Tools for Analysis and Design of Distributed Resources—Part II: Tools for Planning, Analysis and Design of Distribution Networks With Distributed Resources

IEEE Task Force on Analysis Tools
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***Abstract*—Distribution software packages were primarily designed for analyzing radial systems with very limited capabilities for representing distributed resources (DR). Software manufacturers are presently updating and expanding the capabilities of their tools. The challenges, however, are many, since the new tools should be able to represent a wide range of power component models, efficiently compute steady-state and transient unbalanced operating conditions, or cope with DR interconnections whose design cannot be anticipated yet. This paper summarizes the main types of studies related to planning, analysis, and design of distribution networks, analyzes the models required for representing distributed resources, and discusses the future capabilities of distribution software packages. This paper includes test cases that illustrate some of the studies related to planning, analysis, and design of distribution networks with penetration of DR.**

***Index Terms*—Distributed generation (DG), distribution network, distribution planning, distributed resources (DR), fault-current calculation, load flow, modeling, overvoltage, protection, reliability, simulation, storage, transient stability.**

I. INTRODUCTION

DISTRIBUTED resources (DR) can be used to solve problems on the distribution system by supporting voltage and reducing losses, providing backup power, improving local power quality and reliability, providing ancillary services, and deferring transmission and distribution system upgrades [1], [2].

There is, however, a wide range of issues associated with the interconnection of DRs to the distribution system that concerns power utilities. The list includes, among others, voltage control and stability problems, increased fault duty on circuit breakers and protection coordination problems, islanding conditions, power-quality (PQ) issues, personnel safety, overvoltages, and intermittent or stochastic nature of some renewable distributed sources [3], [4].

Some aspects to be considered when analyzing the connection and impact of DRs are the great variety of generating and energy storage devices [5], the fact that some DR devices are connected to the utility network via a static converter [6], [7], and the intermittent nature of some renewable sources. Depending on size, DR devices are connected to either the medium-voltage (MV) level or the low-voltage (LV) level.

All of these issues complicate the analysis and simulation of systems with a high penetration of DRs. Simulation tools must, therefore, combine analysis capabilities with a vast number of modeling capabilities for representing the various generation 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 DR in mind. The absence of DR models specifically for inverter-based devices, such as microturbines and fuels cells, that could represent their performance during various operational modes and disturbances (e.g., voltage dips) may be a serious drawback. There have been, on the other hand, general-purpose simulation tools, such as Electromagnetic Transients Program (EMTP)-type tools [8], based on time-domain solution techniques, which could cope with most of these modeling challenges; however, they are not adequate for some studies, such as reliability assessment, although most EMTP-type tools can perform 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], [9].

Software manufacturers are presently updating and expanding the capabilities of their tools by taking the new challenges into account. 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, [10].

Several surveys on simulation tools for analysis and design of distribution systems and DRs have been published during the past years [11]–[14]. This paper provides a more comprehensive account and presents more topics than those in the aforementioned references, but, due to space limitations, some parts are covered in less detail. Readers are referred to the aforementioned references for more information on simulation tools.

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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 of the practical concerns of future designs (e.g., 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) may also be needed in some studies.

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).

The studies considered in this paper are listed as:

- steady-state studies;
- transient-state studies, which can be divided into electromagnetic and electromechanical transient studies;
- fault-current and protection studies;
- reliability and PQ 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 is as follows.

- The power-flow formulation may be single or three phase.
- The fault contributions from conventional (synchronous and induction) generators can significantly affect the fault withstand requirements of the equipment and the protection system design [15].
- 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 standards recommend avoiding generation islands [16].
- 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 PQ, 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 will be discussed as follows.

- In transient studies (e.g., overvoltages, most PQ studies, dynamic simulations), the mathematical description of a power component depends on the range of frequencies associated with the transient process [17]. Different models are required for different types of electromagnetic transients, with the estimation of parameters being a major challenge [18].
- The representation of mixed phase (single, two, and three phase) connections would be needed for actual cases.
- Although constant P-Q models are used in many studies, a more sophisticated approach for modeling the load can be required. For static studies, it is probably sufficient to use a simple polynomial voltage dependency relationship [19]. For slow dynamic studies, simple damping models are probably adequate [20], [21]. 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 reasonably operate within. These limits may be identified with voltage tolerance curves [22].
- Load duration curves are needed for the 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, as well as some geographic and atmospheric factors.
- Several description details are needed for DRs, including capacity and failure rates, voltage dependencies of conventional units, and the voltage characteristics of converters. Ramp rates for microturbines, fuel cells, or battery storage may also be required.

