Simulation Tools for Analysis and Design of Distribution Networks with Distributed Energy Resources

Juan A. MARTÍNEZ-VELASCO [1], Francisco de LEÓN [2], Venkata DINAVAHI [3]

1) Univ. Politècnica de Catalunya, Spain

2) Polytechnic Institute of NYU, USA

3) University of Alberta, Canada

Summary: Distributed energy resources (DER) are a combination of distributed generation, energy storage and demand-side measures. DER can be used to help utilities solve problems on the distribution system by supporting voltage, reducing losses, providing backup power, improving local power quality and reliability, or deferring distribution system upgrade. They present, however, some important drawbacks such as new protection coordination problems, complicated operating procedures, or intermittent nature of renewable sources. All these issues complicate the analysis of distribution systems with a high penetration of DER devices. Required simulation tools must therefore combine analysis and modelling capabilities for representing the various DER technologies accurately.

Since distribution systems were not designed for the inclusion of DER, most distribution software packages were not designed for the analysis of systems with embedded generation either. Present software designed for the study of distribution systems can efficiently cope with unbalanced load-flow and short circuit calculations, load growth studies, or system restoration and contingency analysis. However, they do not deal with transient stability and small signal stability because traditionally there was no generation at distribution level. This situation is changing, software manufacturers are updating and expanding tool capabilities to take into account the new simulation challenges, and new and specialized tools have been developed to cope with problems related to the installation of DER devices. This paper is aimed at reviewing the present status and the future trends of simulation tools for analysis and planning of distribution systems with penetration of DER, including market-oriented analysis and real-time simulation.

Key words:
Distribution Systems,
Distributed Energy Resources,
Distributed Generation,
Simulation,
Modelling

1. INTRODUCTION

The term Distributed Energy Resources (DER) is used in this work to refer to a variety of power-generating technologies that are often combined with energy storage systems and demand-side measures. It is worth mentioning that other terms such as Distributed Generation (DG) are also used, and that there can be differences in the way they are used in the literature [1 - 6]. The term DG will be used in this work to refer to generating technologies only.

DER devices range in size and capacity from a few kilowatts up to 50 MW, and include several technologies, from both the supply- and the demand-side, that can be installed at or near the location where the energy is required. DER devices can be used to solve problems on the distribution system by supporting voltage and reducing losses, providing backup power and local control of electricity delivery and consumption, saving fuel, reducing purchase power from supplying utility or enabling a more efficient utilization of waste heat in combined cooling, heating and power (CHP) applications, improving local power quality and reliability, providing ancillary services, and deferring transmission and distribution system upgrade, as well as improving reliability [1 - 11].

There is, however, a wide range of issues associated with the interconnection of DER to the distribution system that concern power utilities. The list includes voltage control and stability problems; increased fault duty on circuit breakers and protection coordination problems; islanding conditions, which are not allowed in standards; power quality issues, such as harmonics distortion and flicker; safety of personnel; overvoltages, e.g., ferroresonance; increased complication in distribution planning; intermittent or stochastic nature of some renewable distributed sources; impact on the low voltage ride through capability of the transmission system [7 - 11].

To avoid many of these inconveniences, to take advantage of the new generation technologies and to achieve an optimum power quality, the concept of microgrid was introduced several years ago. A microgrid is a hybrid system with embedded generation that generally operates connected to the grid, but it can eventually (in case of a disturbance) operate as a standalone system; i.e., disconnected from the grid [12, 13]. This can guarantee continuity of service and a high quality of voltage to loads associated to the microgrid in case of disturbance or blackout.

An important milestone is the IEEE Std 1547, a set of standards that is becoming a worldwide norm for interconnection equipment that connects DER to a power system [14, 15]. The IEEE standard specifies the type, production, and commissioning tests to be performed to prove the interconnection functions and equipment of the DER.

One important aspect to be considered is the great variety of generating and energy storage devices, which represent a challenge for modellers [3]. In addition, the behaviour of the various DER technologies can be very different from each other (e.g., photovoltaic installations have no moving parts, while a wind energy conversion unit is a complex mechanical system whose dynamic behaviour is not easy to represent) [4 - 6]. Finally, some generating units are connected to the utility network via a static converter [16 - 18], while others can be connected directly. All these issues complicate the analysis

and simulation of systems with a high penetration of DER. It is therefore very important to understand how both the utility system and DER devices will respond to all type of events (e.g., grid disturbances, faults, loss of generation).

Depending on size, DER devices are either connected to the MV level or at the LV level. This presents a particular challenge for software developers because worldwide the distribution systems have different structures [19 - 23]. In rural areas the distribution is radial and could be single-phase or three-phase. In urban areas the distribution is three-phase, but it could be radial or meshed as in the case of some secondary networks. Worldwide the hardware is much the same and systems have similar voltages and power carrying capabilities. The main difference is the layout. When comparing European systems with North American systems one realizes that a European distribution system has more low voltage kilometres and a North American system has more high voltage kilometres. The secondary earthing in North America is multi-point, while in Europe single-point earthing is preferred. In North America, the primary is generally earthed and in Europe there are four earthing techniques: (1) solidly earthing; (2) earthing through an impedance; (3) earthing through a suppression Petersen coil (tuned to resonate); (4) isolated neutral (un-earthed). Considering this diversity, the development of a fit-all solution to DER simulation and analysis is a major challenge. Simulation tools must therefore combine analysis capabilities with a vast number of modelling capabilities for representing the various DER and energy storage technologies, besides the conventional distribution system components.

Distribution software packages were primarily designed for analyzing distribution systems that are radial and were not conceived with DER in mind. In some cases they provide a mechanism for modelling DER in the form of negative loads via a PQV model for an induction or synchronous generator model. The 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 dips) is a very serious drawback. There have been, on the other hand, general purpose simulation tools, such as EMTP-type tools [24], based on a time-domain solution technique, that could cope with most of these modelling challenges; that is, users could take advantage of capabilities for either representing or developing custom-made models of DER devices, including inverter-based interfaces. However, they are not adequate for some types of studies (e.g., reliability performance, optimization studies or slow dynamic transient stability simulations), 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 [24].

This scenario is changing: 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 DER devices, and a new generation of simulation tools is under development; see for instance [25].

The diagram shown in Figure 1 will be used to classify the studies covered in this work and the organization of this paper. Note that the blocks inserted in the diagram include bulk power generation and transmission. Although these functions are not covered in the paper, they can affect or be affected by a high penetration of DER devices at the distribution level.

The figure divides the studies into three groups, namely: economic operation and feasibility studies of DER installations; planning, design and operation of distribution systems with a penetration of DER devices; market-oriented studies. Neither the design of distribution system components nor the design of DER devices are covered in this paper. This categorization of tasks and tools is not strict. In fact, DER feasibility studies (i.e., optimal selection and sizing of DER devices) can be also seen as a planning task.

The paper has been organized as follows. Section 2 summarizes the main types of simulations and component models that are required in distribution system studies with a penetration of DER devices. Section 3 is dedicated to describe the capabilities of the most common software packages by categorizing them according to the classification of studies presented in Figure 1. The subsequent section is dedicated to introduce real-time simulation platforms and its application to DER studies. Section 5 discusses the new trends in software development for distribution system studies with DER penetration.

Several surveys on simulation tools for analysis and design of distribution systems and DERs have been produced during the last years [8, 24, 26 - 32]. This paper covers more topics than any of those references, but, due to space limitations, some parts are covered with less detail. Readers are referred to the above references for more information on simulation tools.

2. DER STUDIES AND MODELS

2.1. Studies

The studies related to the interconnection of DER devices as well as the development of dedicated software tools are performed under the assumption that the basic distribution infrastructure and characteristics will remain as they are

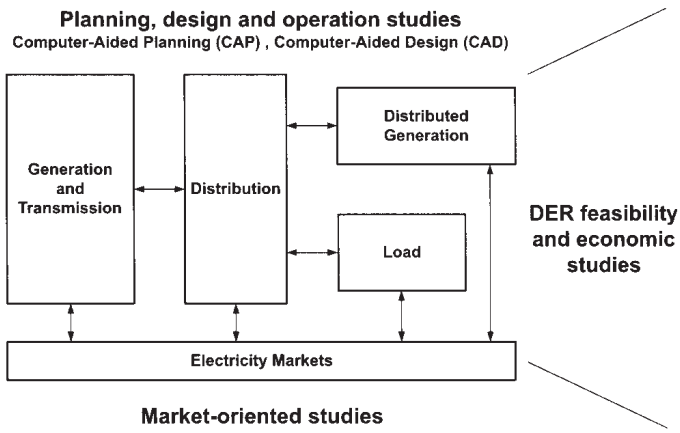


Fig. 1. Diagram of a power system with DER penetration

today. Therefore, current distribution circuit and load models can be useful for studies with a high penetration of DER. Performance criteria currently applied at the distribution system level can be also used for assessing interconnected DER operation; however, the possible interconnections to DER 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. System studies can be classified in many ways. In this work they have been classified into eight groups, whose main goals are detailed in the following paragraphs.

