAnalysis.htm

WindMil is a distribution system analysis program produced by Milsoft to bring together essential applications for utility engineering staff. It allows the engineer to analyze a system by feeder, substation, or the entire network. As will be mentioned later, WindMil is designed to be coupled to another Milsoft database product, LightTable, for protective device coordination. Not only can graphics produced using Geographical Information System (GIS)[2] data be used, but backgrounds or layers can be imported from many formats/sources using an add-on module called "LandBase." The layering process allows the user to show or hide the geographical layering with the electrical one-lines (i.e., one-line diagram representation of transmission/distribution circuits, substations, and power sources).

[2] A powerful layered mapping system to which distribution system features may be added and changed as needed. The system supports mapping, analysis, planning, and decision processes (see gis.com).

CYMDIST is CYME International's primary distribution analysis software designed to assist engineers in distribution planning, operation and optimization studies for radial or looped systems with multiple generation sources. Featuring an efficient graphical user interface, the user can build feeders graphically or import data from other software. Results can be seen directly on one-line diagrams. The analyst can quickly take advantage of CYMDIST's comprehensive set of on screen design and editing features by using CYME's well-designed tutorials and manuals.

EDSA is a diverse company that not only markets numerous distribution system modeling tools, but also is active in defense programs (i.e., shipbuilding), nuclear power, electric propulsion, and advanced power system control. EDSA's Technical 2000 program uses state-of-the-art algorithms and object-oriented programming technology to enable engineers to conduct balanced, three-phase and single-phase system load flow studies on almost any network configuration. Technical 2000 and additional modules provide many capabilities for distribution system analysis including analyzing motor starting, motor operation, sizing and optimization, power quality (i.e., harmonic analysis), and DC Power Flow Analysis (providing voltage profiles on main bus and split bus). The actual features available to the analyst using Technical 2000 depend on the package that is purchased (i.e., 9 packages offered over a wide price range) and/or what selected `features may have been added on since the original purchase.

3. SOFTWARE PROGRAM FEATURES

This section will summarize many important features of distribution analysis software produced by the following companies: Power Technologies (PTI), Milsoft, CYME International, and EDSA Micro Corporation. In marketing the software products, each company presents and highlights a large array of features that range from what one would consider standard or "expected" to others that are highly versatile, innovative, and very powerful. Some features exist only to enhance the convenience and speed at which analyses may be prepared and implemented.

These software tools were all developed independently and are being marketed independently. Therefore the features that are presented for each vary considerably and making comparisons can be complex. One company may advertise "circuit element editors" while another may consider it a feature that buyers would take for granted and thus not necessary to make mention of. Others will go into great detail in discussing "control of line widths, symbol sizes, color of phases" while another will be more concise (i.e., general) in the product description. Some will place marketing emphasis on the wide array of versatile on-screen editing features while another will do the same for the many different types of reports and summaries that can be generated. Because of these differences, it is not always possible to achieve a high level of precision in the comparison of software in this study. Therefore, just because a particular feature is not shown[3] as included in a product, does not mean with 100% certainty that it does not exist. The comparison is of use partly in portraying the general emphases that each vendor has given to their product. It is likely that those emphases are generally reflecting the strongest features that the product offers.

As part of ORNL's broader investigation of these software tools, CYMDIST was used in a number of feeder analyses (see Sect. 4). Therefore, the accuracy and detail pertaining to this product may be slightly enhanced in this report. This should not be seen as an endorsement of the product; in fact, ORNL is in no way endorsing any product but simply reviewing each with the *primary goals* of (1) determining how capable each tool may be for analyzing DER interconnections and (2) summarizing how the tools need to expand in order to fully support DER analyses.

3.1 Basic Features

Table 3.1 shows a summary of some of the most basic analysis tool features provided by PSS/ADEPT, WindMil, CYMDIST, and Technical 2000. The table lists the most fundamental feature first – load flow.

3.1.1 Load Flow

All of the analysis tools described in this report provide ac power flow or load flow analysis from a distribution system model of various electrical components. Load flow is needed to determine the steady state operation of a system under various load demand, source supply, and network configuration of pathways. Provided that load consumption or demand is known at all busses, the load flow analysis can be used to determine (1) voltage magnitude and phase angle at each bus, (2) power flow in each branch (e.g., transformers and lines), (3) power consumption at each power generation source, and (4) system losses. Once this information is derived, the model can

[3] Rather than deal in categories such as unknown, not included, partially included, not applicable, etc., it was decided to leave blank boxes to cover such cases and focus on known features. Listing only known features makes them stand out in the table, facilitating comparisons.

be adjusted to assure that all loads are supplied with power within specified limits of operation. The adjustments may include, (1) generator set points, (2) transformer tap selection, (3) reactive power compensation, and (4) making emergency power available to satisfy voltage operating limits.

Table 3.1. Basic analysis tools

Feature	PSS/ ADEPT	WindMil	CYMDIST	Technical 2000
Load flow for radial or looped networks, balanced and unbalanced	Yes	Yes – size of distribution system limited only by computer	Yes (called "voltage drop" analysis)	Yes – Can simulate more than 50K buses
Three phase/single phase load flow	Yes	Yes	Yes	Yes
Short-circuit analysis (fault current calculations)	Diverse configu-rations	Current – all selected points in system	Diverse configu-rations	Yes – diverse, multiple simultaneous and sliding faults
Motor starting analysis	Yes	Yes	Yes	Yes (see text)
Voltage regulation – auto settings		Yes – set regulation and min. or max. voltages	Yes	Yes – in auto. voltage control routine (see text)
Load balancing to minimize losses		Yes	Yes	
Load allocation using the consumed kWh method, transformer kVA method, or REA method		Yes – also by diversity, season, hp, and length	Yes	
Unbalanced loading, impedance, spacing		Yes	Yes	
Multiple generation sources		Yes	Yes	Yes
Object oriented load flow (3 phase)				Yes
Capacitor bank control (manual or automatic)		Yes	Yes	
Newton-Raphson method	Yes	Yes	Yes	Yes[a]
DC systems and/or devices				Yes – DC & AC/DC load flow
AutoCAD and MicroStation compatible			Imports CAD files	Yes

(a) In addition to Newton-Raphson, Technical 2000 uses the Fast Decoupled method, advanced Gauss Seidel, and other advanced algorithms as required.

The load flow analysis normally uses the Newton-Raphson [8] and decoupled [8] iterative techniques but can also use the ladder load flow technique [9-12] to solve for voltage and current unknowns from the algebraic quadratic equations that describe the distribution system network. The load flow routine is used to calculate bus voltage magnitudes and/or angles (line-to-line, line-to-neutral), branch power, losses, voltage drop, current magnitudes and/or angles, shunt device power, and losses. The results (i.e., bus voltage and angle, current flow and angle, line losses) are available on a phase-by-phase basis for nodes, branches (e.g., lines, switches, transformers, cables, and series capacitors/reactors), and shunt devices (e.g., generators, motors, and capacitors). The power flow calculations are used to check for under/over voltage, overloads, and assessment of losses.

All four analysis tools can model balanced or unbalanced, looped or radial systems with any combination of three-phase, two-phase, or single-phase laterals. Distribution lines can be modeled as 3-phase, two phase, or single-phase and as either overhead conductors or as underground cables. The line models are modeled as pi-equivalent [8,13].

WindMil can model loads lumped at either end of line sections or assumed uniformly distributed over the line section. Loads can be Wye or Delta connected, constant KVA, constant impedance, constant current, or any combination of constant KVA, impedance, and current.

CYMDIST can model one spot (i.e., lumped) load and/or one uniformly distributed load in each section. The spot load can be located at the source end, middle, or far end of the section. The loads can be expressed in terms of real and reactive power, total apparent power and power factor, or real power and power factor. As with WindMil, loads can also be represented by constant KVA, constant impedance, and/or constant current.

Technical 2000 is quite unique in accommodating DC systems and devices in its distribution system analyses and performing DC power flow using the Newton-Raphson method. As indicated in the table, Technical 2000 will model both DC and combined AC/DC systems in the load flow analysis. This strength, which has high importance in DER systems, will be reflected repeatedly in this report.

3.1.2 Short-Circuit Analysis

A major analysis feature shown in the table is short-circuit analysis. Short-circuit analyses, in general, calculate fault current for three-phase, phase-to-phase, phase-to-ground, and double-phase-to-ground faults. Normally, the fault impedance is set to a default value but can be varied by the user. PSS/ADEPT can perform short-circuit analysis for either individual faults or a series of faults placed at any node in the distribution system. Alternatively, PSS/ADEPT can analyze faults applied sequentially to all nodes in the network. Likewise, WindMil will calculate fault current for all or selected points in the system and voltage/current flow for a specified fault at a given point. CYMDIST calculates RMS and asymmetrical and peak values for all shunt fault configurations. Its fault flow and fault voltage routine provides current flow and voltages throughout the network for a fault in a selected bus.