Table I summarizes the studies, models, and performance criteria for each study. Although this list covers most of the main studies, it is by no means complete (e.g., state estimation, contingency reserve, or system restoration studies are not included).

III. SIMULATION TOOLS

A. Introduction

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, some tools do not deal yet with transient and small-signal stability, because traditionally there was no generation and energy storage. Transmission system tools are capable of performing dynamic studies, but they consider that the system is three

TABLE I
PLANNING AND DESIGN STUDIES IN DISTRIBUTION NETWORKS WITH DR

Category		Performance criteria	Models
Steady-state analysis	Voltage drop analysis Distribution component sizing Location and sizing of voltage regulators, capacitor banks and DRs Magnitude and duration of overloads Feeder reconfiguration Load growth/forecasting	Maximum voltage drop Three-phase balance Losses at different voltage levels	Low-frequency three-phase network components models Static load models Low-frequency three-phase network components models Load duration/growth curves
Fault-current 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 components models (symmetrical components) Protective device models Fault characteristics
Reliability and power quality	Average interruption frequency Average interruption duration Harmonics analysis Voltage dip assessment Flicker analysis System/load balancing Application of Custom Power devices	Reliability indices (SAIFI, CAIDI, ASAI) Power quality indices Total harmonic distortion (THD) IEC and IEEE voltage dip indices Flicker severity indices Voltage unbalance indices	Reliability models (outage rates, repair times) 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

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 [11], [13] as follows.

- Distribution system simulators were not designed for the determination of the optimal placement and sizing of DRs.
- Consideration of single-phase DR units in addition to three-phase DR units is a recent issue. Single-phase DRs can have a non-negligible impact on harmonic distortion and unbalanced conditions.
- Some simulators cannot perform dynamic DR assessment, which is needed to determine voltage/current transients as the generation unit is started up, or to determine its response to voltage dips.
- There are no capabilities to customize generator models with characteristics specific to each DR type, such as microturbines, fuel cells, or photovoltaic.
- In general, tools can study peak and off-peak load conditions rather than variable feeder loading conditions; therefore, hand iterations have to be used to analyze DR operations when the load levels and the operating conditions of the feeder vary.

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. Although they have been used and will still be used in those applications not covered by distribution system simulators, they are not as efficient as dedicated tools for some studies (e.g., load flow), cannot perform some important studies (e.g., reliability), and, in general, require some expertise to select, develop, and implement some models.

There are numerous simulation tools for the topics covered in this paper. While most of these tools are either commercially or freely available, some are inhouse tools solely used by their developers. Due to room limitation, it is not possible to describe each tool or even include a complete list. The following section summarizes the main studies that can be performed with the present tools, discusses their main limitations, and suggests some future research [23].

B. *Tools for Planning, Design, and Operation*

This subsection is divided into several parts; each one dedicated to one primary type of studiy, according to the classification used in the previous section.

Steady-State Analysis: Present power-flow tools are used to check for under/overvoltage, overloads, and assessment of losses. DR penetration provides several challenges to the 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 DR models. The primary needs for distribution system load-flow software with DR penetration are to assess voltage profile, losses, and capacity issues for arbitrary DR 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-h 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 s. Adding significant levels of nondispatchable DRs, such as photovoltaic, 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 DRs.

Fault-Current Analysis and Protection: 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 current contribution from conventional generation units may be important. 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 intertie transformer is important and its connection must be properly modeled. 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 DR models, a full range of transformer connections; interface with protection and reliability software, fault current flow under numerous switching states, and overvoltage estimation during faults [13].

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 [24]. The 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, these protective devices need to be re-coordinated or re-designed when DRs generate significant fault currents since this protective approach can fail under some conditions (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). There is thus a need for research on alternate protection strategies for some situations (e.g., where generation units supply fault current levels that can cause maloperation of the feeder protection, or in intentionally islanded systems, where fault currents can be small and vary widely). TOC protection will remain as the preferred protection strategy and it is highly desirable to continue to display the coordination information on the time-current curve. Software tools should therefore recognize the effect caused by the DR installation and the fact that the protected equipment and the various protective devices will now see different fault currents [13], [25]. When several generators provide the fault current, the challenge increases significantly. To effectively assess a given protective system, software tools are required that clearly present the impact of DR infeed current on the standard time-current curves.