Steady state studies: Steady state analysis is intended to be carried out with power flows appropriately modified to capture the behaviour of DER devices and voltage-sensitive loads such as induction machines. The power flow formulation may be single or three phase. Goals of steady state analysis may include, in addition to voltage support and loss reduction studies, other tasks such as finding an optimal location for a micro-source, analyzing the sharing strategy that the units have during an island, or analyzing the harmonic impact of an inverted-based DER. Voltage support studies may include estimates of the benefits of reduced imbalances and improvements in voltage profiles. Voltage support tends to be mostly a concern on long feeders with remote loads. In such case, appropriate placement simply requires locating a unit near the load centre. Proper control of these units can be critical to prevent large voltage fluctuations. Energy costs are needed to assess the value of reduced losses and freeing capacity. Feeder loading conditions vary widely, so the cost of freeing capacity to deliver real power on heavily loaded feeders using DER should be compared to the typical costs for substation and feeder upgrades. Placement of units for optimal loss reduction tends to correlate with optimal placement for freed capacity only if the heavily loading period is of long duration. Assessment needs to consider placement as a trade-off between loss reduction and freed capacity.

Fault-current and protection studies: A fault-current analysis provides the information necessary to design the overcurrent protection system. 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 [33, 34]. Depending on their type and size, DG can cause increases in fault current levels, so that withstanding and interrupting capabilities of protective devices need to be re-evaluated. An important feature to take into account when studying DER addition is that distribution systems were not conceived to have substantial generation embedded; that is, the flow of power is intended from the substation down to the load, and substantial DER penetration may reverse the power flow in localized sections. This is very important because the network protectors can trip preventing flow reversal. Some utilities have already guidelines on how the interconnection can be done [35], but a general approach on how to deal with DG in a determined zone have not been yet established. In islanding situations DG will provide sufficient fault-current levels for reliable protective system operation. Since standard models for both synchronous and induction generators are well established, this impact can be usually assessed. However, accurate models are not always available for inverters, and some discussion is under way on their appropriate performance during faults. On one hand, inverters should not provide fault currents so that the time-current curve coordination of the existing protective devices will not be affected; on the other hand, inverters should mimic a similarly sized synchronous generators during faults to maintain sufficient fault current to protective devices under all system configurations. This second option would cause a fast separation of the DG during system faults; however, DG dropping during a fault can have undesirable and unnecessary consequences for systems with high DER penetration [26].

Overvoltage studies: Although several types of overvoltages can occur in a distribution system [26], those specifically related to DG or that can be exacerbated by DG belong to any of the following conditions: ground-fault overvoltage, load-rejection overvoltage, ferroresonance [36, 37]. They may occur individually or in various combinations depending on the distribution system design. Under some conditions, these overvoltages can be severe enough to damage equipment and customer loads. There are other overvoltage causes (e.g., lightning) whose effect on distribution equipment can be very significant. Different models are required for different types of overvoltages, being the estimation of parameters a major challenge.

Stability studies: They are needed to obtain information on the system to events such as failure in the grid connection and island mode transfer; removal of single phase voltage dips due to unbalanced loads or to distant faults; removal of three phase voltage dips due to motor loads [26, 38]. These studies are to be carried out with a transient analysis tool representing all the control details in generating sources. It is important to define the sensitivity of the loads so that it is possible to identify which loads can be shed during islanding. Detection of grid connection failure is relevant for coordinating the breakers that are responsible for shedding part of the network. Reconnection to main grid after islanding is also important for assessing stability and meeting the requirements of sensitive loads. One important goal is to gain an insight on the DER design in order to achieve the desired performance while minimizing ratings. Another problem to be faced is the voltage control under voltage dips due to machine load changes and faults. In particular, the induction machines need to be fully modelled with an electro-mechanical representation to analyze problems such as motor starting and load change tracking.

Reliability and power quality studies: There is no clear distinction between reliability and power quality. Historically, reliability has been determined on the basis of sustained interruptions, while momentary interruptions have been considered power quality issues. Power quality also covers voltage dips, voltage and current waveforms (e.g., harmonics), and flicker. Different reliability indices have been proposed to measure frequency and duration of sustained interruption [39], frequency of momentary interruptions, or frequency and depth of voltage dips [40]. The first two categories have traditionally been considered reliability issues, while the last two have been considered power quality issues. On the other hand, there is a trend, somewhat independent of DER penetration, to merge these issues. The need for this is

reinforced by the experience according to which the major monetary losses are due to momentary interruptions and voltage dips rather than sustained outages [27].

Distribution planning: The objective of distribution planning is to provide an orderly and economic expansion of equipment and facilities to meet load forecasts with an acceptable level of reliability [41]. Decisions to be taken in distribution planning include system expansion, optimal location of substations and feeders, optimal feeder and substation design, optimal allocation of load and substation capacity. According to [41], planning may involve up to five basic steps: (1) identifying the problem; (2) setting the goal; (3) identifying alternatives; (4) evaluating alternatives; (5) deciding upon, approving, the alternative to be selected and executed. Planning models have been divided into those carried out under normal conditions and those including contingency/emergency issues [42]. Expansion of distribution networks is based on demand projections and needs for equipment replacement; load forecasting and capacity planning are in general the initial steps of a distribution planning process, but tasks such as feeder and substation reliability, asset replacement, and power quality must be also included. DER devices offer a solution to the limitations in the capacity of distribution systems, defer the need for investment at both transmission and distribution, and may improve the reliability of the overall system by increasing generation capacity reserves. In the longer term, power plant companies can reduce investments and meet future growing demand by investing in DER units, which can be installed with shorter times. Standardized methods for distribution planning with DER penetration are not yet established and research on new tools is required.

DER feasibility: The selection of the optimum DER technology and size must be based on several aspects (technical, economic, environmental, and social) and consider load characteristics as well as potential energy storage devices. This step is particularly important 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 to assess the efficiency and its impact on the DER performance. Obtaining a correct solution may be very difficult, since there can be many criteria methods adequate for this task, and the work will require an adequate assessment method. Integration of forecasting and simulation techniques is required to investigate the operation of hybrid systems.

Market-oriented studies: Market liberalisation offers DG producers the possibility to sell power directly to customers and increase competition [43 - 48]. DG producers have a variety of options where to sell electricity if they do not use it for their own purposes. Electricity may be directly sold to customers, to power exchanges, to suppliers and aggregators, or to marketers. These different possibilities affect metering, communication, trading practices and the technology involved in connecting DG to distribution network. Electricity markets favour some DG attributes such as shorter construction lead time, low capital costs, flexible operation and possibility to expand production. In addition, DER may benefit from high electricity prices, because it encourages development of new DG capacity. On the other hand, it can be hard to DG to compete with centralised generation because of the higher costs. Even when DG is less expensive, access rules and transmission costs can raise costs, although DG may be advantageous if it is combined with waste heat utilization.

DG and demand response may participate in market balance. However, the risk of market imbalance increases with a large number of intermittent DGs, whose production is difficult to predict. Balancing power arrangements and penalties from imbalances can be a barrier for DG to enter wholesale markets. By shortening the time frame for announcing estimated production, DG can predict production more accurately. Since the total sum of imbalances of individual generators is higher than the actual imbalance in the system, and the net imbalance is reduced when several DG units work together, pooling of small generators should be permitted [43]. DG and demand resources may be able to offer some ancillary services or help for transmission and distribution constraints [48]. There could be, however, some practical limitations; e.g., the size limit that is required from service providers. As a rule of thumb, DG is not able to maintain the right level of reliability and quality at reasonable costs, but it is capable of producing active and reactive reserve power. According to [49], the small-scale local producer business model for renewable DG is profitable for all actors involved, even when changes in the network tariffs occur, since a decreasing reserve of power generation capacity creates new business opportunities for DG, which may play an important role in balancing services. DG business generally improves if local DG producers are able to sell and trade directly on a power exchange market, and regulatory policies may directly impact the feasibility and attractiveness of DG business models.

