Simulation Tools for Analysis of Distribution Systems with Distributed Resources. Present and Future Trends

Juan A. Martinez, Francisco de León, and Venkata Dinavahi

Abstract—**Simulation tools for analysis and design of distribution systems with distributed resources (DR) must include modeling capabilities for representing the various DR technologies. Since distribution systems were not designed for the inclusion of DR, most distribution software packages were not designed for the analysis of systems with embedded generation either. Present distribution tools can efficiently cope, for instance, with unbalanced load-flow, but they cannot deal with transient stability. This paper is aimed at reviewing the present status and the future trends of simulation tools for planning, design and operation of distribution systems with penetration of DR.**

***Index Terms*—Distribution Systems, Distributed Energy Resources, Simulation, Modeling.**

I. INTRODUCTION

DISTRIBUTED Energy Resources (DR) are a combination of power-generating technologies, energy storage devices and demand-side measures [1] - [3]. Although DR devices can be used to improve the performance of distribution systems and defer transmission and distribution system upgrade, distribution utilities are concerned with a wide range of issues associated with the interconnection of DR, such as protection coordination problems, islanding conditions, or power quality impact, [4], [5].

Some aspects to be considered are the great variety of generating and energy storage devices [6], the fact that some DR devices are connected to the utility network via a static converter [7], and the intermittent nature of some renewable sources. Depending on size, DR devices are either connected to the MV level or at the LV level.

Simulation tools must combine traditional and new analysis capabilities with a vast number of modeling capabilities for representing the various DR and energy storage technologies, in addition to the conventional distribution system components. The development of a fit-all solution for simulation of distribution systems with DR penetration is a major challenge for software manufacturers.

Distribution software packages were primarily designed for analyzing distribution systems that are radial and were not conceived with DR in mind. There have been, on the other hand, general purpose simulation tools, such as EMTP-type tools [8], that can cope with many of the new modeling challenges, but they are not adequate for some types of studies (e.g., reliability performance, optimization studies), although most EMTP-type tools can perform both steady-state and transient calculations, and even allow users to create custom-made packages by adding capabilities from general purpose and specialized simulation tools [8].

Software manufacturers are updating and expanding tool capabilities taking into account the new simulation challenges. New and specialized tools have been developed to cope with some important distribution system problems related to the installation of DR devices, and a new generation of simulation tools is under development; see for instance [9].

This paper includes sections dedicated to summarize the present status of simulation tools (i) for feasibility studies of distributed generation plants, (ii) for planning, design and operation of distribution systems, as well as (iii) new trends in software development for distribution system studies with DR penetration, including real-time simulation platforms. Section II summarizes the type of studies and models that are required to carry out these tasks.

II. STUDIES AND MODELS

The studies related to the interconnection of DR devices and the development of distribution software packages are performed under the assumption that the basic distribution infrastructure and characteristics will remain as they are today. Therefore, current models can be useful for studies with a high penetration of DR. Performance criteria currently applied at the distribution system level can be also used for assessing interconnected DR operation; however, the possible interconnections to DR are many, and it is not realistic to anticipate all the practical concerns of future designs; for instance, the future assessment of island scenarios could be less restrictive than today.

Distribution packages must include models for conventional power components (lines, cables, transformers, voltage regulators, capacitor banks), protective devices, loads, DR devices and associated controls. Models for energy resources (e.g., wind, solar, biomass, fuel or hydro resources)

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are also needed in several studies; e.g., optimum DR selection and sizing.

The required models for the different study objectives can be described in terms of mathematical equations, but the mathematical description and the parameters to be specified for each piece of equipment will strongly depend on the study objectives; e.g., data required for representing a transformer in transient simulations will be very different from the parameters required in reliability studies.

In this paper, studies have been classified into two groups :

1. *Feasibility of DR plants*: A feasibility study of a project must provide information about design, economical viability, and (environmental and social) impact. The selection of the optimum DR technology and size must consider load characteristics as well as potential energy storage devices, particularly when non-dispatchable intermittent energy sources (e.g., wind, photovoltaic) are involved. When designing the generation and the energy storage system, future load characteristics and system operation modes must be addressed. Obtaining a correct solution may be difficult, since there can be many options, and the work will require an adequate assessment method. Integration of forecasting and simulation techniques is required to investigate the operation of hybrid systems and select the optimum choice.
2. *Analysis, design and operation of distribution systems*: The studies considered in this paper are listed below:
   - steady-state studies;
   - transient-state studies, which can be divided into electromagnetic and electromechanical transient studies;
   - fault-current and protection studies;
   - reliability and power quality studies;
   - planning studies.