Reliability and PQ: 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 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 DR reliability models and the effects of DRs on system reliability, considering the impact of various DR operating strategies; for example, the delay of DRs 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 [13]. A study aimed at testing the capabilities available in some distribution reliability planning tools was presented in [14]. The list of capabilities evaluated for each tool included circuit and reliability modeling capabilities, input data requirements, output results (e.g., reliability indices), load modeling capabilities, reliability improvement options, risk assessment, and economic evaluation methods. The tools analyzed are used worldwide by utilities and have very different capabilities. The list of areas recommended in the aforementioned reference 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, and the calculation of voltage dip and momentary interruption indices.

Several tools are presently available for the analysis of harmonics, flicker, voltage sags, and any type of current and voltage waveform analysis. Time-domain EMTP-type tools are a very common approach in PQ studies [29], since they can accurately represent almost any scenario. But for some cases, mostly for harmonic studies, the frequency domain can be faster and accurate enough. Harmonic analysis may also be performed by using a dedicated tool [30] or a capability implemented in some commercial packages. 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 [31], [32]). There are, on the other hand, overvoltages (e.g., lightning) not caused by generation whose effect on distribution equipment, including 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 [33]. These types of tools are also advisable when the transient response of DR devices has to be modeled in high detail.

A tradeoff is usually made between computational effort and accuracy. Selection, development, and implementation of EMTP-based models can require a significant effort, and some expertise is usually needed. This expertise can be very useful to introduce 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. As mentioned in the previous section, high levels of DR penetration raise some issues that need to be addressed through dynamic analysis. Dynamic models of different types of DRs are therefore needed, and they may also need to be incorporated into transmission stability tools. Models should also include the protective relay characteristics so that generators can be removed when they must be during the dynamic event. One way to analyze these situations (i.e., in the absence of transient stability capability) is to use positive-sequence transmission stability programs. Another option is to model the system in time-domain simulation tools, such as EMTP-type tools, which allow more detailed system and DR models, but it will 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 [34]: 1) electrical performance simulators; 2) analytical tools for reliability analysis; and 3) decision support methods to assist in evaluating and selecting from possible alternatives. Present planning tools can be used to assess the tradeoffs 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 [35] 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 DR planning. GIS tools can perform calculations aimed at determining the optimal location for DR 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 [35].

IV. ILLUSTRATIVE EXAMPLES

This section includes three examples that cover some of the main issues associated with the interconnection of DR to a distribution network. A similar organization has been used for each example: an introduction to the case study, a short summary of the main features of the simulation tool used for the study, and some results derived from the scenarios analyzed with each test system.

A. *Optimum Placement of DG Units*

Test System: The objective of this study is to determine the optimum placement of DG units so that the overall test system losses are minimized. The study is carried out using the IEEE 123-bus test feeder [36], which has a nominal voltage of 4.16 kV. Voltage regulators and shunt capacitors are incorporated into the system to address the voltage regulation issue. The system loading is unbalanced, and all loads are spot loads.

The test system is augmented with two three-phase balanced motor loads. One motor is connected to bus 47, which increases the existing load by 105 kW/75 kvar, and the other load is connected to bus 66, which increases the existing load by 75 kW/35 kvar. It is desirable to determine the optimal location (with respect to the system losses) of five generation units. Each unit generates 50 kW at unity power factor. The units are added one by one.