Work has been dedicated during the last decade to modelling DER business and their impact into electricity markets [50 - 56]. European regulatory environments, trading situations and DG business models have been studied in several EU funded projects, like EU-DEEP [43], Sustelnet

Table 1. Distributed energy resources in electricity markets.

Strengths	Environmental benefits
	Additional products in the market
	More competition
	Decrease in prices
	More revenues
Weaknesses	High costs
	Non-mature technologies
	Small generation volume for trading
	Non predictability and intermittence
	Impact on network operation and design
Opportunities	Green energy (wind, photovoltaic and biomass)
	Peak shaving
	Ancillary services
	Aggregation
	Trade on power exchange
Threats	Policy
	Negative attitude by large companies
	Complex operation of distribution networks
	Transmission congestion

[44], BUSMOD [45] or ENIRDGnet [46]. A summary of conclusions from these projects is presented in Table 1. The future of electric power markets with a high penetration of DER was also explored in an EPRI report issued in 2003 [57]. Policy programs proposed in several US states to encourage DER penetration and their participation in retail markets was summarized in [58].

Table 2 summarizes the studies described in the previous paragraphs, except those related to feasibility and market studies. The table shows the performance criteria and the adequate models for each study. Although this list covers most of the main studies, it is by no means complete. Other studies to be considered are contingency reserve or system restoration.

2.2. Models

Software tools must include models for power components (lines, cables, transformers, voltage regulators, capacitor banks), protective devices, DER devices and loads. Modelling capabilities should represent a wide range of load models, covering from office loads to large motors. The machine loads will usually have a three phase connection to the network, but smaller loads will be also connected on a per phase basis. Data for all components must be identified and voltage level across the system must be defined. Simulation should cope with up to three voltage levels: the grid connection point at high voltage, which is stepped down to the feeder level and further reduced to low voltage load level. Sources for induction and synchronous machine data can be found in the classical literature. Data from the literature is also available for transformers, lines and cables. Modelling of energy resources (e.g., wind, solar, biomass, fuel or hydro resources) are also needed in several studies. They are a fundamental aspect in feasibility studies, but some of them may be also used in transients simulations.

An important drawback in many studies may be the lack of reliable information. In general, DER manufacturers consider that the information regarding the parameters of generators and control systems is proprietary information. Therefore, it seems recommendable to develop typical data for each type of DER for benchmarking purposes. 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.

Some important aspects, to be considered when selecting models for a given study, are discussed below.

— In transient studies (e.g., overvoltages, most power quality studies, dynamic simulations), the mathematical description depends on the range of frequencies associated to the transient process [59].
— The representation of mixed phase (single-, two- and three-phase) connections may be needed for actual cases. Mutual impedances between phases may be also required, and neglecting them may lead to inaccurate results when unbalanced flows are significant. In general, data from most utilities do not have accurate mutual impedance parameters. Line and cable geometry can be used to determine parameters with a fair degree of confidence by using routines available in many simulation tools.
— Three-phase models of static load characteristics are available but constant load (P and Q) models are used in many studies. For static studies, it is probably sufficient to use a simple polynomial voltage dependency relationship [60, 61].
— Three phase load models with accurate representations of dynamic characteristics are not widely available. For the purposes of slow dynamics, simple damping models are probably adequate [60, 61]. Induction machines exhibit frequency and voltage unbalance dependencies that might interact unfavourably with load following service.
— Three phase loadings with accurate descriptions of imbalances are not widely available. Reasonable assumptions on load imbalances, such as less than 20% along the main feeder, can be used for studies with a fair degree of confidence.
— Load duration curves are needed for assessment of placement and controls. Load patterns can vary significantly from feeder to feeder. For static studies, assuming a few load levels with specified yearly durations would suffice. This is important for economic studies of freed capacity, which may only be relevant for the few hours of peak load each day. To reflect the actual energy costs, studies of losses should be integrated across the load duration curves, rather than mere peak load studies.
— Load sensitivity models must 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 [62, 63]. Other indices to identify the sensitivity of a load are the maximum amount of time that the load can be tolerated off line, or the unbalance that the load can tolerate at its terminals.
— 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 the DER units [64]. They must include capacity and failure rates for microturbines, fuel cells, battery storage and energy storage capacitors. Similar data for renewables (wind and solar) may also be beneficial. Models of the voltage dependencies of units of traditional designs (without inverters) and the voltage characteristics of converters are needed. Ramp rates for micro-turbines, fuel cells or battery storage may also be required.

3. SIMULATION TOOLS

3.2. Introduction

Since distribution systems were not designed for the inclusion of DER, software packages for distribution systems were primarily designed for analyzing radial distribution

Table 2. Planning and design studies in distribution networks with DER interconnection

Category	Subcategory	Performance criteria	Models
Voltage support	Voltage drop analysis Distribution component sizing Location and sizing of voltage regulators, capacitor banks and DERs	Maximum voltage drop Three-phase balance	Low-frequency three-phase network components models Static load models
Loss reduction	Magnitude and duration of overloads Location and sizing of capacitor banks Feeder reconfiguration Load growth/forecasting	Losses at different voltage levels	Low-frequency three-phase network components models Load duration/growth curves
Fault-analysis and protection	Short-circuit calculations Selection, location and setting of protective devices (relays, reclosers, fuses, ...) Islanding detection and setting	Equipment safety Coordination requirements	Low-frequency three-phase network com-ponents models (symmetrical components) Protective device models Fault characteristics
Reliability	Average interruption frequency Average interruption duration	Reliability indices (SAIFI, CAIDI, ASAI)	Reliability models (outage rates, repair times)
Power quality	Harmonics analysis Voltage dip assessment Flicker analysis System/load balancing Application of Custom Power devices	Power quality indices Total harmonic distortion (THD) IEC and IEEE voltage dip indices Flicker severity indices Voltage unbalance indices	Frequency-dependent models (including non-linearities) for a frequency range of a few kHZ Power electronic based modes, including Inverter-based interfaces
Overvoltages	Resonance and ferroresonance Switching and fault overvoltages Lightning overvoltages Location and selection of arresters	Insulation coordination requirements	Frequency-dependent non-linear models (from DC to a few MHz) power distribution components and surge arrester models
System stability	Transient stability (loss of load, loss of generation, faults) Voltage stability Load following Generator and motor start-up	Power balance in island mode Frequency and voltage deviations	DG low-frequency transient models Inverter-based interface models Excitation control models Prime mover models Dynamic load models
Distribution planning	Distribution expansion Optimal location of substations and feeders Optimal feeder and substation design Optimal allocation of load and substation capacity	Economic costs Reliability indices	Models used in those simulation tools needed for distribution planning [41]

systems and not conceived for the analysis of systems with embedded generation. Tools designed for distribution system analysis are capable of efficiently computing unbalanced load-flow, short circuit, optimal capacitor placement, load balancing, load allocation, load growth, feeder interconnection, switching optimization, system restoration and contingency analysis; however, they do not deal with transient stability and small signal stability, because traditionally there was no DG. Transmission system tools are capable of performing dynamic studies, but they consider that the system is three-phase, so they are not capable of dealing with unbalanced systems or with two- and single-phase sections. Inadequacies that can be found in most distribution system simulation tools are listed below [8, 26]:

— Distribution system simulators were not designed for the determination of the optimal placement and sizing of DER.
— Consideration of single-phase DER vs. three-phase DER is a recent issue. Single-phase DER can have a non-negligible impact on harmonic distortion and unbalanced conditions.
— Simulator capabilities could not perform dynamic DER assessment, needed to determine voltage/current transients as the generation unit is started up or its response to voltage dips.
— There were no capabilities to customize generator models with characteristics specific for each type of DER, such as microturbines, fuel cells or photovoltaics.
— Tools could study peak and off-peak load conditions rather than variable feeder loading conditions; therefore, hand iterations had to be used to analyze DER operations when the load levels and the operating conditions of the feeder varied.