   This list is not complete since other studies (e.g., restoration) could be added.

A discussion about aspects to be considered when studying distribution systems with DR penetration follows:

- The power flow formulation may be single- or three-phase.
- The fault contributions from conventional (synchronous and induction) generators can significantly affect both the fault withstand requirements of the equipment and the protection system design [10].
- Distribution systems have not been conceived to have substantial generation embedded, power is intended to flow from the substation down to the load, and substantial DR penetration may reverse the power flow in localized sections.
- A general approach on how to deal with local generation during islanding has not been yet established, although some standard recommend avoiding generation islands [11].
- The study of electromechanical transients in distribution systems is a new subject due to the connection of conventional (synchronous and induction) rotating machines. The list of issues includes interaction between generators, islanding and the effect on global stability. A high penetration level of DRs may impact the stability of a regional grid; for example, a transmission-level voltage dip may cause all generators in the area to trip off, which in turn may hurt the overall stability.
- There is no clear distinction between reliability and power quality, and there is a trend, somewhat independent of DR penetration, to merge these issues.
- Standardized methods for distribution planning with DR penetration are not yet established and research on new tools is required.

Some important aspects to be considered for implementation, selection and usage of models are discussed below.

- In transient studies (e.g., overvoltages, most power quality studies, dynamic simulations), the mathematical description of a power component depends on the range of frequencies associated to the transient process [12]. Different models are required for different types of electromagnetic transients, being the estimation of parameters a major challenge [13].
- The representation of mixed phase (single-, two- and three-phase) connections can be needed for actual cases.
- Although constant P-Q models are used in many studies, a more sophisticated approach for modeling load can be required. For static studies, it is probably sufficient to use a simple polynomial voltage dependency relationship [14]. For slow dynamic studies, simple damping models are probably adequate [15], [16]. Sensitive load models must also include the identification of system sections that can trip off during voltage dips and the safety limits that the loads can be reasonably operated within too. Such limits may be identified with voltage tolerance curves [17].
- Load duration curves are needed for assessment of DR placement and controls. For static studies, assuming a few load levels with specified yearly durations may suffice. This is important for economic studies of freed capacity, which may only be relevant for the few hours of peak load.
- Renewable resources vary by location and in general exhibit seasonal and daily (hour-by-hour) variability. The characterization of renewable resources requires, therefore, data on the available resource, their variability and some geographic and atmospheric factors.
- Various description details are needed for DRs, including capacity and failure rates, voltage dependencies of conventional units (without inverters) and the voltage characteristics of converters. Ramp rates for micro-turbines, fuel cells or battery storage may also be required.

Fig. 1 shows a schematic diagram with the relations between the models and studies listed above. The figure shows also the performance criteria used in these studies.