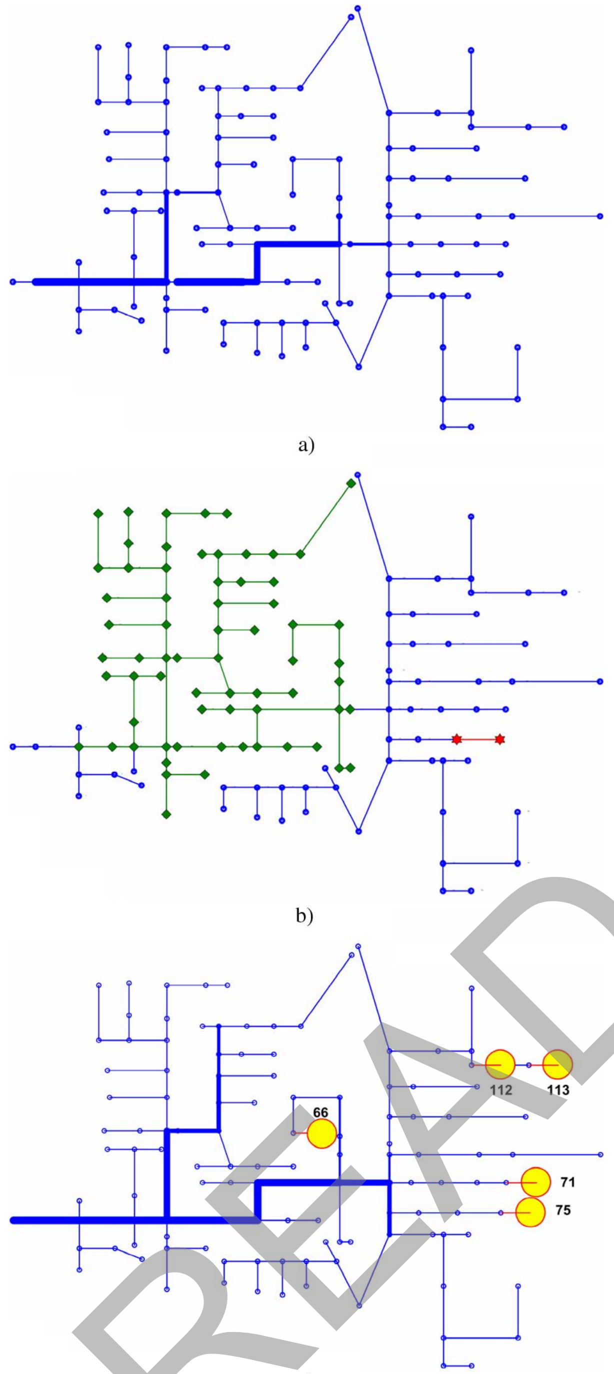
Simulation Tool: A model of the IEEE 123-bus test feeder has been built with OpenDSS, which is an open-source, frequency-domain software tool for steady-state analysis and design of distribution systems [37]. This tool can be employed for the analysis of distribution networks with integrated DR units. The applications of OpenDSS also include unbalanced load modeling, harmonic modeling, loss calculations, and DR modeling.

OpenDSS enables incorporating information about time and location dependency of the system components. This feature makes OpenDSS particularly useful for DR integration studies since the availability of some DR units varies with time. Moreover, OpenDSS can simulate a circuit with an arbitrary number of phases (e.g., single- and three-phase branches).

OpenDSS uses text-based scripts to describe the network. Its main strength is in its solution engine that can be interfaced to other software environments (e.g., MATLAB) through a common object model (COM) connection. This feature greatly contributes to the scalability of OpenDSS since new models and components can easily be added to it. This feature also facilitates postprocessing of the simulation results in a software environment that offers suitable plotting and calculation tools.

The circuit elements in OpenDSS are categorized based on their function as: power delivery (line, transformer, capacitor, and reactor); power conversion (storage, load, generator, voltage source, and current source); control (relay, storage controller, and fuse); and meters. OpenDSS represents system elements by their admittance matrices, which are amalgamated to form the overall admittance matrix of the system.

The present study is carried out by employing the solution mode *autoadd*. In this solution mode, OpenDSS tests each bus of the system to determine whether it is the optimum bus for


a)

b)

c)

Fig. 1. Example A: Losses, power flow, and voltages of the system with DG. (a) Losses. (b) Voltages. (c) Actual placement of all five DG units.

placement of the DG unit. It is also possible to ask OpenDSS to search only a subset of system buses.

Simulation Results: Under normal conditions, system voltages do not violate the standard 5% limits. After the connection of the new loads, middle buses (57 to 66), which are close to the load at bus 66, experience a low voltage (though still over 0.95 p.u.), and an increase of losses and power flows.

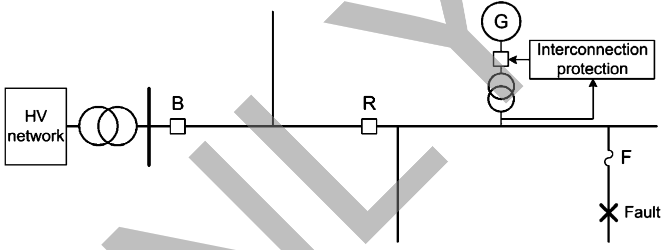
After connecting the DG units to the system, OpenDSS is used to determine the optimal bus for one DG unit. The optimality criterion is to minimize the system-wide losses. Fig. 1 shows the optimal placement of the five DG units, the losses, and bus voltages with the installed DG units. A dot indicates a bus with a voltage of more than 1.02 p.u., a diamond shows a bus with a voltage between 0.98 and 1.02 p.u., and a star shows a bus with a voltage lower than 0.98 p.u.

These locations are normally the locations where the DG units will have the greatest impact. Almost all buses (except two buses) are now within the stringent 2% limit.