There have always been software tools in which the radial topology was not a restriction. Simulation tools that can be included in this group are EMTP-type programs, which were originally designed for simulating any power system topology. Most EMTP-type tools can be used in both steady state and transient simulations, have capabilities for accurately representing any type of DER device, and users can take advantage of these capabilities to develop custom-made models [24]. Although they have been used and will still be used in those applications not covered by distribution system simulators, they are not so efficient as dedicated tools for some studies (e.g., load flow), cannot perform some important studies (e.g., reliability) and, in general, require

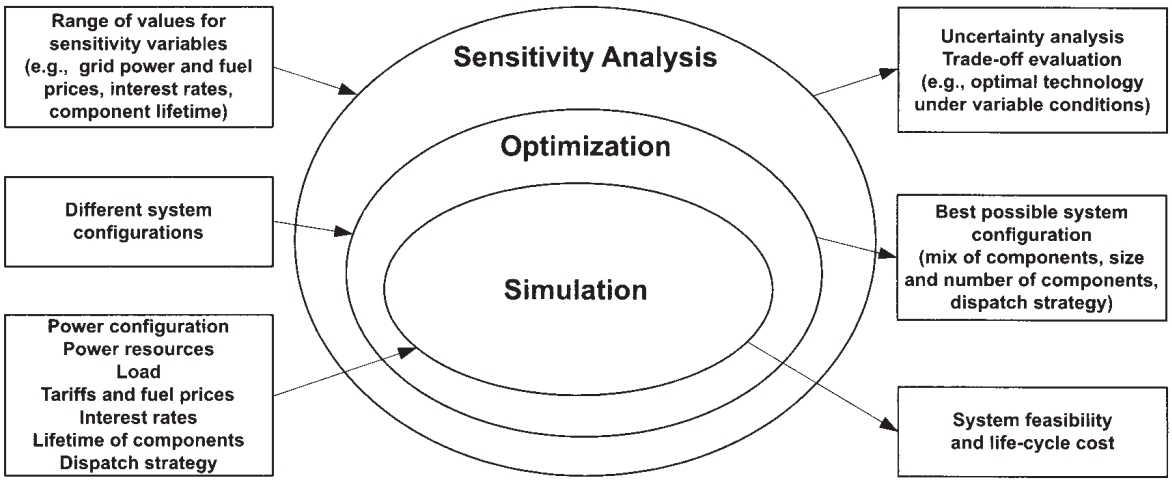


Fig. 2. HOMER modules for simulation, optimization, and sensitivity analysis (based on [66])

some expertise and a significant effort to select, develop and implement some models.

The number of current simulation tools related to the topics covered in this paper is well above one hundred. There are both commercially and freely available tools, although a third group should be added since there are some on-site programs that are only used by the developers; for instance, the Distribution System Simulator (DSS) developed by EPRI [26]. Due to room limitation it is not possible to describe each tool, or even include a complete list. The following subsections discuss the present capabilities and the future requirements of simulation tools for the studies analyzed in Section II. This section has been divided, according to Fig. 1, into three parts dedicated to analyze simulation tools for feasibility and economic operation of DER installations, computer-aided planning and design of distribution systems with DER penetration, and DER business, respectively.

3.2. Tools for selection, size and economic operation of DERs

A DER installation is by default connected to a nearby load and may consist of any combination of electrical generation and energy storage technologies. Several tools are presently available with capabilities to deal with energy storage in conjunction with intermittent renewable resources. These tools vary in terms of capabilities, structure, scale of application, and computing code/platform. Those analyzed in this section cover a wide range of applications, but in general it can be said that they have been designed as decision support tools that can help users to either select the optimal technology and size, or minimize operation costs. In all cases they use load duration curve analysis.

Feasibility simulation programs can be used to analyze different DER technologies and sizes from among the available alternatives by using a multiple criteria analysis approach to adequately address the trade-offs between supply reliability, economics, financial risks and environmental impacts. Several commercially or freely available simulation tools for the selection and design of DER devices running as either standalone or grid-connected are presently available.

One of the most widely used tools in this field is HOMER (Hybrid Optimization Model for Electric Renewables), an optimization model developed by the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy [65]. HOMER can help in the design of both off-grid and grid-connected systems, and is used in this paper as a reference model for feasibility studies. This tool models systems with single or multiple sources and finds the least cost combination of components that meet electrical and thermal loads [66]. HOMER optimizes the life-cycle cost; it is an economic model that can be used to compare different combinations of component sizes and quantities. It is also used to explore how variations in resource availability and system costs affect the cost of installing and operating different system designs. This tool allows users to perform three-level studies: simulation, optimization, and sensitivity analysis, see Figure 2.

Other tools that have been developed for similar objectives are listed and described below.

- RETScreen is a tool made available by the Government of Canada through CANMET Energy Diversification Research Laboratory, which can be used to evaluate the energy production, life-cycle costs and greenhouse gas emissions reduction for various renewable energy technologies [67]. RETScreen includes eight independently working technology modules. The model is used for each technology using the same five step standard analysis procedure: (1) definition of the energy model; (2) cost analysis; (3) greenhouse gas analysis (optional); (4) viability (financial) analysis; (5) sensitivity and risk analysis (optional).
- D-Gen PRO is a tool designed for economic analysis and feasibility of DG [68]. This tool uses climate data from over several locations and can create new climate locations. It performs economic analysis of life cycle cost savings, payback, internal rate of return, average cost of on-site generated kWh, monthly utility costs. This tool consists of on-site generation modelling capabilities (weekend operation, part load efficiency, thermal recovery, automatic generator deployment) and rate-handling capability.

— The Distributed Generation Analysis Tool is a screening tool that performs life-cycle cost analysis and environmental impact assessment [69]. Data input to this tool includes capital and maintenance costs, performance data for generators (turbine, micro-turbine, fuel cell), generator usage plan, financial parameters, fuel and electricity rates or air emissions factors.
— The DIStributed Power Economic Rationale SElection (DISPERSE) tool estimates the DG market potential in a specific region [70]. Simulations use databases of industrial and commercial sites (location, facility type and size); the model assigns electric and thermal load profiles specific to the application and region. Combining this information with DG costs and performance data, the model performs a life-cycle cost analysis, based on the unit life, cost and performance data, as well as fuel prices. The best DG technology is selected based on the lowest DG competing electricity price. Sensitivity analysis on important variables can be conducted.

There are several tools, such as HYBRID2 [71] or Remote Area Power Supply Simulator (RAPSIM), which were mainly developed for simulation of off-grid hybrid systems. Some of them can also analyse grid-connected systems; for instance, HYBRID2 is a powerful tool that allows users to analyse grid-connected systems by using the so-called pseudo-grid model, a grid link that mimics a grid connection and is able to provide power to and accept power from the grid system up to the rated power level of the link.

Several simulation tools have been developed to optimize costs and operating efficiencies under varying system operating conditions. One of these tools is DER-CAM (Customer Adoption Model) [72], an economic model implemented in GAMS (General Algebraic Modeling System) software and developed at Lawrence Berkeley National Laboratory of the U.S. Department of Energy. Its main objective is to minimize the cost of operating on-site generation and combined heat and power (CHP) systems, either for individual customer sites or microgrids [73, 74]. It can be used to select which DG and/or CHP technologies should be adopted and how it should be operated based on specific site load, price information, and performance data for available equipment options. Inputs into the model are the customer's load profiles, the customer's electricity tariff, gas prices, and other relevant prices; the capital, operating and maintenance, and fuel costs of the various available technologies, together with the interest rate on customer investment; the basic physical characteristics of alternative generating, heat recovery and cooling technologies. Outputs are the capacities of DG and CHP technology or combination of technologies to be installed; when and how much of the capacity installed will be running, the cost of supplying the electric and heat loads, see Figure 3. DER-CAM assumes that customer decisions are based only on economic criteria. Deterioration during the equipment lifetime is not considered, start-up and ramping constraints are not included, reliability and power quality benefits, as well as operation and maintenance costs, are not taken into account.

Another tool aimed at optimizing the hourly unit commitment is FIDO (Fully Integrated Dispatch and Optimization), which simulates the operation of utility generation, incorporating the hour-by-hour performance of intermittent renewable power, demand-side technologies, and market power transactions [75].