The EDSA fault simulation includes a broad array of features and includes single- and three-phase analyses, DC analysis, and calculations based on a number of standards.[4] Although the

[4] IEEE std 141-1986 and 242-1986, IEEE std 399 Violet Book, ANSI C37, IEC 909, and IEC 363.

features of the module are too many to list, some of the most important include:

- Loop and radial configurations
- Balanced or unbalanced networks
- Up to 99 cycle faults (3, 5, and 8 cycle ANSI faults)
- Min. and max. faults
- Sequence branch currents/voltages
- Stress and withstand analyses
- Derating of breakers
- Automatic error checking
- Arcing fault contributions
- User-defined safety margins
- Cable, motor, and transformer databases
- Complete text reporting

3.1.3 Motor Analysis

The WindMil motor analysis or "motor start flicker" models one or multiple motors (based on rated load and speed parameters) at any combination of 3 operating modes: running, locked rotor, and/or during soft start. The model permits unbalanced motor starting for single-phase motors and for three-phase motors on unbalanced circuits (e.g., three-phase motor connected to two-phase primary through an open Wye-Delta transformer). The graphical display of the results uses colors to indicate problems.

The Technical 2000 Motor Starting Analysis is designed to include a variable frequency drive, solid state torque ramp, solid state voltage ramp & control, solid state current limit & ramp, shunt capacitance, series resistance and reactance, auto transformer, and more. (The motor parameters estimation is based on a sequential augmented Lagrangian optimization algorithm.)

3.1.4 Voltage Regulation

The WindMil "Set Regulation" or "Line Drop Compensation" feature helps to define voltage and regulator settings. It permits the analyst to specify the low and high voltage limits, the most desirable voltage, and the tolerance on regulation settings.

A mention should also be made of EDSA's AC load flow analysis and its unique main feature, the *automatic voltage control expert system*. As seen in Table 3.1 under, "Voltage regulation – auto settings," this EDSA voltage control system is listed because of its ability to (1) determine transformer voltage tap settings required to meet all user specified criteria, (2) determine the level of reactive power to maintain specified voltage, and (3) automatically calculate the size of a capacitor (or inductor) required to provide necessary reactive power balance that will bring the voltage within the user specified guidelines.

3.2 Analysis Features

This section considers the next-level-down analysis capabilities provided by the vendors. As indicated in the previous section, load flow analysis is very fundamental to distribution system analysis. The load flow model lays a foundation that is relied on for many subsequent analyses described in this section that may include evaluations of protection coordination, transient stability, harmonic distortion levels, and interface to component time-current curves.

Table 3.2 provides a summary of the next-level-down analysis capabilities provided by PSS/ADEPT, WindMil, CYMDIST, and Technical 2000. The table excludes optimization studies and individual equipment models that will be looked at later.

Table 3.2. Analysis capabilities of each distribution system analysis tool

Analysis feature	PSS/ ADEPT	WindMil	CYMDIST	Technical 2000 *(see text for full list)*
System Restoration (e.g., switching solutions)			Yes – includes feeder balancing	
Protection Coordination/Verification	Yes (if installed)		Yes	Yes – includes breaker de-rating based on elevation/ambient temp.
Integrated Harmonic Analysis	Yes (if installed)		Yes	Yes (if installed)
Re-conductoring studies	Yes		Yes	
Transient Stability Simulation				Yes[a] (if installed)
Line Constant Calculations	Yes (if installed)	Yes	Yes	Yes
Lightly Meshed Systems	Yes			
Network & Data Validations	Yes	Yes		
Interface to Component Time-Current Curves		Yes – using Milsoft's LightTable program		
Makes Use of GIS		Yes – in database	Yes	
Load Control Points (source, feeder, and down line)		Yes		Yes
Sectionalizing (coordination for all overcurrent devices)		Yes	Yes	
Charging Current		Yes – overhead and underground		
Circuit Transfer - extract substation or feeders to data base		Yes – after editing/modeling, changes are fed back		
Area Interchange Control (each area w/ dedicated generator)				Yes

(a) Advanced trapezoidal algorithm (50,000+ buses)

Eighty percent (80%) of the analysis features shown in the table are provided by only one or two vendors reflecting a lack of common features among the 4 vendors. It appears that each vendor has developed a product with its own unique emphasis and analytical direction. PSS/ADEPT has a unique focus on lightly meshed systems and network/data validations. Not listed in the table are their additional (less analytical) features of load scaling, machine scaling, and load snapshots where the user defines "pictures" of loads. PSS/ADEPT also has useful Input Data Validation and Network Validation features that allow the analyst to check the network for any bad data or unusual circumstances (e.g., zero impedance in a line) at any time. This Network Validation can be initiated by the analyst or can be set up to run prior to performing any analysis. The PSS/ADEPT harmonic analysis can be used to calculate total harmonic distortion, telephone influence factor, and Thevenin impedance. The model can be applied to static loads, induction machines, synchronous machines, shunt capacitors, lines and cables, and transformers. For each item, the harmonic models can be used to determine the impedance values at a given harmonic number.

As with PSS/ADEPT, WindMil has an overall check feature, called "Network check," that looks for bad data or unusual circumstances. WindMil has its unique focus on the use of component time-current curves (i.e., from its own LightTable add-on module), charging current, and circuit transfer. In the circuit transfer, the analyst can extract individual substation or feeders into a separate database for editing and modeling and then reapply the changes back. WindMil uses Carson's Equations [9,13,14] to calculate distribution line constants from physical characteristics that are provided by the user (spacing, conductor size, pole configuration).

CYMDIST's unique emphasis includes a module that provides *service restoration* via automatic switching solutions that restore power, multiple faults consideration, and multiple objectives algorithm with priority customer consideration. CYMDIST's system restoration routine determines the radial configuration that restores service for an equipment outage. The new configuration is obtained by changing the switching status (open/closed) of tie switches. Not listed in the table is the reliability assessment module that is separate and will be discussed later. As with WindMil, CYMDIST uses Carson's Equations to calculate distribution line constants from physical characteristics that are provided by the user (spacing, conductor size, pole configuration). Two other recently added and noteworthy features in CYMDIST are Load Growth for Distribution Planning and Load Allocation Using Multiple Meters.

EDSA's Technical 2000 provides unique capabilities in transient stability simulations and area interchange control. In the area interchange control, many areas can participate and each has a dedicated generator for controlling tie-line power.

Table 3.2 does not list all of the analysis features that are included in Technical 2000. Section 3.7 lists 36 features that are either included (depending on what package is initially purchased) or can be added on (i.e., purchased) later. The standard analysis features that are *always* included in Technical 2000 include: AC power flow (1 and 3 phase), AC multi-motor starting, AC short circuit analysis (3-phase ANSI/IEEE and IEC 909), device coordination (1 phase, 3 phase, and DC), reactor sizing (power quality), and design optimization algorithms for both arcing fault calculations and electrical load schedules.

3.3 Optimization Tools

Table 3.3 lists the optimization analysis tools for the different vendors. Feeder or system reconfiguration for loss minimization is an important tool found in some of the listed products. This loss minimization routine finds the configuration of the radial network with the lowest total loss. The configuration is achieved by altering the switching status (open or closed) of tie switches to form a new radial configuration. The network reconfiguration can be constrained by branch limits to avoid overloads. PSS/ADEPT calls their routine "tie open point optimization" and it can consider several load levels simultaneously, each with a relative duration. It finds the one radial configuration that minimizes overall losses and/or produces the highest financial return when all these load levels are analyzed. The WindMil version permits the addition of new switches at the user's request and does not limit either the size of the system or the number of possible switching options.

Table 3.3. Optimization analysis tools

Item	PSS/ ADEPT	WindMil	CYMDIST	Technical 2000
Feeder reconfiguration for loss minimization via switching	See tie point optimization	Yes	Yes	
Tie point optimization (loss min.)	Yes (if installed)			
Optimal power flow (active/reactive)				Yes
Capacitor placement/sizing for loss minimization	Yes (if installed)	Yes	Yes	Yes - sizing
Phase configuration based on losses		Yes		
Optimal sizing of transmission line, generator, and transformer				Yes

Technical 2000 features an AC Active Optimal Power Flow (AOPF) and Reactive Optimal Power Flow. AOPF uses an algorithm more sophisticated that either the Newton-Raphson or Fast Decoupled methods. The AOPF algorithm considers system power generation at a calculated (rather than specified) condition that will not exceed the maximum load restriction imposed on the system branches. This is referred to as "branch security." AOPF can also be used to find the most economic operating load flow solution while ensuring that all conditions for branch security are satisfied. The load flow solution is obtained without load shedding when possible.

Loss minimization routines not only minimize loss in a radial network by altering the status of switches but also by changing the switching state (open or closed) of existing capacitors. During this routine, voltage limits and branch overload limits are enforced. The WindMil load balance or tap phasing optimization routine calculates optimal 1- and 2-phase tap phasing based on kW loss reduction. The WindMil Feeder Optimization analysis calculates optimal switching configuration for minimal losses and the addition of new switches at the user's request. The analysis graphically displays changes in switching status and changes in flow direction using a defined color scheme.

Table 3.3 also shows that optimal capacitor placement and sizing is available in all of the products. The PSS/ADEPT version performs optimization for the highest financial return considering the initial cost of the capacitor, annual maintenance cost of the capacitor, and the costs of real/reactive power losses. The user of this version chooses the connection type, the size of the capacitor bank, the number of capacitors available, and the nodes eligible to receive the capacitors. Also PSS/ADEPT can analyze several load levels at the same time. The WindMil program provides capacitor placement given single-phase capacitor unit size and percent source power factor limit. The analyst can allow placement of capacitors on underground (UG) line elements, 2-phase, or single phase. The program provides a graphical display of recommended capacitor installations.

3.4 Equipment Models

Table 3.4 lists the types of equipment that each product models. Of course, lines, transformers, generators, switches, etc. *have* to be included in each to support any realistic level of network modeling. The main value of this table is seeing where modules are needed from certain vendors and where the scope of modeling may vary (e.g., as seen for motors).