Table II summarizes the specifications of each DG unit and the improvement they cause.

TABLE II
EXAMPLE A: ADDED GENERATORS (ALL GENERATORS ARE 50 kW WITH UNITY POWER FACTOR)

Order	Bus	Phases	Percent Improvement
1	123	1	8.64
2	112	1	7.24
3	71	1	6.61
4	66	3	6.05
5	75	1	5.81



HV equivalent: 110 kV, 1500 MVA, X/R = 10
Substation transformer: 110/25 kV, 8 MVA, 8%, Yd
DG interconnection transformer: 25/6 kV, 7 MVA, 4%, Yd
Lines: $Z_{1/2} = 0.61 + j0.39$, $Z_0 = 0.76 + j1.56$ Ω/km

Fig. 2. Example B: test system.

B. Impact of DG on the Coordination of Protective Devices

Test System: Fig. 2 shows the configuration of the system analyzed in this paper (a 25-kV overhead distribution feeder) and the parameters of some components. The diagram depicts the location of the protective devices and the fault that will be considered for analyzing protective device coordination.

Generator protection provides the detection of internal short circuits and abnormal operating conditions. Interconnection protection provides the protection that allows generators to operate in parallel with the grid. Utilities usually leave the responsibility to the generator owners to select the level of appropriate generator protection; however, they specify interconnection protection (winding configuration of the intertie transformer, general requirements and settings of interconnection relays, CT and VT requirements, functional protection requirements, and speed of operation to disconnect the generator prior to utility system automatic reclosing) [38].

Since a high percentage of faults in overhead distribution networks is temporary, utilities use fuse saving to prevent unnecessary lateral fuse operations. This practice is implemented with

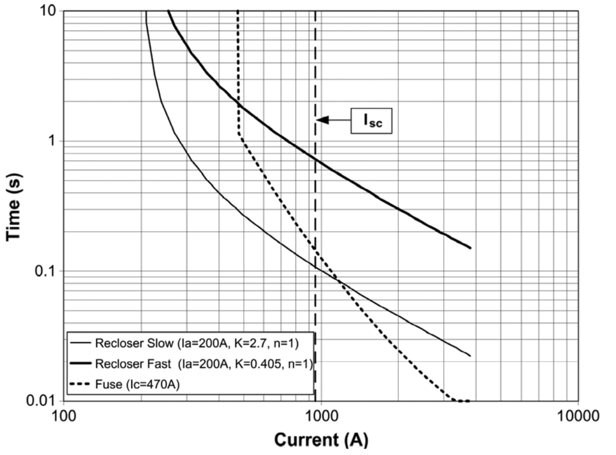
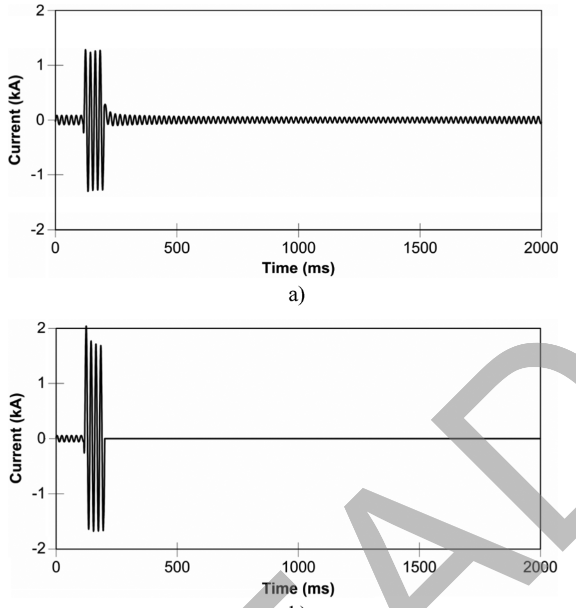


Fig. 3. Example B: time–current characteristics of the recloser and the fuse.



a)

b)

Fig. 4. Example B: simulation results with DG. (a) Current through the recloser R. (b) Current through the fuse F.

an instantaneous relay on a breaker or the fast curve on a recloser. Assume that there is a temporary fault downstream the fuse, see Fig. 2. The fault current is sensed by the fuse F and the recloser R. Without generation, the fault current through both devices is basically the same. However, the connection of the generation unit can impact the coordination between these two protective devices and force the fuse to act before the recloser [25]. This problem can be solved by replacing the fuse with a sectionalizer.