III. Tools for Selection and Economic Operation of DRs

A DR installation is by default connected to a nearby load and

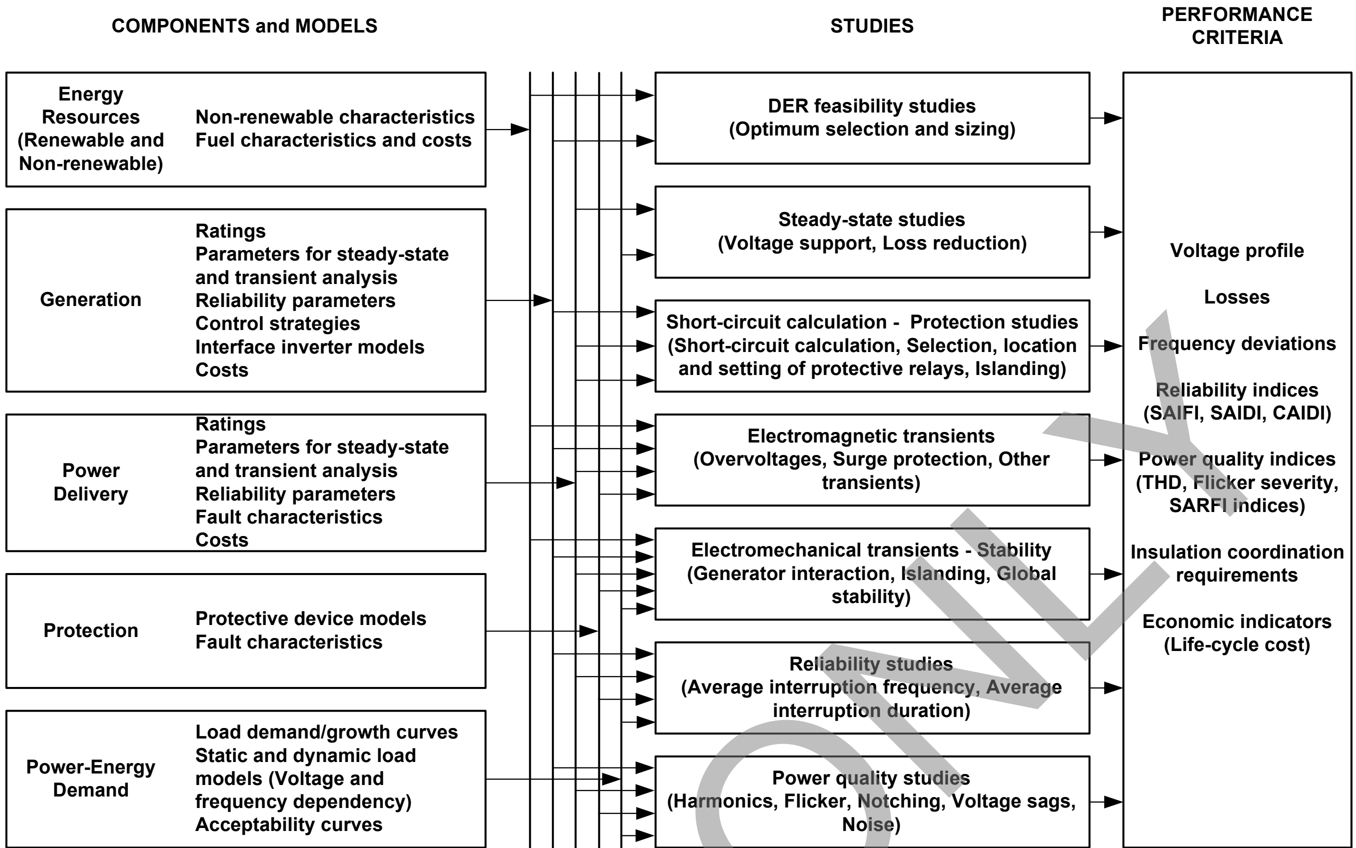

Fig. 1. Models and studies for distribution systems with DR penetration.

may consist of any combination of electrical generation and energy storage technologies. Several simulation tools can be presently used for the design of distributed-power plants. These tools vary in terms of capabilities, structure, scale of application, and computing code/platform. They have been designed as decision support tools that can be used to select the optimal technology and size, and allow users to analyze different technologies and sizes from among the available alternatives to adequately address the trade-offs between economics, financial risks and environmental impacts. The capabilities of the most commonly used packages are summarized in the next paragraphs.

- HOMER is an economic model that compares different combinations of component sizes and quantities, and explores how variations in resource availability and system costs affect the cost of systems with single or multiple sources, which can be either off-grid or grid-connected [18]. This tool allows users to perform three-level studies: simulation, optimization, and sensitivity analysis.
- RETScreen can be used to evaluate energy production, life-cycle costs and greenhouse gas emissions reduction for various renewable energy technologies [19]. The model uses the same five-step standard analysis procedure for each technology: (1) definition of the energy model; (2) cost analysis; (3) greenhouse gas analysis; (4) viability analysis; (5) sensitivity and risk analysis.
- Hybrid2 can simulate several types of electrical loads, wind turbines, photovoltaic, diesel generators, battery storage, and power conversion devices [20]. A variety of different control strategies may be implemented to incorporate detailed diesel dispatch as well as interactions between diesel generators and batteries. Hybrid2 allows users to analyze also grid-connected systems and provides a financial model to calculate the economic worth of the project.