Table 3.4. Equipment models

Hardware Item	PSS/ ADEPT	WindMil	CYMDIST	Technical 2000
Transmission Lines or Cables (pi-equivalent)	Yes	Yes	Yes	Yes
Generators (synchronous or induction)	Yes	Yes – as negative load or swing kVar	Yes	Yes
Transformers (3-winding)	Yes – see text	Yes – all common connections	Yes – all common connections	Yes – see text
Regulators (single/3-phase)		Yes – includes line drop compensation and voltage settings	Yes	
Capacitors	Yes – in CAPO module	Yes – series or shunt	Yes – series or shunt	Yes – economic analysis/reporting
Switches	Yes	Yes	Yes	Yes
Overcurrent Devices	Yes – in protection coordination, fuses & relays	Yes – fuses, sectionalizers, relays, breakers, and more.	Yes – in CYMTCC module	Yes – various magnetic breakers and circuit breakers
Motors	Yes	Yes – locked rotor, soft start, running	Yes - starting	Yes[a]
DC Lines and Converters				Yes
Batteries				Yes – in DC power flow module

(a) Single/multiple motors modeled for motor starting and motor operation. Considers any branch/bus and is quite versatile. Motor starting also simulated in DC power flow module.

Equipment models are typically quite versatile. For instance, the PSS/ADEPT transformer model can be, wye-wye, wye-delta (" 30°), delta-wye (" 30°), delta-delta, wye-connected regulator, and delta-connected regulator. The transformers can have any phasing (e.g., ABC, AB, BC, CA, A, B, or C). WindMil and CYMDIST also include all common connections. CYMDIST permits user-specified grounding impedances and primary side tap setting. In Technical 2000, the AC power flow feature models fixed tap, voltage control, phase shifter (active power control), reactive power control, and 2- & 3-winding types. There is also a 1-phase transformer analysis in the fault simulation analysis.

As part of the load flow/voltage drop routine, the WindMil program models conductors using an accurate Carson equation-based calculation of line impedance [9,13,14] for overhead and underground lines from the physical data of the conductor and configuration on the pole. Built-in conductor definition data is included. Cables can be different in each phase, have unbalanced spacing, concentric or tape shield neutrals, and extra neutrals.

The generator models provide for the specification of rated power and rated voltage (P&V) and power factor or real and reactive (P&Q) power. In the case of Technical 2000, a load can be modeled as a generator (negative load) bus as either constant kVA or impedance.

The motor starting analysis calculates voltage and currents in the network when motors are started in the system. The before/after network results for starting motors provide the pre-start, post-start, and difference in the voltages for the network. PSS/ADEPT can perform a motor starting analysis for individual or multiple machines in the system. The WindMil program analyzes single or multiple motors with locked rotor, soft start, and/or while running.

3.5 Screen Editing

This section summarizes screen-editing features as presented by each vendor's user manuals and Internet site. The user interface is designed with a one-line diagram display of the network from which the user can create, edit, and navigate the network using their computer mouse. Also, the user can typically zoom in or out on a selected portion of the network, node or branch.

Table 3.5 is perhaps only useful in arriving at a general idea of the relative emphasis or importance that screen editing is given by each vendor as reflected in the user's manuals and marketing material. CYME International is clearly proud of their CYMIST editing features (the table shows only a partial listing of their features); this is a positive indication to their credit.

3.6 Display and Reporting

Table 3.6 summarizes the display and report features of the products. Most of the table shows various display features however a few reporting features are listed at the bottom. This is another area where omissions may have only limited significance. For instance, it is doubtful that only Technical 2000 provides arrow indicators in their power flow display; however, the other vendors were silent on the subject.

In reporting, PSS/ADEPT can provide customizable tabular reports for fault current, power (kW), reactive power (kVar), energy cost, demand cost, and maintenance cost. The PSS/ADEPT reports are, branch current, power, and power loss reports; input list of network data report; node voltage reports; shunt current and power reports; status reports; network summary report; power flow summary and details; fault all current report; and the optimization reports for both capacitor and tie open point. Items in the reports may be sorted by device name, node base voltage, phasing, device type, node name, or tree. Add-on analysis features such as harmonic analysis produce additional reports (e.g., for this case, harmonic voltage & spectrum, impedance vs. frequency, and nodal impedance).

Table 3.5. On-screen design and editing

Display Interface	PSS/ADEPT	WindMil	CYMDIST	Technical 2000
Automatic re-conductoring and re-phasing of selected sections			Yes	
Change layout of the sections or feeders/cut & graft sections	Yes		Yes	
Edit several feeders simultaneously, in single or different windows		Can work on all or one circuit(s).	Yes	
Group sections into zones			Yes	
On-line editing and zooming (buses or nodes, branches, shunts)	Yes			Yes
Panning of diagram		Yes	Yes	
Circuit element editors	Yes	Yes	Yes	Yes
Positioning and editing features including move, rotate, mirror, scale, extend, trim, split, fillet, offset, join, etc.			Move, resize, and locate are listed	Yes
Grids and rulers	Yes		Yes	Yes
Drag and drop shapes quickly with automatic snap and align into position	Yes			Yes – includes auto-rotate
Digitizer utility		Yes[a]		

(a) Program speaks during circuit design allowing analyst to concentrate on model building without constantly glancing at the screen.

WindMil prints out colored graphical displays and tabular reports. New options have been added for "enhanced sectionalizing" custom reports. The WindMil background display relies on GIS to create a realistic geographical background to the electrical system model. Using the LandBase option, the display shows streets, rivers, roads, etc., all of which can be embedded in layers and supported by database platforms.

CYMDIST's display seemed very well designed and user-friendly. For example, there are 6 zoom buttons located on the control bar that performs such functions as zooming in, zooming out, going to previous view, zoom to locate, zoom to fit, etc. In Reporting, CYMDIST provides excellent displays such as a voltage drop profile (i.e., voltage vs. distance) in which phases are designated by color.

Technical 2000 provides detailed views/reports on system behavior including violation reports on under/over voltage events. As another example, the Technical 2000 fault simulation analysis provides full text reporting on faults.

Table 3.6. Display and reporting

Display and Reporting Features	PSS/ ADEPT	WindMil	CYMDIST	Technical 2000
A. Displays				
Power flow display (arrows indicating direction)				Yes
Color displays (overloads, different feeders)		Yes - by phase, feeder, element, etc.	Yes – by # of phases, section, under/over voltage, etc.	
Abnormal conditions/violations flagging	Network validation	Yes	Yes	Yes
Background and graphic files		Yes – imported from GIS and other graphic sources[a]	Yes – imported from GIS and CAD	Yes – DWG, DXF, JPEG, BMP, TIFF, PNG, etc.
Display selected number of phases or selected equipment	Yes		Yes	Yes
Displays voltage/capacity problems	Yes	Yes	Yes	
Special purpose displays		Yes – nine items[b]		
Display of capacitor location/load flow	Yes	Yes	Yes	Yes
Display control (e.g., zoom, pan, size labels & end points, change colors)	Yes	Yes	Yes – including 6 zoom buttons	Yes
Phase voltage and fault current profiles	Yes	Yes	Yes	Yes
Graphical display of results by pointing to a selection		Yes	Yes	
B. Reporting				
Summary reports of various types	Yes	Yes	Yes	Yes
Display/print results boxes or entire report		Yes – custom printouts at no extra cost	Yes – including voltage drop profile	
Reports (kW, kVar, and costs for energy, demand, and maintenance)	Yes			Yes

(a) AutoCAD DWG, AutoCAD DXF, MicroStation DGN, ESRI Shape Files, MapInfo Vector, TIFF, bitmap, Blue Marble, JPEG and Vector Product Format. Background via GIS.
(b) Displays of load allocation, voltage drop, fault current and flows, sectionalizing, load balance, motor analysis, feeder optimization, and set regulation.

3.7 Add-on Modules and Other Features

Table 3.7 shows many of the modules that the vendors produce for harmonic analysis, capacitor optimization, reliability analysis, enhanced graphics, etc.