The economics of grid-connected DER operation including net-metering can be analyzed with Clean Energy Technology Economic and Emissions Model (CETEEM) [76], a tool designed to assess the economics and emissions of criteria pollutants and greenhouse gases associated with the use of clean energy technologies for distributed power generation. CETEEM combines MATLAB/Simulink and Excel capabilities, can analyze PEM (proton exchange membrane) fuel cell systems powered by hydrogen produced with natural gas reformers, and can be modified to characterize other clean energy technologies and fuelling arrangements.

A tool for analysis of wind energy penetration is Wind Deployment Systems (WinDS), a multi-regional, multi-time-period, geographic information system (GIS), and linear programming model, developed by NREL [77]. WinDS uses a discrete regional structure, with explicit accounting for the transient variability in wind output, and consideration of ancillary services requirements and costs. This model was not explicitly developed for distribution levels. An

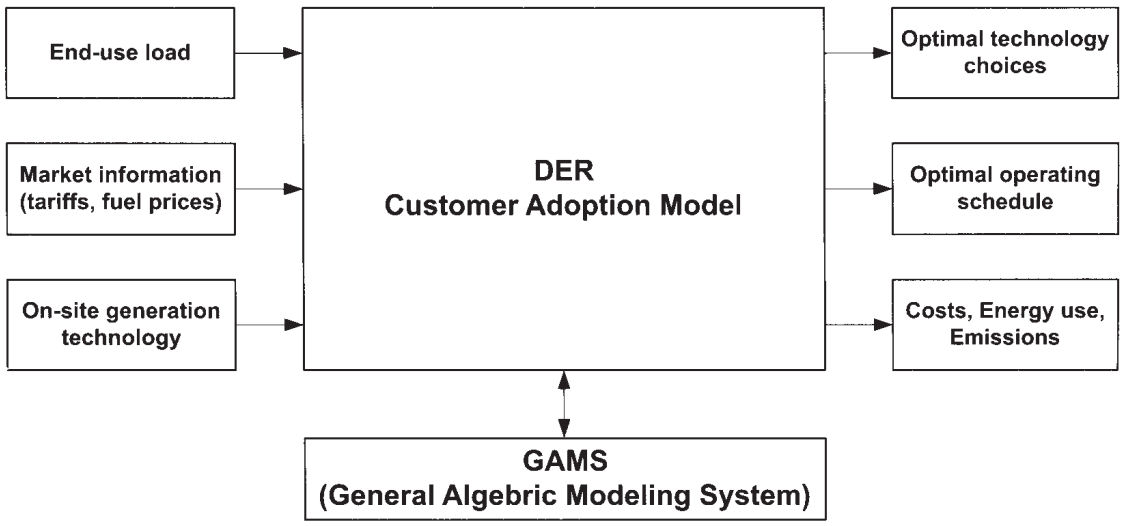


Fig. 3. DER-CAM structure

expanded version, HyDS (Hydrogen Deployment Systems model), includes the production of hydrogen from three competing technologies (wind, steam methane reforming, and distributed electrolysis powered by electricity from the grid) along with hydrogen storage and transportation [78].

Photovoltaics (PV) is a field in which a significant activity has been performed. In addition to most of the tools mentioned above, designers can presently choose among a countless number of dedicated simulation tools for feasibility studies of either grid-connected or standalone PV arrays. A non-complete list of photovoltaic system analysis and design programs would include among others PVFORM, PVGRID, PVWATSS, PV F-CHART, PV-DesignPro, SolarPro, PV*SOL, PVSYST, GridPV, NSOL, WATSUN-PV and SAM (Solar Advisor Model). For a survey of software tools for PV applications, see [29].

3.3. Tools for planning, design and operation of distribution systems with DER

Current limitations and future needs for simulation tools are discussed in the following paragraphs. Each part is dedicated to a primary function, according to the classification presented in Section II.

Load flow: Present power flow tools are used to check for under/overvoltage, overloads, and assessment of losses. DER penetration provides several challenges to standard distribution system load-flow software: it must be able to model a portion of the transmission/subtransmission system, voltage-control equipment, unbalanced systems, single-phase loads, single- and two-phase lines, and any transformer connection; it must efficiently handle load and generation profiles; it must include optimization routines for feeder reconfiguration or capacitor placement/size, and include or accommodate accurate DG models. The primary needs for distribution system load-flow software with DER 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 modelling wind generation, in which the step size might be as short as 1 second. Adding significant levels of non-dispatchable DG, such as photovoltaics, to the distribution system increases the complexity of the analysis: time- and location dependent relationships between feeder segment loads and PV output require running many additional studies to determine the range of operating conditions that the new system will experience. A single load value and a generator output value may not suffice for determining the impact of DG.

In addition to software packages developed by major vendors, several simulators are currently available that allow users to analyze the demand and the energy supply with a temporal resolution, considering certain distributed generating and energy storage technologies. The list can include SIMREN [79], the Integrated Power System Simulation (IPSYS) [80] and DESIGEN [81].

Fault-current analysis: Fault-current analysis may be performed by using a standard short-circuit program; however, DER addition increases the time varying nature of the fault current, and a more sophisticated approach is advisable. The short circuit contribution of DG units may be important. Synchronous generators will supply the most current, although induction generators can also feed fault current. Short-circuit contributions of inverter-based distributed generators vary by inverter design. In many cases, the inverter control will act within milliseconds to protect the inverter electronics; in some cases, an inverter can output two to four times full load current for several cycles. The duration of fault current output also depends on the amount of capacitance on the inverter DC bus. The DG transformer is important and its connection must be properly modelled. If a grounding transformer interconnection is used, its effects on line-to-ground short-circuit currents will be significant. The list of capabilities of a fault-current simulator must include a broad array of features: single- and three-phase analyses, DC analysis, balanced or 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 [26].

Protection: Radial distribution systems are generally protected by time overcurrent schemes that rely on the fact that the fault current flows from the substation transformer toward the fault, with little if any fault contribution from the load [18, 82]. Coordination among devices is achieved through variable time delays in each protective device. Reliability is enhanced on these systems through restoring unfaulted feeder segments by switching those segments to adjacent feeders following an interruption. Present software packages include time-overcurrent coordination (TOC) capability and a library of curves for relays, fuses, and reclosers. However, these protective devices need to be re-coordinated or re-designed in situations in which DG generates significant fault currents (fault current supplied by DG will increase the fault current flow at the fault location while reducing the fault contribution from the utility source), since this protective approach can fail under some conditions. There is thus a need for research into alternate protection strategies for some situations; e.g., where DG units supply fault current levels that can cause misoperation of the feeder protection, or in intentionally islanded systems, where fault currents can be small and vary widely. TOC protection will remain the preferred protection strategy and it is highly desirable to continue to display the coordination information on time-current curve. Software tools should therefore recognize the effect caused by the DG installation and the fact that the protected equipment and the various protective devices will now see different fault currents [26]. When several DG units provide fault current, the challenge increases significantly. To effectively assess a given protective system, software tools will be required that clearly present the impact of DG infeed current on the standard time-current curves.

Reliability: A reliability tool uses equipment outage frequency and repair time statistics to calculate standard industry customer and system reliability indices [83]. The calculation results can be used to evaluate the reliability of a network configuration, a protection scheme, or to propose

alternatives. A distribution system reliability tool must provide consistent, accurate comparisons between competing design options. There is a need for research into DG reliability models and into the effects of DG on system reliability, considering the impact of various DG operating strategies; for example, the delay of DG in coming back on line after a fault must be considered in determining the appropriate response of the unit to system restoration following an interruption [26]. A study aimed at testing the capabilities available in some distribution reliability planning tools was presented in [27]. The list of capabilities evaluated for each tool included circuit and reliability modelling capabilities, input data requirements, output results (e.g., reliability indices), load modelling capabilities, reliability improvement options, risk assessment and economic evaluation methods. The tools analyzed are worldwide used by utilities and have very different capabilities. The list of areas recommended in the report for future research and improvements included the following items: 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: Software is presently available for analysis of harmonics, flicker, voltage dips and any type of current and voltage waveform analysis. However, very different tools have been used to date for these purposes. EMTP-type tools are a very common approach in power quality studies [84], since they can accurately represent almost any scenario. But for some cases, mostly for harmonic studies, frequency-domain can be faster and accurate enough. Harmonic analysis may also be performed by using a dedicated tool [85], or a capability implemented in some commercial packages. Another option is PQSoft, a family of programs for power quality analysis [86], which enable users to assess system performance (e.g., power quality indices) from power quality monitors or to evaluate the economics of power quality problems along with potential solutions.