Simulation Tool: The study has been performed with the Alternative Transients Program (ATP) by using a custom-made library of protective device modules [39]. The model includes feeder and interconnection protective devices, but not generator protection. The interconnection protection is at the primary side of the transformer and includes relay functions for the detection of loss of parallel operation with the utility system, fault backfeed protection, and detection of damaging conditions (i.e., negative sequence and loss of synchronism).

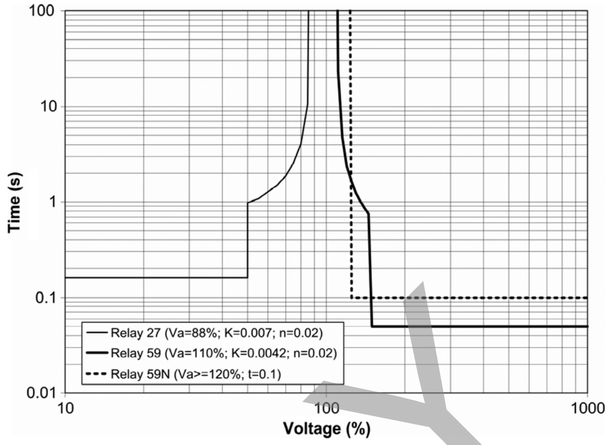
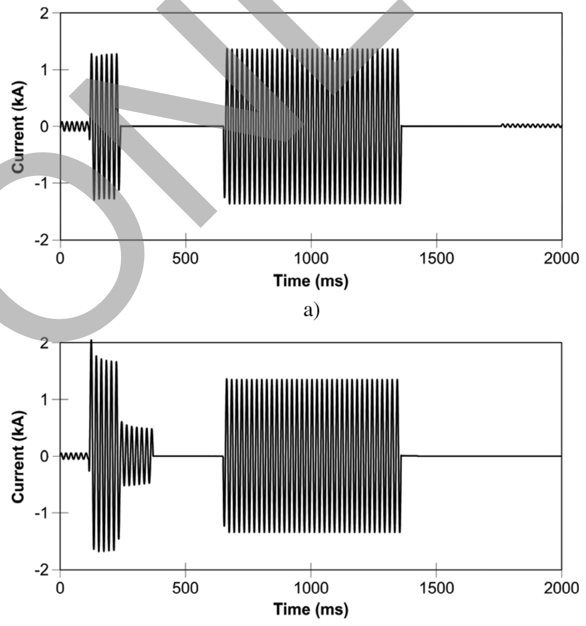


Fig. 5. Example B: over/undervoltage relay characteristics.



a)

b)

Fig. 6. Example B: simulation results with the sectionalizer. (a) Current through the recloser R. (b) Current through the sectionalizer.

The simulations have been carried out by using a lineal representation of transformers (i.e., saturation effects are not accounted for) and without including instrument transformer models.

Simulation Results: Fig. 3 shows the characteristics of the recloser R, and the fuse F, for which the minimum melting time curve is used as well as the fault current value sensed by both devices, without generation. The first operation of the recloser is made by using its fast curve, while the second operation is made by using the slow characteristic.

When a generator is connected and the point of common coupling is between the recloser and the fuse, as in Fig. 2, the current through both devices will be different. The current through the recloser will decrease and the current through the fuse will increase with respect to the values without generation [25]. This may cause a miscoordination between both devices, and the fuse could open first, even if the fault is temporary. Fig. 4 shows the