In the case of Technical 2000, many features are either included or can be added later depending on the package originally purchased (i.e., depending in large measure on price). Features that are *always* included in Technical 2000 are shown at the end of Section 3.2. The features that may not be originally included in a package and may therefore be "add-ons" include the following:

Power Flow Analysis
- AC Advanced power flow with motor torque
- AC Unbalanced load flow – 3 phase
- AC Voltage profile
- AC Active optimal power flow
- AC Reactive optimal power flow
- AC/DC integrated load flow
- AC load flow with DC lines
- DC power flow
- Load forecasting

Power Quality Analysis and Mitigation
- Power factor correction
- Harmonics analysis with automatic filter sizing
- Distribution and substation reliability analysis
- Block-based reliability analysis
- Capacitor sizing & optimization

Fault Analysis/Protection Coordination
- AC short circuit – 1 phase
- AC short circuit – IEC 363
- DC short circuit
- Arc fault energy – NAPA 70E-1995

Dynamic Behavior Simulation
- Motor torque and performance
- Advanced transient stability
- Electromagnetic Transient Analysis

Design Optimization
- Motor parameter estimations
- Ground grid design
- Cable pulling in 3D
- Shielding effectiveness
- Robotic welders

Sizing Optimization
- Battery sizing
- Cable ampacity IEC
- Generator set sizing
- Transformer sizing
- Wire and conduit sizing
- Bare wire sizing
- Short line parameters
- Transmission line constants
- Cable tray analysis
- Transmission line sag and tension

The distribution *reliability analysis* routines of many vendors provide predictive reliability calculations for a radial network. The routines use equipment outage frequency and repair time statistics to calculate standard industry customer and system reliability indices [15,16]. The calculation results can be used to evaluate the reliability of a network configuration, a protection scheme, or proposed alternatives. PSS/ADEPT's reliability analysis uses a hierarchical Markov simulation technique to calculate standard IEEE reliability indices. The routine uses a database of failure rate and repair time information and displays the results in colored, one-line diagrams based on targets selected by the user thus giving a clear indication of trouble spots in the network. CYMDIST's module provides computation of system indices (i.e., SAIFI, SAIDI, CAIDI, ASAI) [15,16] and customer's indices (i.e., outage frequency and duration). It provides extensive modeling of networks and loads, flexible load models for uniform and spot loads, and a full range of equipment models. The EDSA advanced reliability model is quite extensive and features the same system indices as CYMDIST. The indices cannot only be used to examine system performance but also to conduct sensitivity and selection studies of system configurations. The EDSA module is divided into two types of analyses, (1) distribution and substation system reliability and (2) reliability evaluation of block-based distribution systems. The substation reliability portion contains 26 of the world's standard configurations. The block-based analysis uses reliability blocks and branches such that one or more electrical component (e.g., breaker and a transformer) may be part of a block or branch. Many further details are provided on the EDSA website.

Table 3.7. Add-on module analysis tools

Module	PSS/ ADEPT	WindMil	CYMDIST	Technical 2000
Distribution reliability	Yes (DRA)		Yes (RAM)	(a)
Harmonic analysis	Yes		Yes (HARMO)	(a)
Capacitor optimization	Yes (CAPO)	Yes	Yes	(a)
Contingency analysis	Part of PSS/O[b]	Yes	Yes (CAM)	(a)
Switching optimization	Yes (TOPO)	Nodal reducer (circuit reducer)	Yes (SOM)	(a)
Load scaling	Yes (LDSC)	Yes	Yes	(a)
Graphic overlay		Yes – GIS using LandBase option	Yes (MAP)	
Time current curve display & analysis		Yes (LightTable)		

(a) May already be included depending on what Technical 2000 package is originally purchased, if not, can be purchased as an add-on – also applies to many other features (see text).
(b) PSS/0, which is mentioned only here, provides *online* network analyses.

Table 3.8 shows miscellaneous program features, such as the use of separate databases, help utilities, etc. Not surprisingly, all are Microsoft (MS) Windows-based products and that is generally true beginning with the Windows 95 "B edition" to recent versions (e.g., NT, 2000, XP).

The WindMil program is designed to mesh quite well with another of Milsoft's products, LightTable. LightTable is an extensive component database containing manufacturer's component curves for over 4,000 overcurrent protection devices.

Table 3.8. Other features

Feature	PSS/ADEPT	WindMil	CYMDIST	Technical 2000
Import/export from other data base		Yes – from Milsoft's LightTable	Yes – from CYMTCC	Yes
Multiple level undo/redo	Yes	Yes	Yes	Yes
Help utility	Online Help	Yes – context sensitive	Yes	Yes
Provides means to share data with coworker or technical support		Yes – using a zip utility		Yes – using "Collaborative Engineering Environment" on Internet
Platform – supported by various versions of MS Windows	Yes	Yes	Yes	Yes

4. ASSESSMENT OF DER SIMULATIONS

Having completed a survey of distribution analysis software presently available, this study concludes with an overall assessment relative to the growing need for software that can provide versatile and dynamic analyses of DER. This represents an important new application for the various software packages analyzed in this report.

4.1 Evaluation of Software For Use in DER Analyses

An earlier phase of this study focused on (1) locating and obtaining useful distribution data that would support the planned modeling, (2) looking at various electricity network software to identify which ones would be suitable for modeling DER parameters in a network analysis, and (3) selecting a DER distribution system analysis tool and system data that would be most appropriate for performing the analysis.

This section describes a study performed at ORNL in which a distribution analysis tool was used to perform the actual system analysis of the electric distribution system with the interconnection of DER. The technical results of this application of the CYMDIST tool to feeder data from a southern utility are provided in Appendix A.

In Sect. 4.2, below, is an assessment of the inadequacies found in the analysis tool that was used in the trial modeling exercise and a delineation of recommendations of functional improvements for the tool that would make it better suited for DER optimization studies. These recommendations are especially for the tool to be capable of considering multiple DER locations, sizes, multiple device types, and various DER penetration levels in the distribution system.

4.2 Evaluation Results and Recommendations

Surveying the electricity distribution system analysis tools available from the industry, it quickly became apparent that commercially available tools were basically designed for distribution system planning, voltage-drop analysis, and fault study purposes. These tools were primarily designed for analyzing distribution systems that are radial – that is, the power flows from the utility source (substations) to the loads. They were not conceived with distributed generation in mind because distribution networks evolved to transport power from the utility substation unidirectionally along feeders then along laterals to loads. In many cases, the conductors decrease in size/capacity as the power flow gets closer to the load. These tools provided a mechanism for modeling DER in the form of negative loads via a PQV model (see Sect. 4.2, Item 4, regarding tool inadequacies) for an induction or synchronous generator model. There was an absence of DER models specifically for inverter-based devices such as microturbines and fuels cells that would represent their performance during various operational modes and disturbances (e.g., voltage sags). Furthermore, there was no specific device parameter information on various DER devices other than voltage rating, power output and interconnection requirements. The analysis tools were not designed for studies of multiple DER placements and locations in a distribution system and would not facilitate introducing DER systems of various sizes. In particular, the tools were not designed to make batch runs of varying DER locations, sizes, and penetrations and various network loadings and load distributions. The tools were designed more for interactive analysis where one particular problem such as a new load or new conductor was being considered.

The modeling exercises for the DER analysis involved many manual iterations of the model and, though the results demonstrate that some useful information can be obtained, perhaps the most valuable result of the study is the list of identified inadequacies of commercially available distribution analysis tools, such as the one that was used for this DER case study (i.e., CYMDIST). The distribution software analysis program used in the study, and others like it, are fine products in light of what they were designed to do. However, the intent of highlighting "problems" is to suggest features (i.e., needed enhancements) for a more powerful tool with a broad range of analysis applications.

The following inadequacies were identified for the modeling tool used in this study and for others like it:

1. One of the primary weaknesses of the tool is that it was designed for manual placement and sizing of DER and not for easily determining the optimal placement and sizing of DER. Furthermore, they were designed, for the most part, to feed power in a unidirectional flow from substation to loads along and at the end of feeder laterals. However, the companies producing the analysis software have only recently given consideration to modeling distributed generation on distribution feeders. Some have only recently given consideration to single-phase DER vs. three-phase DER. Single-phase DER could present more of a challenge for harmonic distortion and unbalanced conditions.
2. There is a lack of any macro or scripting capability for implementing batch runs needed for executing several iterations such as what is required to optimize DER placement and sizing and to consider various DER locations and penetration levels as well as network loadings and load distribution levels. Distribution system analysis programs were designed to assess voltage drop issues related to load additions, feeder upgrades, motor startup issues, and fault current analysis and relay coordination more in an interactive mode than a sensitivity mode.
3. The analysis program allows the user to only model one type of DER generator per line section or load location per bus or node. Thus, the program doesn't allow multiple DER types or sizes at the same load location.
4. DER generators can only be modeled as synchronous or induction generators in a simple model scheme where the real power or reactive power is set and where a fixed or variable power factor is used (i.e., referred to as a PQV model representing the real power value (P), the reactive power value (Q) and the voltage value (V)). The reactive power value can only be varied for a given real power value if the power factor can be varied.
5. There is no capability to customize the DER generator model with characteristics specific for each type of DER, such as a microturbine, fuel cell, photovoltaics, etc. The generator models are designed for a rotating-based generator instead of inverter-based power technologies, such as microturbines that produce high-frequency AC that is rectified to DC and then converted to 60-Hz AC. The analysis tool doesn't allow modeling of this type of DER.
6. The model is not capable of performing a dynamic DER assessment, such as to determine (1) the voltage/current transient as the DER is started up or as its power setting is adjusted or (2) the response of the DER to a feeder voltage sag.
7. The analysis tools are designed to study peak and off-peak load conditions rather than variable feeder loading conditions that occur over the full operating period of the DER. Thus, many analysis iterations would be required to analyze DER operations as the daily/seasonal/yearly load levels and distribution conditions of the feeder vary.

It is hoped that this effort, which is in its infancy, can be continued so that useful DER feeder studies can become commonplace. Immediate additional areas for system study include the following:

1. Study DER on the feeder models that we currently have data for or entirely different feeder models, especially with operating problems, and provided by a utility or utilities willing to participate in the analysis and provide additional information and data to fully understand the DER benefits and impacts.
2. Study DER on feeder models with unbalanced load and voltages.
3. Analyze DER capable of supplying reactive power as needed (i.e., supplying variable power factors).
4. Study DER on feeders with voltage-sensitive loads (only constant power considered so far).
5. Model single-phase DER (only three-phase DER considered so far) to determine unbalanced operation impacts.
6. Study DER on generator types that are current limited to evaluate motor starting capability and impact on circuit protection.
7. Study motor starting on DER, especially inverter-based generators with unbalanced conditions (e.g., voltage, windings).