Some knowledge is needed on the impact of DG inverters at frequencies above 3 kHz. Different modelling approaches can be used [87], although the most accurate models will be usually those implemented in a time-domain simulation tool (e.g., an EMTP-type tool). A current source model is accurate enough for most applications in which a linear model of the system may be used. Some programs only model balanced three-phase harmonics; however, for analyzing multiple single-phase DER applications, modelling all phases independently is important. Another consideration is how to model the generators since DG can be a sink of harmonics. Synchronous generators are normally modelled by means of their negative-sequence reactance, while induction generators are represented by means of the locked rotor inductance.

Flicker analysis is important for DG with fluctuating output, since it may be the limiting factor for certain types of generators. Flicker is difficult to quantify since it depends on human perception, which varies from person to person. The traditional way is with a flicker curve where the change in voltage is plotted against the frequency of change [88], [89]. This curve is easy to model and apply, but it has several limitations. The most significant one is that it does not accurately represent flicker for many types of DGs. Wind and solar generators do not vary periodically, and the output change is not instantaneous. Modelling multiple DG units is another challenge. The flicker of some DGs 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 performed by means of simulators with capabilities for short-circuit calculations. A detailed study on modelling guidelines for voltage dip studies using a time-domain simulation tool can be found in [90].

Electromagnetic transients: Electrical transient phenomena involve frequency ranges that vary from DC to several MHz. The causes of electromagnetic transient phenomena can be many (e.g, ferroresonance, capacitor switching, fault initiation and clearing, line and cable energisation, line and cable reclosing, breaker and disconnector restrikes, or lightning surges), and even phenomena related power electronic converters running under either steady state or transient conditions can be included within this category. Fast transients are generally simulated by means of a time-domain solution technique, with EMTP-type tools being the most common approach [91]. There are many scenarios in which the transient response of DER devices has to be modelled in high detail and for which an EMTP-based simulation is also advisable. Some of the situations include analyzing the origin and effect of DER overvoltages, such as ferroresonance or neutral shift, evaluating voltages during out-of-phase reclosing with DER devices or surge protection against lightning surges, analyzing converters waveform notching or high frequency noise, evaluating, determining converter harmonics and inter-harmonics, analyzing the effectiveness of protection [92]. A trade-off is usually needed between computational effort and accuracy. Selection, development and implementation of EMTP-based models can require a significant effort, and some expertise is usually needed. On the other hand, this expertise can be very useful to introduce system simplifications and reduce this effort.

Stability: Traditionally, the need for dynamic analysis of distribution systems has been limited; as a result, products available for this purpose are also limited. High levels of DG penetration raise some issues that need to be addressed through dynamic analysis. The list of dynamic problems that are of concern when applying DG [26] includes interaction between multiple DG units, islanding and the effect on global stability. An accurate dynamic model will predict whether islanding will occur and if the protection scheme will operate to remove DG when an island occurs. High penetration level of DERs may impact the stability of a regional grid; for example, a transmission-level voltage dip may cause all DERs in the area to trip off, which in turn may hurt the overall stability. Another scenario that has caused some concern is the widespread use of active anti-islanding techniques that are intentionally unstable controllers on some types of DG. Dynamic models of different types of DER are therefore needed and DER models may need to be incorporated into transmission stability tools. Models

should also include the protective relay characteristics so that generators can be removed when they should be during the dynamic event. 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 model the system in time-domain simulation tools, such EMTP-type tools or the SimPowerSystems blockset [93], which would allow more detailed system and DER models, but it would take much more effort to set the models up.

Distribution planning: A distribution planning package is a set of tools that can be grouped into three distinct categories [41]: (1) electrical performance simulators, usually embodied in packages aimed at predicting distribution system behaviour; (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 DER units and building new or upgrading existing networks, or building new conventional central power plants. In general, estimating the deferral benefit to a utility, assessing the trade-off between deploying DER units and conventional central generation, or calculation transmission losses reduction should not be difficult.

The integration of DER devices must take into account multiple factors, such as the existing resources, costs, or the environmental impact. Geographic information systems (GIS) are suitable tools for solving these problems [94], 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 [94]. A survey on GIS tools, a study of their capabilities and some recommendations for their use in planning studies was presented in the European DISPOWER project [95].

Table 3 shows a list of simulation tasks, the most common tools and some directions of future research.

3.4. Tools for power market studies

The development of simulation tools to take into account the multiple products of the deregulated power industry and the independent reactions of the many participants in this industry can be extremely complex. There are several aspects that contribute to this complexity: electricity/energy markets are changing, the market rules are also changing, the differences between regional/national markets can be very significant, DER penetration offer new opportunities but also new threats (see Section 2), the DER role is changing as the level of penetration increases, and the barriers for DER participation in markets are different in different countries.

According to the conclusions presented in [96], an electricity market simulator should include capabilities to produce nodal spot or locational marginal prices for all of the busses, buyer and seller market clearing prices for all of the zones, ancillary service prices (including regulation, spinning reserve, non-spinning reserve by designated availability, replacement reserve), prices for emission allowances, prices for capacity, transmission capacity allocation. The report identifies functional data (e.g., modelling of fuel constrains, bilateral contracts, or global warming and emission constraints) and source data (e.g., data base management tools or specific data requirements) gaps, details methodologies and tools for assessment of bottleneck elimination, provides modelling and data requirements for each function, and analyzes the major strengths and shortcomings of some electricity market simulators (e.g., GridView, AURORA, MAPS, PROSYM, UPLAN, PROMOD).

A thorough analysis of bidding models and solution techniques to be applied in market simulators was presented in [97].

The requirements for new simulators to address market transaction control interactions, as well as to capture the dynamic coupling between power systems and energy markets, were analyzed in [98].

Other surveys on electricity market simulators were presented in references [30] and [99]. Presently, there are many commercial tools designed to analyze market transactions, estimate contracts or re-dispatch congestion, but no one can fully satisfy the challenge of a significant level of DER penetration. New custom-made or in-house tools have been developed to cope with some of these issues, see for instance references [100] and [101].

4. REAL-TIME SIMULATION PLATFORMS

Real-time simulators are proving to be very effective in the design and development of DERs. The design of DERs and their controllers involve repeated cycles of simulation and testing from the conceptual stage to the prototype implementation stage. Due to the overwhelming complexity of DER configuration, modelling requirements, and controller functionality, traditional non-real-time software tools can be very time consuming, thus creating unnecessary delays in the design process. A real-time simulator can not only speed up the entire design process significantly, but it is also the only tool capable of interfacing with the device-under-test under real-time conditions. For over seventy years real-time analog simulators (also known as Transient Network Analyzers) have been used for various applications in power systems, but over the last fifteen years significant advances have been made in real-time digital simulators. These simulators 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, see Figure 4. Due to rapid advances in digital processors, parallel processing, and communication technology, these simulators are becoming increasingly popular for a variety of applications.

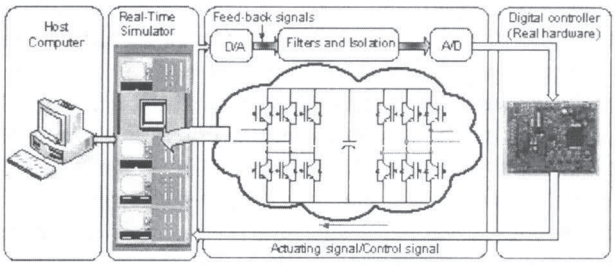
To emulate a physical system faithfully, a real-time digital simulator should be capable of solving the system differential equations within the allocated time-step. For example, if a transient event happens in 10 μs in the actual system, the real-time simulator should be able to perform the necessary

Table 3. Present software packages and future research for planning, design and operation of distribution systems.