Other tools for economic analysis and feasibility of distributed generation are D-Gen PRO or the Distributed Generation Analysis Tool.

Simulation tools for feasibility analysis and design of either grid-connected or standalone photovoltaic (PV) panels should be also considered. The package list for PV system analysis and design could include, among others, PV-FORM, PVGRID, PVWATSS, PV F-CHART, PV-DesignPro, SolarPro, PV*SOL, PVSYST, GridPV, NSOL or WATSUN-PV. For a survey of tools for PV applications, see [21].

The results derived from these tools can be complemented by using other tools developed to optimize costs and operating efficiencies under varying system operating conditions, or to estimate the market potential of some distributed generation technologies. The list could include DER-Customer Adoption Model (DER-CAM) [22], DIStributed Power Economic Rationale SElection (DISPERSE), Clean Energy Technology Economic and Emissions Model (CETEEM) [23], Wind Deployment Systems (WinDS), or Hydrogen Deployment Systems (HyDS).

IV. Tools for Planning, Design and Operation of Distribution Systems with DRs

Current limitations and future needs for simulation tools are discussed in the following paragraphs. Each part is dedicated to a primary function.

Load flow: DR penetration provides several challenges to standard distribution system load-flow software: it must be able to model voltage-control equipment, unbalanced systems, single-phase loads, single- and two-phase lines, and any transformer connection. In addition, it must handle load and generation profiles, or accurate generation models. The primary needs for distribution system load-flow software with DR penetration are to assess voltage profile, losses, and capacity issues for arbitrary distributed resource studies, as well as to support subsequent analyses: reliability, protection coordination, transient stability or harmonic distortion levels. On the other hand, the calculations can be over an arbitrary time period. Although a 1-hour step is used in distribution planning studies, the duty-cycle model can be used for modeling wind generation, in which the step size might be as short as 1 second. Adding significant levels of non-dispatchable generation to the distribution system increases the complexity of the analysis.

Fault-current analysis: Fault-current analysis may be performed by using a standard short-circuit program; however, DR addition increases the time varying nature of the fault current, and a more sophisticated approach is advisable. The short-circuit contribution of DRs may be important. Short-circuit contributions of inverter-based distributed generators vary by inverter design. The list of capabilities of a fault-current simulator must include a broad array of features: single- and three-phase analyses; DC analysis; balanced and unbalanced networks; minimum and maximum faults; derating of breakers; arcing fault contributions; accurate and flexible DG models; a full range of transformer connections; interface with protection and reliability software; fault current flow under numerous switching states; overvoltage estimation during faults [24].

Protection: Radial distribution systems are generally protected by time overcurrent schemes that assume that the fault current flows from the substation transformer toward the fault, with little if any fault contribution from the load [25]. Coordination among devices is achieved through variable time delays in each protective device. Present software packages include time-overcurrent coordination (TOC) capability and a library of curves for relays, fuses, and reclosers. However, protective devices need to be re-coordinated or re-designed in situations when DR generate significant fault currents (fault current supplied by local generation will increase the fault current flow at the fault location while reducing the fault contribution from the utility source [10]), since this protective approach can fail under some conditions. Since TOC protection will remain the preferred protection strategy, software tools should be adapted to recognize the effect caused by the DR installation.

Reliability: A reliability tool uses equipment outage frequency and repair time statistics to calculate standard industry customer and system reliability indices [26] - [28]. The results can be used to evaluate the performance of a network configuration or a protection scheme. Capabilities available in some distribution reliability planning tools were analyzed in [29]. The list of areas recommended in that report for future research and improvements included full three-phase representations; integration with advanced metering systems and information for characterizing load profiles and for forecasting; built-in equipment reliability databases; addition of risk assessment methods, economics of reliability, and economics of different maintenance and operation approaches for improving reliability; automatic reconfiguration algorithms; calculation of voltage dip and momentary interruption indices.