Acknowledgement

The work described in this report was conducted by Oak Ridge National Laboratory (http://www.ornl.gov/) in coordination with the Consortium for Electric Reliability Technology Solutions (http://certs.lbl.gov/CERTS.html) on behalf of the U.S. Department of Energy (http://www.eren.doe.gov/deer.html).

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APPENDIX A - DER Steady State Modeling and Assessment

This is a summary of the distributed energy resource (DER) steady state modeling and assessment work performed by ORNL during FY 1999 and FY 2000.

The reasons for performing the DER steady-state analysis study are two-fold. First, the objective of the study was to determine the adequacy of presently available software-based distribution system tools for studying electric distribution systems with interconnected DER and the related issues. Second, the study was to determine some of the steady-state benefits of DER based on a commercially available software tool that has the functions representative of most currently available distribution system analysis tools. Specifically, the particular software tool chosen was used to model a feeder with DER data by using network and load data provided by a southern electric utility. The tool was tested to see how well one could assess the benefits and impacts of introducing DER, in this case a DER generator, to the distribution network.

The system benefits that can be provided by distributed generation (DG) include, (1) voltage support by leveling the voltage profile from substations to loads, (2) generating capacity relief via reduction in feeder load demand, and (3) feeder loss reduction. Following from these are other advantages such as an increased distribution system capacity, decreased system generation peak demand, and less variation in demand.

Scope

Phase 1 of the study was performed in FY 1999 and involved (1) locating and obtaining useful distribution data that would support the goals of the study, (2) looking at various electricity network software to identify which ones would be suitable for modeling DER parameters in a network analysis, and (3) selecting DER tool and system data that would be most appropriate for performing the analysis planned for Phase 2.

Phase 2 of the study was conducted the following year to, (1) perform the actual system analysis of the electricity distribution system with the introduction of DER, (2) identify inadequacies in the tool, and (3) recommend functional improvements for the tool that would make it better suited for DER optimization studies, especially to consider multiple DER locations, sizings, and multiple device types.

Analysis and Results

It is instructive to describe briefly the difficulties encountered in initiating a study of this type since it illustrates barriers that must be dealt with and resolved in the future. Obtaining adequate data both for the electric network and the DER model was one of the first activities. Initially, our CERTS utility partner, Southern California Edison (SCE), indicated that it could provide feeder data and load information needed to conduct the study. However after many delays and false starts regarding several possible feeders that could be studied it proved to be impossible to obtain the necessary feeder data from them. One reason was that it was not possible to get full buy-in by the SCE department that would be providing the data or reduce their confidentiality concerns. Also, model data for various DER devices, such as microturbines, was not available from the manufacturers according to our CERTS university and laboratory members, the Power System Engineering Research Center (PSERC) and Sandia National Laboratory. Subsequently, another electricity provider was contacted in a Southern State and feeder data proved to be more readily obtainable. The particular utility was not involved directly in the study and the data that they provided was sanitized to eliminate specific feeder names and location. Also, since the utility was not directly involved, no specific information about feeder operational problems or loads on the feeders could be ascertained.

Surveying the electricity distribution system analysis tools available from the industry, it quickly became apparent that commercially available tools were basically designed for distribution system planning, voltage-drop analysis, and fault study purposes. These tools provided a mechanism for modeling DER in the form of negative loads via a PQV model (see Item 4 regarding tool inadequacies in the Conclusions section) for an induction or synchronous generator model. There was an absence of DER models specifically for devices such as microturbines and fuels cells that would represent performance during various operational modes and disturbances (e.g., voltage sags). Furthermore, we did not have any specific device parameter information on various DER devices other than voltage rating, power output and interconnection requirements. The analysis tools were not designed for studies of multiple DER placements and locations in a distribution system and would not facilitate introducing DER systems of various sizes.

In spite of the above obstacles, a decision was made to use the most suitable available program, CymDist by CYME International, Inc., for the analysis software. A significant reason for choosing this particular analysis tool included the fact that it was representative of most distribution system analysis tools in terms of functionality and its ability to use network and load data along with Geographical Information System (GIS) data. Also, the feeder data provided by a Southern electric utility was provided to ORNL in CymDist data format. The key functions of this tool that would benefit the study included the following capabilities:

1. Models single and three-phase DER,
2. Represents one-line diagrams via GIS data,
3. Provides balanced/unbalanced voltage drop analyses, and
4. Represents loads as constant power, constant current, constant impedance or a combination of the three. Thus, loads could be represented as voltage sensitive.

In Phase 1, the project successfully obtained feeder data that would support the proposed analysis. Table A.1 summarizes many of the parameters of the data that were obtained from the Southern electric utility. Feeders 1 through 5 are designated at the top of the columns and beneath them are listings for line voltage, total load, total real and reactive power, current flow, load mix, and other basic parameters. Feeder 2 was selected for the Phase 2 analysis since it had a desirable combination of advantages over the other feeders. These advantages, evident in the table, include (1) a mix of customers (i.e., 19% residential, 3.2% commercial and 78 % industrial loads), (2) a high dependence on capacitors (i.e., 78.8% power factor without capacitors), (3) high losses (i.e., 438 kW with capacitors and 721 kW without capacitors), and (4) both a long feeder section of almost 15 miles and numerous line sections in the model.

Table A.1. Parameters relating to the five Southern utility feeders

Feeder Characteristics	1	2	3	4	5
Line voltage (kV)	12.47	12.47	12.47	12.47	12.47
Total apparent load (kVA)	4,458	5,705	13,206	3,656	5,580
Real load (kW)	3,349	4,489	11,590	2,684	4,237
Reactive load (kVar)	2,943	3,520	6,330	1,573	3,632
Total current flow (A)	156	236	531	158	197
Load (% residential kW)	0.4	19.3	0	42.1	0.4
Load (% commercial kW)	5	3.2	100	0	0
Load (% industrial kW)	94.5	77.5	0	57.9	99.6
Pf with & w/o caps (%)	99.4/73.2	93.2/78.7	99.2/87.7	97.3/89.3	99.5/75.2
Lowest voltage (%) with & w/o caps	96.9/70.3	96.7/90.9	98.9/93.5	97.9/93.3	97.9/93.6
Available capacitors (#/total kVAr)	8/3,600	12/6,300	9/7,500	9/4,200	9/5,700
Capacitor control	manual	manual	manual	manual & voltage controlled	manual
Regulators	2	3	0	1	0
Longest feeder section (miles)	32.3	14.6	9	9.4	11.7
Losses (kW) with and w/o caps	325/1,115	438/721	179/239	167/172	135/224
Losses (kVar) with and w/o caps	390/1,115	427/729	459/625	193/211	180/308
No. of line sections in model	1,397	1,658	1,778	1,612	779
Spot loads in model	98	235	386	292	38
Industrial spot loads	76	37	0	141	35
Commercial spot loads	18	13	386	0	0
Residential spot loads	4	185	0	151	3

Once the feeder was selected, the CymDist analysis tool was used to obtain results for various sizes and placements of DER. Since the tool does not have a macro language to permit the running of batch analyses, it was necessary to perform a number of manual iterations to consider several different DER sizes and placements. These sizes, also referred to as levels of DER penetration, were chosen to be 30 kW, 60 kW, 120 kW, 240 kW, and 480 kW (see Table A.2). The logic for the sizes related to the fact that commercial microturbine generators, available in the smaller sizes, could be paralleled together to achieve the larger sizes. Also, the industry has future plans to build DER devices of the larger sizes. A fixed power factor (pf) was used for the DER models (since devices such as the microturbines have inverter-based power conditioning and have been designed to provide constant pf) and the loads were kept balanced. Out of the 1,658 line sections in the model for the selected feeder, one line section was selected for the analysis. Note that each line section has a single aggregate load associated with it and, since the utility was not directly involved in the analysis, further details about the load makeup at the line section could not be ascertained beyond what was given in the CymDist data (e.g., number of individual loads and load types). In the analysis, the location of the DER was often placed at the load location and, for comparison, upstream of the load location.

Table A.2. Modeling cases - DER sizes and placements

Case	Power (kW)	Location
1	0	N/A
1-1	30	DER at load point
2-1	30	DER upstream of load
1-2	60	DER at load point
2-2	60	DER upstream of load
1-3	120	DER at load point
2-3	120	DER upstream of load
1-4	240	DER at load point
2-4	240	DER upstream of load
1-5	480	DER at load point
2-5	480	DER upstream of load

Figure A.1 shows the resulting capacity support for the first case where the DER was placed at the load site and Figure A.2 shows a second case where the DER was placed upstream of the load site. In the first case it is evident that the reactive power (kVar) and especially the real power (kW) levels decrease as expected, especially at the two or three highest DER penetrations. Ultimately, a 12% decrease in real power is predicted by the model for 480 kW of DER. In contrast, the second case shows about a 10.5% reduction in power for the same level of DER. The two cases show roughly a 7% reduction in reactive power for the first case and 5% for the second case.

Furthermore, when the DER is at the load point, the reduction in real power is almost twice that for reactive power while, for the case where the DER is upstream of the load, the reduction in real power and reactive power is 83% and 71% less, respectively. This shows how advantageous it is (i.e., at least for this feeder) to locate the DER in close proximity to the load when trying to reduce feeder real and reactive power demands.