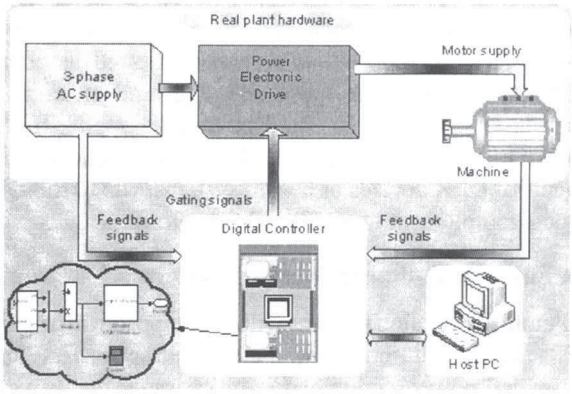
Study	Present tools	Future Research
Load flow	ASPEN, BSI-DPFLOW, CYMDIST, DEW, DSS – EPRI, EDSA, ETAP, FeederAll – ABB, IPSA, NETBAS, PSS/ADEPT, SynerGEE, SIMPOW, SKM, WindMil	Should include transmission and distribution in a common analysis framework. Distribution software needs to consider unbalanced conditions. There is also the need to have a common database for equipment, including DER. Presently, the available data details for distribution and transmission studies are different. In transmission system studies the load (in power units) is always known because it is measured. However, in distribution systems the actual load is not measured at every point and the measured load at the feeder head needs to be "allocated" using prediction tools relying on the existing measurement points and historical data.
Fault-current analysis	ASPEN, CYMDIST, DEW, DSS – EPRI, EDSA, ETAP, FeederAll – ABB, IPSA, NETBAS, PSS/ADEPT, SIMPOW, SynerGEE, SKM, WindMil	Properly model the contribution of the DER to the short-circuit current considering the interconnection type and the settings of any power electronic controllers. Ideally the user should be able to select in a drag-and-drop fashion the DER by manufacturer and model. The new tools should be capable of computing short-circuit currents in phase with fewer approximations than the currently used sequence component calculation approach.
Protection	ASPEN, CYMDIST, DSS – EPRI, EDSA, ETAP, IPSA, PSS/ADEPT, NETBAS, SynerGEE, SKM, Wind-Mil	The inclusion of DER with bi-directional flow of power will require the analysis of the distribution systems as if it were a transmission system including (unbalanced) distance protection. Consideration to the policy for island operation needs to be included too. Some utilities may want to prevent islanding altogether for safety reasons.
Reliability	CYMDIST, DEW, DISREL, EDSA, ETAP, NETBAS, PSS/ADEPT, RA-MELEC, SynerGEE, WindMil	DER may enhance reliability when islanding (or parallel) operation is permitted under abnormal conditions. This will require the development of software capabilities to model ma-nual or automatic reconfiguration of the system. Additionally, the software needs to be able to incorporate the varied opera-ting policies of different companies with regards to DER.
Power quality	ETAP, HarmFlo, IPSA, PQSoft, SynerGEE, CYMDYST, EMTP-type tools	Software used for power quality analysis should be able to represent accurately the characteristics of DER. Depending of their type and controller settings, different DER may produce positive or negative effects for quality problems (harmonics, voltage dips, flicker, etc.).
Electromagnetic transients	EDSA, EMTP-type tools (EMTP-RV, ATP, PSCAD/EMTDC, NETOMAC, MicroTran, DigSilent, ARENE), SimPowerSystems	EMTP-type tools already have the capabilities necessary for transient analysis of distribution systems with DER. Substantial modelling details may be necessary to properly evaluate the effect of DER. However, unless the GUI (graphical user interface) has a list of DER by manufacturer and model, the user will not easily have all necessary data. A concern is the large size of the network that needs to be reduced to a manageable size.
Stability	EDSA, ETAP, IPSA, SIMPOW, CYMDIST, EMTP-type tools, SimPowerSystems	Transient and small-signal stability programs need to be developed considering: (1) the unbalanced nature of distribution networks; (2) the inter-connection of the DER; (3) the enormous size of the distribution networks, perhaps via equivalents.
Planning	AEMPFAST, IPM, NETBAS, UPLAN, GIS Tools	Planning is a broad concept that includes many of the tasks performed by tools analyzed in this table. In addition to those researches, packages should incorporate routines for different optimal calculations (e.g., DER location and sizing) and links to the GIS. Although interfacing with GIS is already available in many present packages, cleaning data is very much a work in progress and more effort is necessary to have a reliable error-free GIS.

computations for the transient and output the results within 10 μs. It is not sufficient for the end of the simulation run to coincide with the real-time clock; instead, the computation of every time-step must be executed within the same corresponding interval of real-time. The simulator must also be able to effectively interface and synchronize with actual external hardware. With the introduction of fast switching power electronic apparatus into the conventional power system model, the requirements for the real-time digital simulator have become even more stringent. Interfacing with real-time digital simulators is an ongoing research topic where several important issues are being addressed. One such issue is the interfacing of discrete switching signals coming from a digital controller with a fixed time-step real-time model of a power electronic apparatus in the simulator. Several algorithms have been proposed for correcting switching errors and extra delays for power electronics in real-time digital simulators [102 - 104]. There are also commercially available packages such as ARTEMIS [105] that address this issue.

Commercially available real-time digital 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 modelling packages such as MATLAB/Simulink are driving the current trend of using PC-clusters for real-time and hardware-in-the-loop simulations. The PC-cluster based real-time simulator [106] is built entirely from high performance commodity-off-the-shelf components to sustain performance at a reasonable cost. Real-time simulation and off-line model preparation are divided between two groups of computers comprising the target cluster and hosts making the configuration flexible and scalable. The cluster nodes can be configured as centralized



a) Hardware-in-the-loop simulation



b) Controller prototyping

Fig. 4. Applications of real-time digital simulators

or distributed servers interconnected with low-latency high-bandwidth communication such as Infiniband which offers communication speeds of up to 10Gbits/s. Alongside general purpose processors field programmable gate arrays (FPGAs) are also making significant inroads into real-time simulators. FPGAs have been proven to offer high-speed high-precision simulations in standalone configurations [107, 108], and also as accelerator components in PC-cluster simulators.

Currently, real-time digital simulators are used to address simulation needs for a large spectrum of power system studies, 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, harmonics and power quality evaluation, variable-speed drives. Not much experience is already available in the simulation of DER devices, although these simulators have been proved to be very useful in the simulation of wind farms [109, 110], and multi-machine ship power generation [111]. The possibility of using a single simulation platform that could reproduce the performance of a complete distribution system with several inverter-based interfaced DER units in real-time is a challenge for developers and manufacturers, see Section 5.

5. FUTURE TRENDS

In addition to the future improvements that developers of distribution system software packages could add into their products, it is worth mentioning some trends that might significantly alter the current situation. The alternatives discussed in this section include the development of multi-agent simulation tools, multi-domain tools, and the future real-time simulation platforms.

5.5. Multi-agent simulation tools

The coupling of power systems and markets impacts broad areas of the electric power industry. Energy trading products cover shorter time periods and demand response programs are moving toward real-time pricing. Market-based trading impacts the physical operation of the system, while the boundaries of these coupled systems extend beyond the boundaries of utility operations. 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, DER devices, energy markets and new business strategies result in very high uncertainty.

A tool under development to address these simulation gaps is GridLAB-D [25]. This tool is a simulation environment that can be integrated with a variety of third-party tools, and that combines end-use and power distribution automation models. GridLAB-D can determine the simultaneous state of independent devices, each of which is described by multiple differential equations solved only locally for both state and time. According to the developers, this tool can handle widely disparate time scales, is easy to integrate with new modules and third-party systems, does not need to integrate all the device's behaviours into a single set of equations and can examine the interplay of every part of a system with every other. Its present development incorporates modules to perform power flow calculations, to model end-use appliance technologies, equipment and controls, to use data collection on every property of every system object, and to manage boundary conditions including weather and electrical boundaries. Future capabilities will include among others 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 modelling 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 DER 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 behaviours.

5.2. 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). Many programming packages offer a flexible and adequate environment for these purposes. Commercially and freely available simulation tools can be used to develop custom-made models not implemented in specialized distribution power packages. The main characteristics of some of these tools are summarized in the following paragraphs.

Modelica is a freely available, object-oriented language for modelling complex and heterogeneous physical systems

[112]. Models of standard components are available in libraries, while specialized algorithms can be implemented to enable handling of very large models. Symbolic transformations algorithms have to be applied to transform the original set of equations into a form that can be integrated with standard methods. To perform this task some simulation environments, such as DYMOLA or MathModelica, have been developed [113].

INSEL (Integrated Simulation Environment Language) is a graphical programming language developed at the Faculty of Physics of Oldenburg University (Germany) for modelling of renewable energy systems [114]. INSEL has been used as a tool for planning, monitoring and visualising energy systems. Validated models that support particular problems related to renewable energy systems, such as photovoltaic modules, inverters, thermal collectors and meteorological parameters, are already available [115].