Power quality: Very different tools have been used to date for analysis of harmonics, flicker, voltage dips and any type of current and voltage waveform analysis. Time-domain EMTP-type tools are a very common approach in power quality studies [30], since they can accurately represent almost any scenario. But for some cases, mostly for harmonic studies, a frequency-domain approach can be faster and accurate enough. Harmonic analysis may also be performed by using a dedicated tool [31], or a capability implemented in some commercial packages [32]. Some programs only model balanced three-phase harmonics; however, for analyzing multiple single-phase DR applications, modeling all phases independently is important. Another consideration is how to model generators since they can be a sink of harmonics. Synchronous generators are normally modeled by means of their negative-sequence reactance, while induction generators are represented by means of the locked rotor inductance. Flicker analysis is important for generation with fluctuating output, since it may be the limiting factor for certain types of generators. Modeling multiple generators is another challenge, since the flicker generated by some units may be totally independent, but others, such as PV, may show a high correlation since they will be located close together geographically. Voltage dip analysis can be also performed by means of simulators with capabilities for short-circuit calculations.

Overvoltages: Several types of overvoltages can occur in a distribution system with local generation (ground-fault overvoltage, load-rejection overvoltage, ferroresonance [33]); under some conditions, these overvoltages can be severe enough to damage equipment and customer loads. There are, on the other hand, overvoltages (e.g., lightning) not caused by generation whose effect on distribution equipment, included generators, can be very significant. Overvoltages are generally simulated by means of a time-domain solution technique, with EMTP-type tools being the most common approach [34], [35].

Transient stability: Stability programs for distribution systems are not yet available, so one way to analyze these situations is to use a positive-sequence stability program such as PSS/E or ETMSP. Another option is to use time-domain simulation tools, such as EMTP-type tools, which would allow more detailed models, but would take much more effort to set the models up.

Planning: A distribution planning package is a set of tools that can be grouped into three distinct categories [36]: (1) electrical performance simulators; (2) analytical tools for reliability analysis; (3) decision support methods to assist in evaluating and selecting from the possible alternatives. Present planning tools can be used to assess the trade-offs between deploying small DR units and building new or upgrading existing networks, or building new conventional central power plants. The integration of DR devices must take into account multiple factors, such as the existing resources, costs, or the environmental impact. Geographic information systems (GIS) may solve these problems [37], since they can handle information of very diverse origins and formats (maps, photographs, satellite images, tables, records, or historical time series) and offer a variety of structured data models suitable for the storage, manipulation, and analysis of the information needed in DG planning. GIS tools can perform calculations aimed at determining the optimal location for DG facilities with a given technology (i.e., photovoltaic or wind systems), or be used in applications of spatial load forecasting that allow users to identify areas with a future increase in demand [37].

V. Future Trends

A. Real-time simulation platforms

Power quality and stability issues that can arise in distribution systems equipped with multiple DRs interfaced through power electronic converters cannot be accurately analyzed with traditional tools [38]. Due to the complexity of DR configuration, modeling requirements, and controller functionality, traditional off-line software tools can be very time consuming. Real-time simulators can significantly speed up the simultaneous simulation of fast transients caused by power electronic systems [39], [40], faults and equipment switching, as well as the slower electromechanical and voltage stability phenomena. Due to rapid advances in digital processors, parallel processing, and communication technology, these simulators are becoming increasingly popular for a variety of applications. They are useful for testing manufactured equipment in a hardware-in-the-loop (HIL) configuration or for rapid control prototyping (RCP), where a model-based controller interacts in real-time with the actual hardware. Currently, real-time digital simulators are used to address simulation needs for a large spectrum of power system studies [41] - [43], such as to test protective relays and digital controllers for power electronic based FACTS, Custom Power and HVDC systems in closed-loop, and for transient simulations of large-scale systems aimed specifically at analyzing a variety of operating scenarios and fault conditions.

Commercial packages and simulators, such as RTDS and OPAL-RT, are at the forefront of this rapidly expanding market. Significant advances in the general purpose processor technology and the development of accurate power system models in mathematical modeling packages such as MATLAB/Simulink are driving the current trend of using PC-clusters for real-time and hardware-in-the-loop simulations. Field programmable gate arrays (FPGAs) offer high-speed high-precision simulations in standalone configurations [44], [45], and run as accelerator components in PC-cluster simulators.

Although not much experience is already available in the simulation of DR devices, these simulators have been proved to be very useful in the simulation of wind farms [46] - [48], and multi-machine ship power generation [49]. The possibility of using a single simulation platform that could reproduce the performance of a complete distribution system with several inverter-based interfaced DR units in real-time is a challenge for developers and manufacturers. Testing complex integrated power electronic systems may be one of the biggest future challenges.