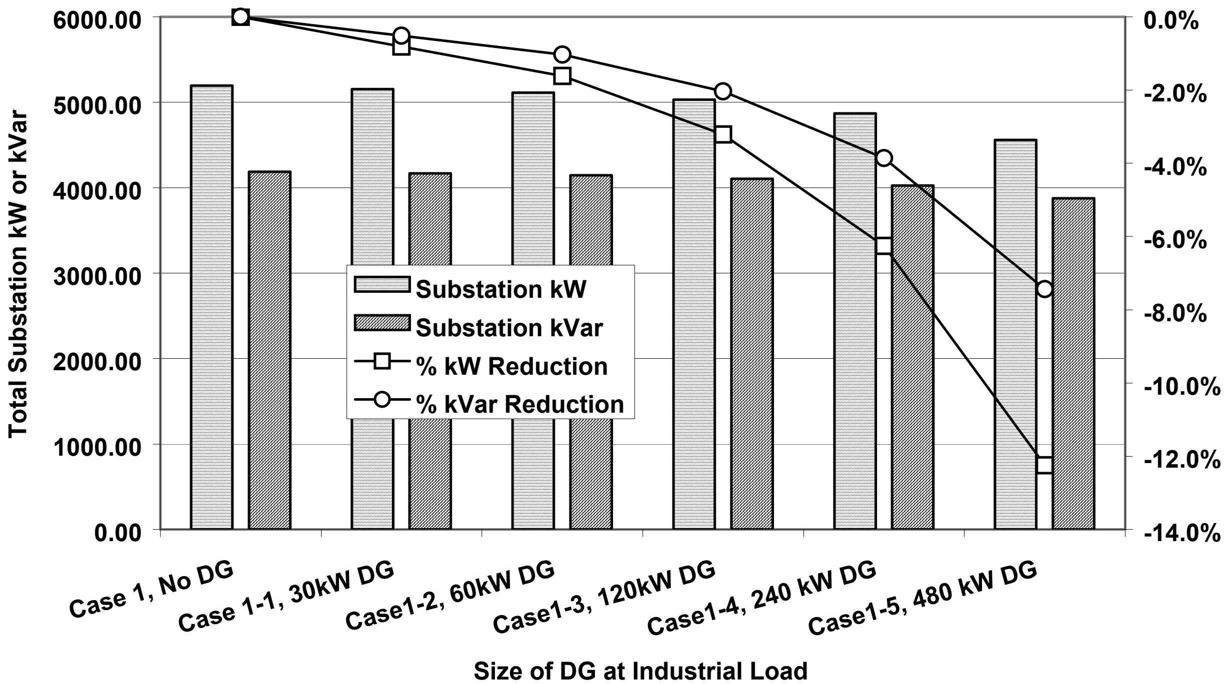

Fig. A.1. Capacity support provided by DER at the load point

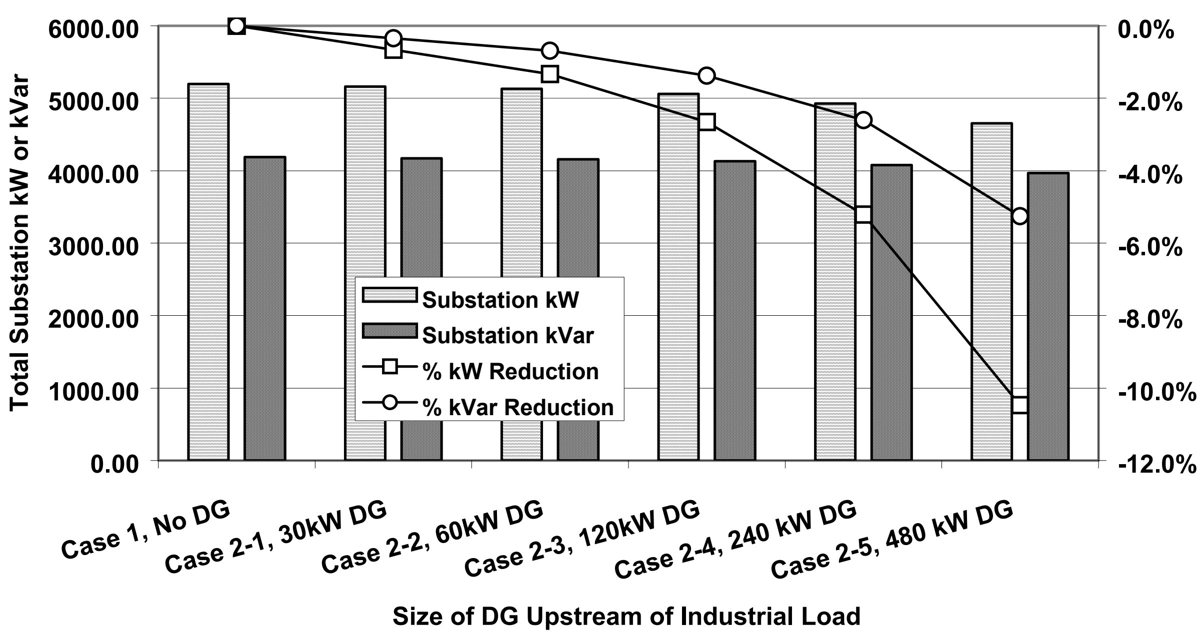

Fig. A.2. Capacity support provided by DER upstream of load

Figure A.3 shows the voltage support provided by DER when it is located at the load point. The chart shows per unit phase voltages (i.e., actual voltage divided by ideal voltage) vs. distance from the substation (i.e., from 0 miles to greater than 8 miles). The thinnest line plot represents no DER on the feeder and each succeeding thicker line plot represents increasing DER penetration on the feeder. At approximately 5 miles there is clearly a voltage boost provided by a voltage regulator.

This modeling of the feeder provided an interesting insight on DER interconnection. Note the divergence of the curves at distances greater than 4 or 5 miles. The positive effects of DER at 120 kW and especially at 480 kW become more apparent over these distances. The 480 kW case even appears to provide a limit to the voltage decay after 7 miles. This indicates how little current is being supplied through the feeder lateral with the DER operating at the load site.

Figure A.4 shows voltage support provided by DER when it is located upstream of the load. The chart shows per unit phase voltage vs. distance over identical ranges as the previous plot. The order of the correlation is also identical, the significant difference being that the DER penetration levels no longer show an increasing positive effect on voltage support at distances greater than 4 miles. Clearly the model shows that this is a less optimal placement of DER for providing voltage support for the feeder.