TRNSYS (TRaNsient SYstem Simulation Program) includes a graphical interface, a simulation engine, and a library of renewable energy and emerging technologies [116]. This package has been used for solar system design and building thermal performance. A library of components, known as HYDROGEMS [117], has been developed to simulate renewable energy-based generation; the list of components includes photovoltaic arrays, wind power systems, diesel engine generators, advanced alkaline water electrolysis, high-pressure hydrogen gas storage, metal hydride storage, fuel cells, compressors, power conditioning equipment, and logical control functions.

VisSim combines a block diagram interface with a simulation engine, and allows users to construct, modify and maintain system models. The simulation engine provides solutions for linear, nonlinear, continuous time, discrete time, time varying, SISO, MIMO, and hybrid system design. This tool has been used to develop NREL's RPM-SIM, a modular simulation system to study the system dynamics of wind-diesel hybrid power systems under different generation/load conditions [118].

MATLAB/Simulink is a well known modelling 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 DER applications: SimPowerSystems [93], for simulation of power systems transients with capabilities for representing distributed generators and inverter-based interfaces; Wind Turbine Blockset [119], developed at the Institute of Energy Technology of the Aalborg University (Denmark) for simulation of wind power systems; PV Toolbox [120], developed by Natural Resources of Canada for simulation of PV hybrid systems; CETEEM (Clean Energy Technology Economics and Emissions Model) [76], developed for evaluating the economics and the emissions from different energy technologies.

Capabilities for multi-domain simulation of DER devices can be also found in other packages that offer different environment and solution methods. Open connectivity for coupling to other tools (e.g., to MATLAB/Simulink), a programming language for development of custom-made models and a powerful graphical interface are capabilities available in some circuit-oriented tools that can be used for expanding their own applications and for developing sophisticated DER models. These capabilities are available in several EMTP-type tools and in other circuit-oriented packages. One of these tools is CASPOC, a tool designed to model and to simulate power electronics and electrical drives whose capabilities have been used to model distributed generators and energy storage devices [121].

Although all the above tools are powerful simulation tools, one should not expect their application to the analysis and design of a whole distribution system. Dedicated distribution software packages are more adequate and efficient for those tasks. These tools could instead be applied for the development and testing of highly detailed and accurate models of DER devices or hybrid systems, which should be a good complement for CAP and CAD tools.

5.3. Future real-time simulation platforms

Future distribution systems will be equipped with multiple DERs interfaced through power electronic converters. There are several power quality and stability issues that can arise in these situations. Traditional power quality and stability software tools are not equipped with proper models to accurately perform critical simulations. Platforms capable of simultaneously simulating the fast transients caused by power electronic systems, faults and equipment switching, as well as slower electromechanical and voltage stability phenomenon are therefore required.

Advanced testing methods need to be developed to evaluate system functionality, security and reliability within a reasonable time period and for operating conditions too dangerous to be tested on the actual system. The number of specific performance design requirements is finite, but the number of possible operating conditions and failure modes is almost infinite. Design of optimal testing methods related to very complex systems may be more complex than the design itself.

HIL simulation is necessary to assess both the hardware and software during normal and abnormal operating conditions. For conventional power systems, several contingencies cannot easily be reproduced at commissioning or are simply not permitted due to cost or security reasons and must be therefore simulated. The increasing use of power electronic systems requires particular attention. Due to the large number of very fast acting devices, stability and security analyses of these systems are more complex than those of conventional power systems. Power electronic controllers can be optimized and tested in real-time using prototype systems more or less similar to the production systems. This solution may be adequate at the subsystem level but it is impractical for very large systems containing dozens of subsystems, which are integrated with large electromechanical systems. Consequently, testing complex integrated power electronic systems may be one of the biggest future challenges. The advances in digital processor performance and communication technologies, as well as the development of efficient simulation solvers, enable the deployment of large-scale real-time digital simulators.

The new generation of real-time simulation tools should have the following characteristics [122]:

— Powerful and optimized for power electronic simulation; i.e., capable of simulating very large systems including several interconnected power electronic systems. They must be capable to simulate long-term phenomena simultaneously with very short transients and fast switching events requiring sub-microseconds time-steps, as well as balanced and unbalanced operating conditions.
— Designed for real-time and even faster-than-real-time simulation; i.e., capable of simulating a large number of subsystems in real-time with prototypes or actual electronic controllers connected in closed-loop, and complex systems in faster-than-real-time to implement predictive control and protection strategies designed to prevent catastrophic events upon real-time analysis of the complete system behaviour.
— Capable of 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.
— Easily scalable to enable the simulation of very small and very large systems, and capable of starting projects with small, low-cost systems, and then increasing the simulator capabilities as needed.
— Based on simulation tools with an open architecture to facilitate the interface between simulation systems and prototype systems developed by several teams to form an integrated simulation. They should enable users to develop their own simulation software and capabilities to interface with commercial software.
— Easily upgradeable, and capable of integrating high-end general purpose processors with reconfigurable processor technologies such as FPGAs to achieve the best performance at the best price.

6. CONCLUSIONS

Design, test and integration of DER into distribution systems constitute a major challenge. According to reference [123], planning tools should include among others power flow capabilities for simulating the annual load characteristics and the growth of loads over time, provide multiphase short-circuit capability to perform protective relaying analysis during various unbalanced faults, and have capabilities for economics analysis. A significant effort has been made over the last decade in software development. Presently, there are simulation tools that can help on any task related to feasibility studies of DER installations, on planning, design and operation of distribution networks with DER penetration, and on the economic assessment of on-site generation units or microgrids.

This paper has reviewed the most commonly used simulators and reported their main limitations. Some of the most important conclusions of this survey may be summarized as follows:

— Many different software tools need to be used to analyze the electrical performance of distribution systems and DER devices. An all-in-one analysis package or a suite of programs that could operate on the same database is a requirement to facilitate the study of the same system for different types of calculations.
— Time-domain simulation will continue playing a major role in assessing system performance and security for both normal and abnormal operating conditions. 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 modelling and analysis, e.g., an EMTP-type tool.
— An increasing use of power-electronic systems for interfacing the DER to the grid will justify the application of real-time simulation platforms in design, analysis and testing tasks.
— Powerful screening type tools would be without any doubt useful for utility distribution operators and DER designers.
— Optimal placement algorithms are foreseen applications. Algorithms for optimal capacitor placement and sizing are already available in some packages. An optimal routine for DER location and sizing could include increased feeder capacity, loss reduction, voltage support, the possibility of islanding minimization, peak feeder current and power factor, utility load locations and line impedances, daily load-cycle characteristics, economic parameters, availability of fuel supply, DER size, control method, and range of power factor possible.
— Multi-domain simulations are emerging as a powerful approach for the study and design of new micro-generation and storage technologies, in which mechanical, thermal, electrical, electronic and control subsystems can play an important role.

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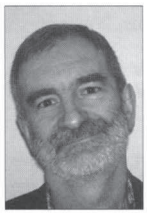

Juan A. Martinez
was born in Barcelona (Spain). He is Profesor Titular at the Departament d'Enginyeria Elèctrica of the Universitat Politècnica de Catalunya. His teaching and research interests include Transmission and Distribution, Power System Analysis and EMTP applications.

Francisco de León
was born in Mexico City in 1959. He received the B.Sc. and the M.Sc. (Hons.) degrees in electrical engineering from the National Polytechnic Institute, Mexico City, Mexico, in 1983 and 1986, respectively, and the Ph.D. degree from the University of Toronto, Toronto, ON, Canada, in 1992. He has held several academic positions in Mexico and has worked for the Canadian electric industry. Currently, he is an Associate Professor at the Polytechnic Institute of NYU, Brooklyn, NY. His research interests include the analysis of power definitions under nonsinusoidal conditions, the transient and steady-state analyses of power systems, the thermal rating of cables, and the calculation of electromagnetic fields applied to machine design and modeling.

Venkata Dinavahi
received the Ph.D. in electrical and computer engineering from the University of Toronto, Toronto, ON, Canada, in 2000. Presently, he is an Associate Professor at the University of Alberta, Edmonton, AB, Canada. His research interests include real-time simulation, electromagnetic transient analysis, power electronics, embedded systems, and parallel and distributed computing. He is a senior member of IEEE and chairs the IEEE PES Task Force on Interfacing Techniques for Simulation Tools.