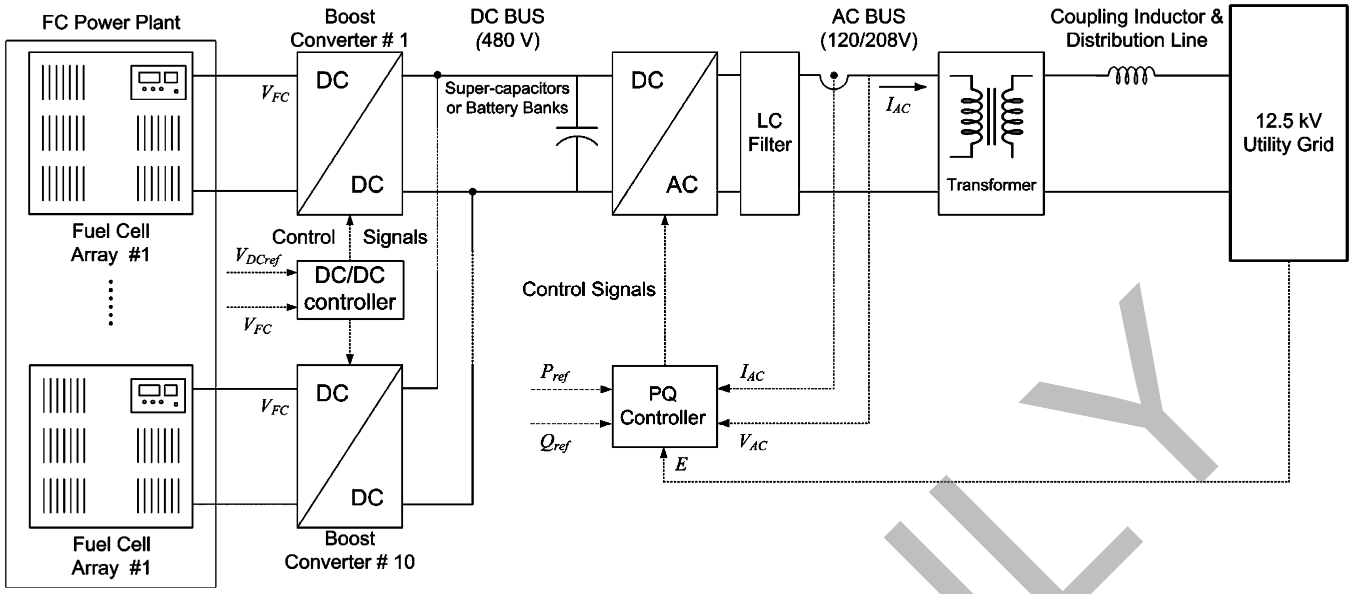


Fig. 7. Example C: diagram of a grid-connected FC system [40].

fault currents that result after connecting the generator. Note that the fuse opens first, so neither the recloser nor the interconnection protection of the generator act in response to this fault. The fault current through R decreases and the fault current through F increases when the generator is connected, leading to miscoordination of protective devices.

This problem may be solved by replacing the fuse with a sectionalizer, which is coordinated with the recloser. In this case, the sectionalizer will open after the first reclosing and before the second operation of the recloser.

In the previous case, the fuse did open first, so the main feeder and interconnection protections did not operate, and the generator was separated from the fault. In case of correct operation, the recloser should open and reclose before the sectionalizer opens; however, at the time the first reclosing operation is made, the generator should have been separated from the distribution feeder. The characteristics of the voltage relays that will act against loss of parallel are shown in Fig. 5.

Fig. 6 shows the results when the sectionalizer is installed instead of the fuse. Note that in this case, the interconnection protection decouples the machine from the network before the first reclosing operation, which takes place after the generator is decoupled from the feeder.

C. Dynamic Behavior of an FC System

Test System: Fig. 7 shows the schematic diagram of the test system. It consists of a fuel-cell (FC) array connected to a distribution system through an inverter and a step-up transformer. System ratings and parameters are provided in [40].

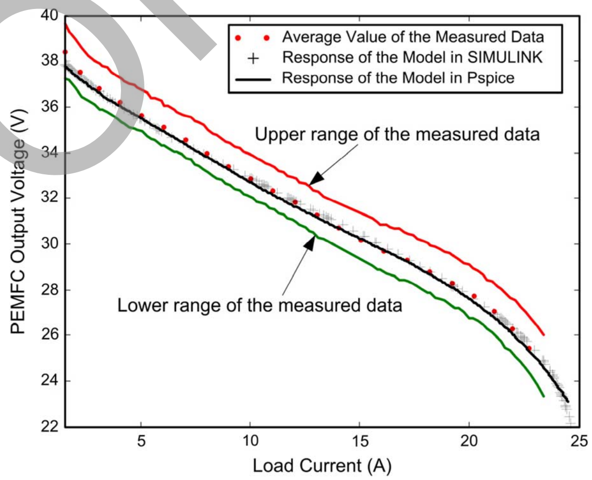


Fig. 8. Example C: PEMFC $V - I$ characteristic [40].

The PEMFC power plant consists of ten FC arrays connected in parallel. Each array consists of 96 500-W FC stacks. According to the $V-I$ characteristic of each stack, shown in Fig. 8, when the stack load current is more than 23 A, the FC is in concentration zone, which should be avoided [41], [42]. To leave some safe margin, the FC is operated around the point where its current is 20 A (rated operating point) and its output voltage is about 27 V. Therefore, 8 series of FC stacks are needed to obtain a voltage of 216 V. The number of FC series stacks needed to compose a 48-kW FC array is 12, so each FC array consists of 96 stacks.