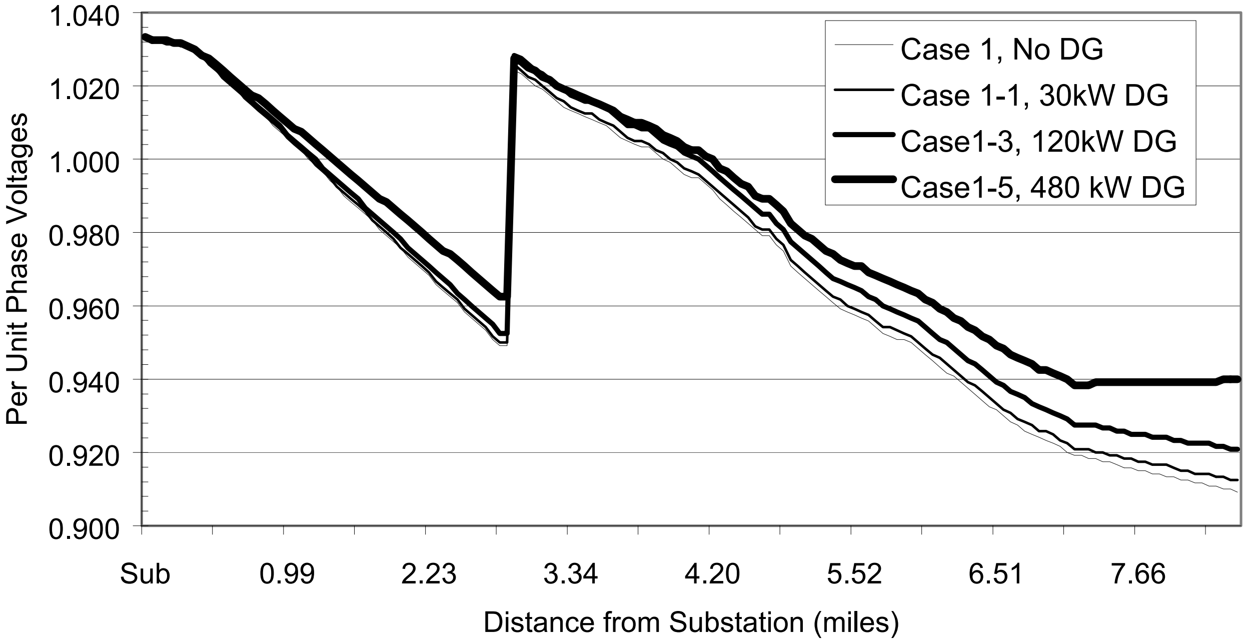

Fig. A.3. Voltage support provided by DER at the load point

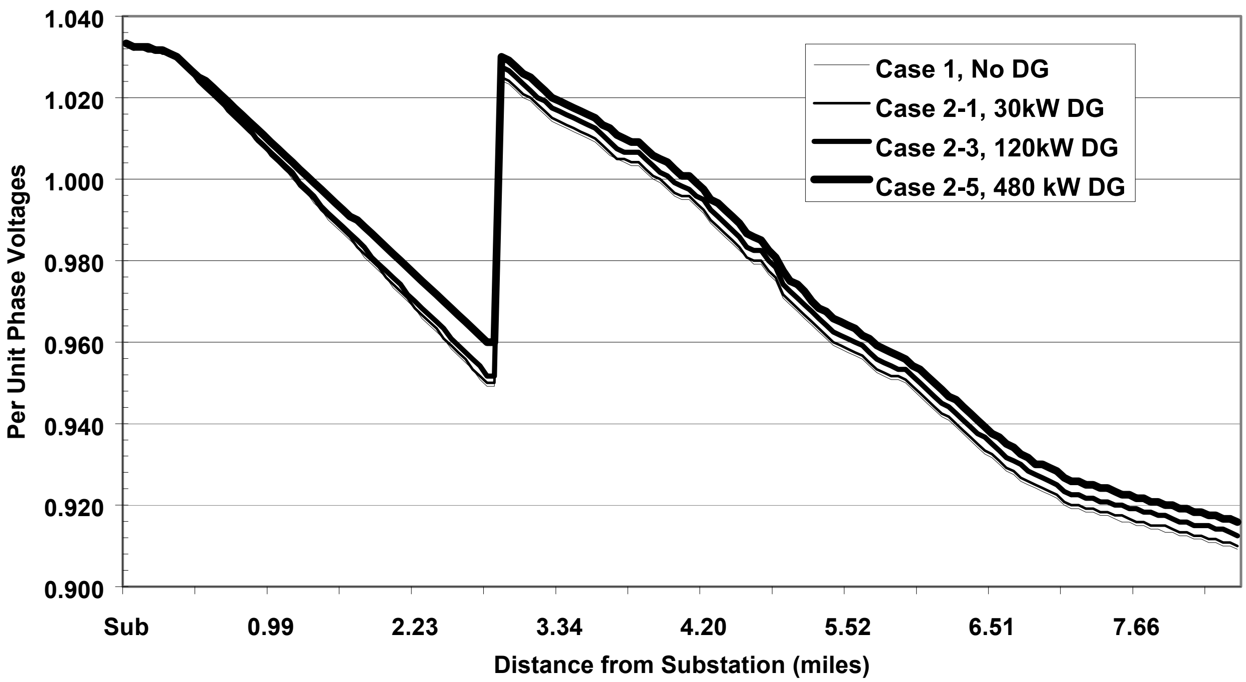

Fig. A.4. Voltage support provided by DER upstream of load

Figure A.5 shows total line losses vs. level of DER penetration (increasing DER size or DER devices) at the load. The bars indicate real and reactive power losses and the line plots indicate percentage of real and reactive power reduction. A strong line loss reduction trend is evident for increasing DER penetration and, at 480 kW of DER generation, line loss reduction exceeds 20% for both real and reactive power (the two being very similar).

Figure A.6 shows total line losses vs. level of DER penetration for the case where the DER is placed upstream of the load. The only significant difference in this case vs. the previous case is that the line loss reductions are more modest. In this case, at 480 kW of DER generation, line loss reduction is under 9% for both real and reactive power.

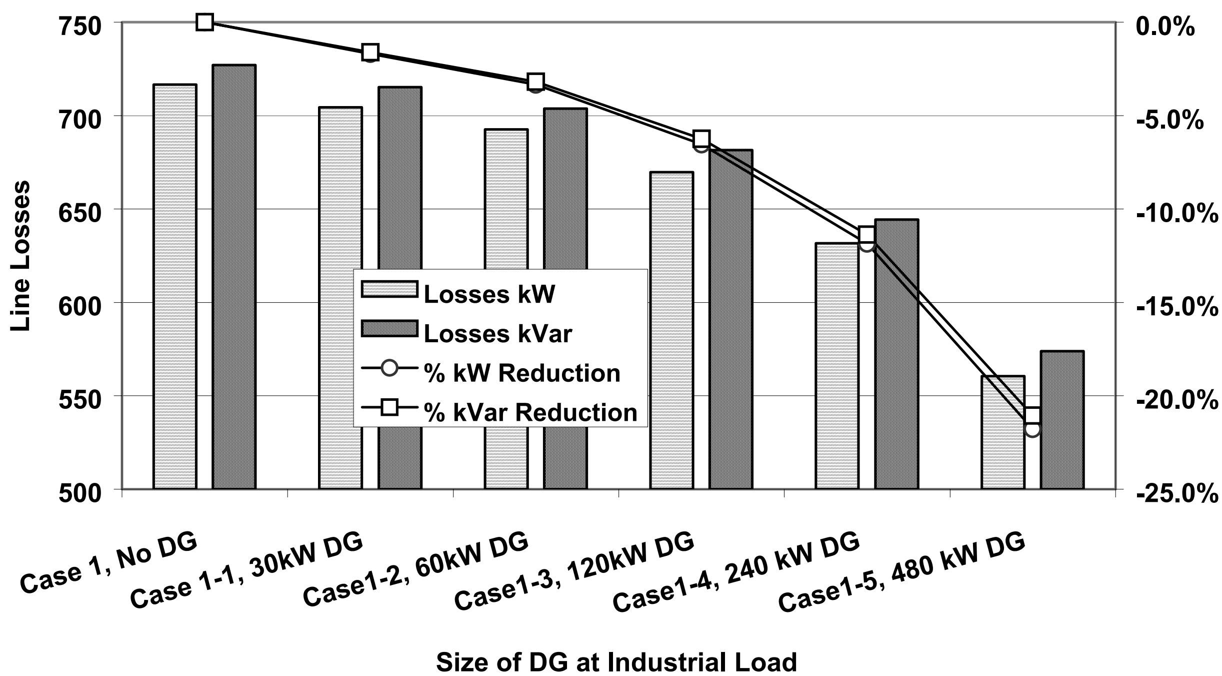

Fig. A.5. System loss reduction provided by DER at the load point

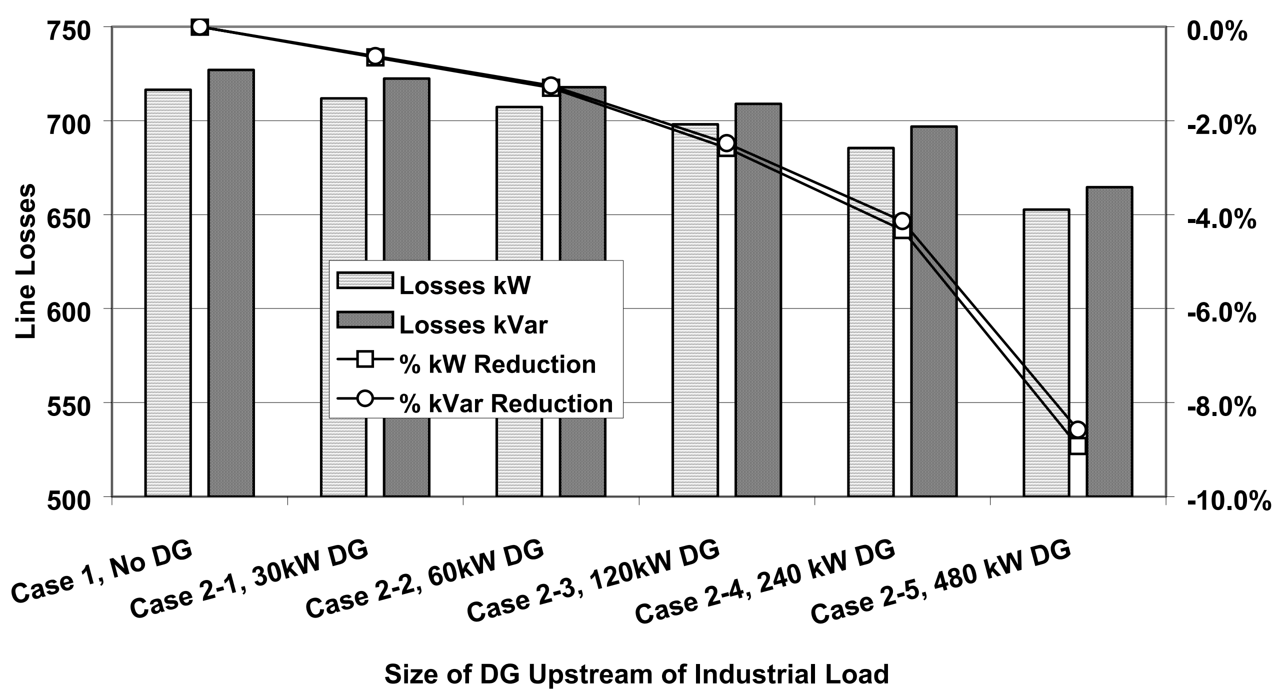

Fig. A.6. System loss reduction provided by DER up steam of load point

Further experimentation with the feeder data has shown that there are diminishing returns for DER benefits as penetration levels are increased. Lower returns per unit of DER kVA are evident for generation capacity relief, voltage support, and feeder loss reduction. Furthermore, these diminishing returns appear regardless of the DER's placement in the feeder (at the load vs. upstream of the load).