The new generation of real-time simulation platforms should be capable of simulating long-term phenomena simultaneously with very short transients and fast switching events requiring sub-microseconds time-steps, performing multi-domain and multi-rate simulation (i.e., capable of simulating the dynamic response of all aspects and components affecting the system performance and security assessment), and integrating high-end general purpose processors with reconfigurable processor technologies, such as FPGAs, to achieve the best performance at the best price [50].

B. Multi-agent simulation tools

The coupling of power systems and markets impacts broad areas of the electric power industry. Present simulation tools do not provide the analysis capabilities needed to study the forces driving change in the energy industry. The combined influence of information technology, DR devices, energy markets and new business strategies results in very high uncertainty. A tool under development to address these simulation gaps is GridLAB-D [9], a simulation environment that can be integrated with a variety of third-party tools, and that combines end-use and power distribution automation models. Its capabilities will incorporate modules to perform power flow calculations, models for end-use appliance technologies, equipment and controls, retail market models, energy operations (e.g., distribution automation, load-shedding programs, and emergency operations), models of SCADA controls and metering technologies, external links to other simulation and modeling system or graphical user interface for creating input models and for execution and control of the simulation. These capabilities will allow users to study the potential and benefit of deploying DR devices, the interactions between multiple technologies (how under-frequency load-shedding remedial action strategies might interact with appliance-based load-relief systems), or the interaction between physical phenomena, business systems, markets and regional economics, and consumer behaviors.

C. Multi-domain simulation tools

The variety of generation and energy storage technologies that will interact in future distribution systems will require the application of simulation tools capable of connecting and interfacing applications from different types of physical systems (mechanical, thermal, chemical, electrical, electronics). Several packages offer a flexible and adequate environment for these purposes, and they can be used to develop custom-made models not implemented in specialized distribution power packages.

The list of tools includes from programming languages for modeling complex and heterogeneous physical systems, such as Modelica or INSEL (Integrated Simulation Environment Language), to simulation engines, such as VisSim or TRNSYS (TRaNsient SYstem Simulation Program). All these tools have been applied to the development of models or specialized tools and libraries for simulation of renewable energy-based generation [51] - [54].

MATLAB/Simulink is a well known environment that can be included in this category. This tool has capabilities for solving large scale systems and provides an open architecture which can be used for rapid testing of new solution methods and prototyping of new models. Several MATLAB-based toolboxes have been developed for DR applications; e.g., SimPowerSystems [55], Wind Turbine Blockset [56], PV Toolbox [57] or CETEEM [23].

Capabilities for multi-domain simulation of DR devices can be also found in other packages that offer different environment and solution methods. Open connectivity for coupling to other tools, a programming language for development of custom-made models and a powerful graphical interface are capabilities available in some tools that can be used for expanding their own applications and for developing sophisticated DR models. These capabilities are available in several EMTP-type tools and in other circuit-oriented packages [58].

The above tools are powerful enough, but one should not expect their application to the analysis and design of a whole distribution system, for which dedicated distribution software packages are more adequate and efficient. These tools could instead be applied for the development and testing of highly detailed and accurate models of DR devices.

VI. Conclusions

The integration of DR devices into distribution systems is a major challenge. Present simulation tools can help on any task related to feasibility studies of DR installations, as well as on planning, design and operation of distribution networks with DR penetration.

Presently, several different software tools must be used to analyze the electrical performance of distribution systems and DR devices, so an all-in-one analysis package or a suite of programs that could operate on the same database would obviously facilitate the study of the same system for different types of calculations. Voltage regulation, harmonics or overcurrent coordination issues can be analyzed with standard distribution analysis tools. Other issues, such as islanding, ferroresonance or stability require more advanced modeling and analysis, e.g. an EMTP-type tool. In any case, time-domain simulation will continue playing a major role in assessing system performance and security for both normal and abnormal operating conditions.

An increasing use of power-electronic systems for interfacing the DR to the grid will justify the application of real-time simulation platforms in design, analysis and testing tasks. Multi-domain simulations are emerging as a powerful approach for the study and design of technologies in which mechanical, thermal, electrical, electronic and control subsystems can play an important role.

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