A boost converter is used to adapt the output voltage of each FC array to the dc bus voltage and smooth the FC output current [43], [44]. In this example, the dc bus voltage (dc/dc converter output) is 480 V. The controllers for the boost dc/dc converters are designed to keep the dc bus voltage within an acceptable band (±5% in this case).

Pulsewidth modulated (PWM) voltage source inverters (VSIs) are used to interconnect the FC plant to the utility grid for power control purposes [45]. In this example, a three-phase six-switch inverter interfaces the dc bus with a 120-V/208-V ac power system. The inverter controller controls the real and reactive power flows to the utility grid. Real and reactive power flows follow their respective reference values, which can be either set as fixed values or to follow a certain load demand.

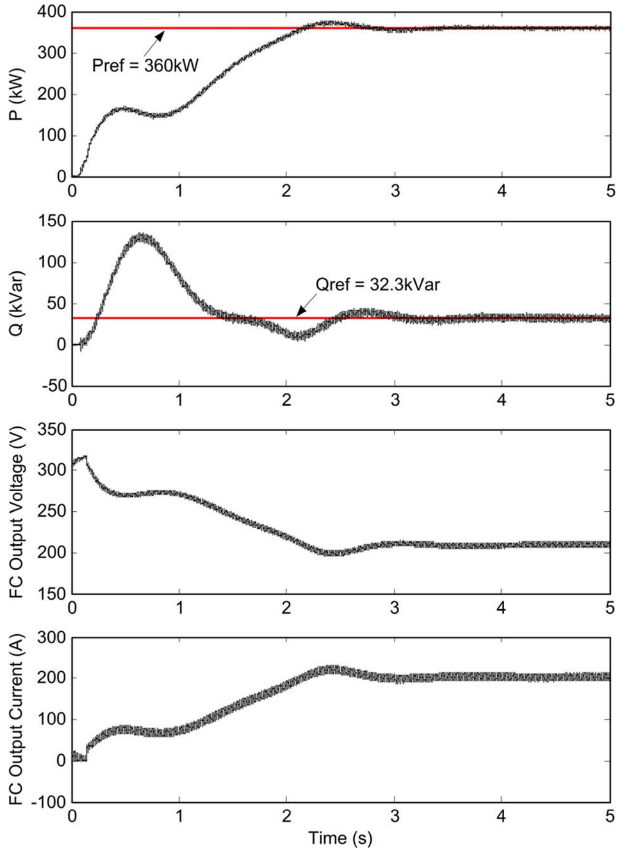


Fig. 9. Example C: simulation results under heavy load [40].

Supercapacitors or battery banks are connected to the dc bus to provide storage capability and fast dynamic response to load transients.

An LC filter is connected to the output of the inverter to reduce the harmonics introduced by the inverter.

A 208-V/12.5-kV step-up transformer connects the FC power system to the utility grid through a coupling inductor and a short distribution line. The coupling inductor is needed to control the real and reactive power flow between the FC DG system and the utility grid, and to limit disturbance and fault currents.

Dynamic models are considered for the FC plant, the dc/dc converters, and the three-phase inverter, while the step-up transformer and the distribution network are represented by simple RL decoupled branches. A detailed description of the models is given in [40].

Simulation Tool: The test system model has been built in SimPowerSystems [46], a tool box based on the general-purpose modeling environment MATLAB/Simulink, and specialized for the simulation of power systems transients.

Simulation Results: When a utility is operating under heavy load, the FC array may be required to deliver active and reactive power to the grid to help boost the system voltage. In turn, under light loading, the power required from the FC array will be normally low, and it may be set to consume the excessive reactive power from the grid (i.e., $Q < 0$).

Assume the reference values of P and Q are, respectively, set as 360 kW and 32.3 kvar with a ramp startup in 2 s. The voltage at the utility grid is set to 0.98 p.u. Fig. 9 shows the output voltage and current curves of each FC array, as well as the real and reactive power delivered from the FC array system to the grid when the DG system reaches its steady-state operation from the initial startup. Note that when the system reaches steady state, the FC output current ripple is about 10%, and the FC output voltage ripple is less than 3.3%. These relatively small variations of the current and voltage are indicative of the healthy operation of the fuel cells.

V. CONCLUSION

This paper has reviewed the main features available in commonly used simulators and reported their main limitations for planning, analysis, and design of distribution networks with DR penetration.

Many different software tools need to be used to fully analyze the electrical performance of distribution systems and DR 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 normal and abnormal operating conditions. Issues, such as ferroresonance or stability, require advanced modeling and analysis.

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