Figure A.7 illustrates the diminishing capacity relief for the five levels of DER generation when placed at the load. The five bars indicate substation real power reduction per unit of DER total power and the line plot shows substation *reactive* power reduction per unit of DER total power. Whereas the real power reduction for 30 kW of DER is 1.33 kW/DER kVA, the power reduction for 480 kW is only 1.26 kW/DER kVA. The reduction in capacity relief is diminishing in a pronounced fashion for the two highest levels of DER (i.e., 240 kW and 480 kW). The reactive power case shown by the line plot has essentially the same trend although the actual reduction is 0.69 kVar/DER kVA for 30 kW of DER and only 0.62 kVar/DER kVA for 480 kW of DER.

Figure A.8 illustrates diminishing voltage support for the five levels of DER generation placed at the load. The five bars indicate the percentage[5] of voltage improvement per unit of DER total power. The figure shows voltage improvements of 0.0095% per DER kVA for the three lowest levels of DER (i.e., 30 kW, 60 kW, and 120 kW) but it ultimately decreases to about 0.0048% per DER kVA at the highest level of DER (i.e., 480 kW).

[5] Although the voltage support units seem very small (e.g., 0.004%), keep in mind that these are "per DER kVA" and would be multiplied by large values depending on the size of the DER unit (e.g., 300 kVA).

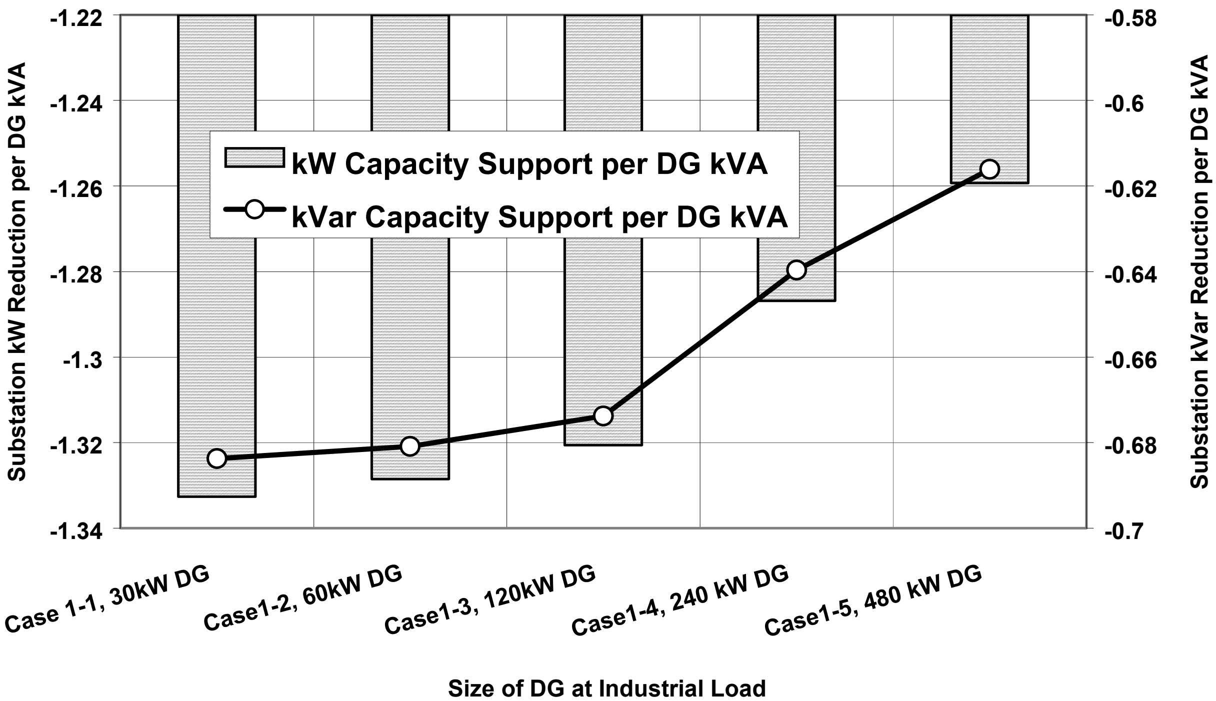

Fig. A.7. Diminishing capacity support from DER at the load

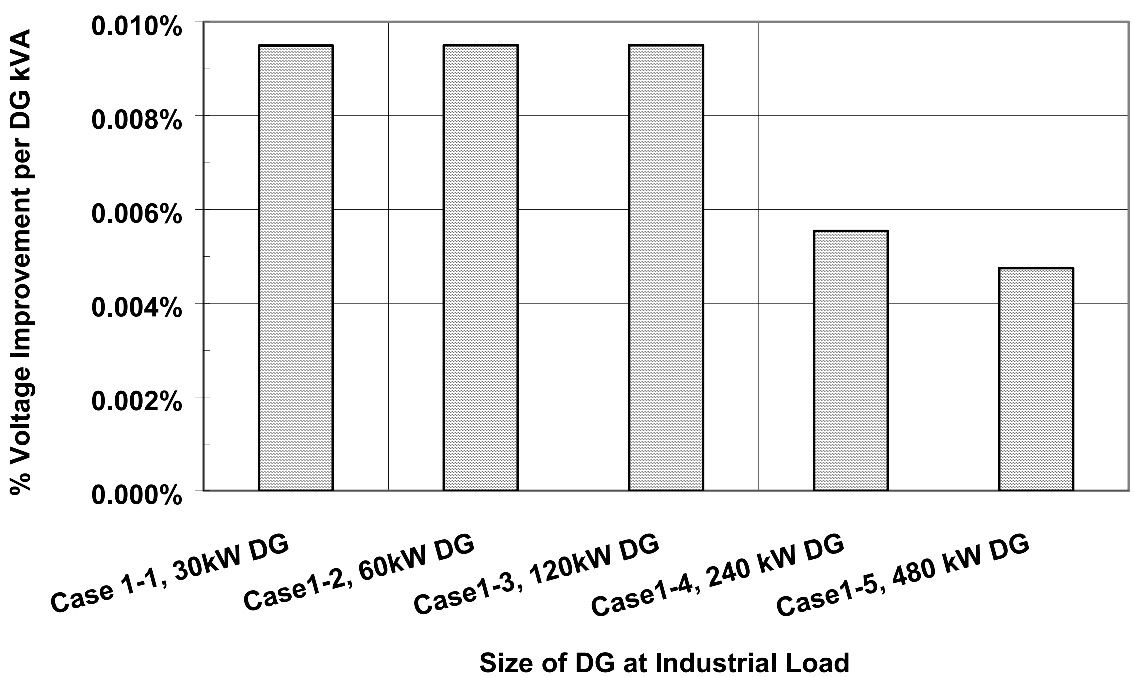

Fig. A.8. Diminishing voltage support from DER at the load

APPENDIX B – Vendor information

Shown below are addresses, phone numbers, examples of a main product, and Internet site addresses for the software vendors that were considered in this study:

Product: *PSS/ADEPT*
Company: Power Technologies
1482 Erie Blvd., P.O. Box 1058
Schenectady, NY 12301-1058 USA
Phone: (518) 395-5000
Website: http://www.pssadept.com/

Product: *WindMil*
Company: Milsoft Integrated Solutions, Inc.
4400 Buffalo Gap Road, Suite 5150
Abilene, Texas 79606
Phone: (915) 695-1642
Toll-Free: (800) 344-5647 (US only)
Fax: (915) 690-0338
Website: http://milsoft.com/

Product: *CYMDIST*
Company: CYME International
3 Burlington Woods, 4th Floor
Burlington, MA 01803-4543
Phone: (800) 361-3627 or (781) 229-0269
Fax: (781) 229-2336
Website: http://www.cyme.com/

Product: *Technical 2000*
Company: EDSA Micro Corporation
11440 West Bernardo Court
Suite 370
San Diego, California 92127
Phone: (858) 675-9211
Fax: (858) 675-9724
Website: http://www.edsa.com/

The following companies, although not selected for analysis, also provide quality products useful in analyzing electric power distribution systems:

Product: SynerGEE Electric
Company: Advantica Stoner
Suite 200, 1910 South Blvd., Charlotte, NC 28203 (other offices in PA & TX)
Phone: (704) 714-3000
Website: http://www.stoner.com/products/synergee_electric.htm

Product: Dapper Demand Load Analysis
Company: SKM Systems Analysis - P.O. Box 3376
Manhattan Beach, CA 90266
Phone: (310) 698-4700
Fax: (310) 698-4708
Website: http://www.skm.com/products/dapper.htm

Product: Distribution Workstation
Company: EPRI Customer Assistance Center (EPRICAC)
Phone: (800) 313-3774 or askepri@epri.com
Technical Information: Don Von Dollen (650) 855-2679
Website:
http://www.epri.com/corporate/products_services/services_training/pwrdeliv_sheets/SO-113872.pdf

Product: Power System Toolbox (PST) & MATLAB
Company: Cherry Tree Scientific Software
RR#5 Colborne, Ontario, Canada K0K 1S0
Phone and Fax: (905) 349-2485
Email: cherry@eagle.ca
Website: www.eagle.ca/~cherry/

Product: ABB Feederall
Company: ABB USA
Phone: (203) 750 2200
Fax: (203) 750 2263
Website: http://www.abb.com/us or
http://www.abb.ch/global/abbzh/abbzh251.nsf!OpenDatabase&db=/global/seapr/SEAPR035.NSF&v=63126&e=us&c=86DA89DC3E8226FD412567FC002FA5F1

Product: Power*Tools for Windows
Company: SKM Systems Analysis, Inc.
Phone: 1-800-232-6789 or contact sales@skm.com
Website: http://www.skm.com/products/index.htm