EXPLORING THE REQUIREMENTS AND CONSIDERATIONS FOR A PROBABILISTIC SIMULATION TOOLSET LEVERAGING OPENDSS

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ABSTRACT

Deterministic analysis has served and will continue to serve the industry well in distribution system analysis. However, with increasing penetration of distributed energy resources, the deterministic approach may no longer be enough. This paper explores the current state of probabilistic distribution system analysis and proposes requirements for a probabilistic toolset allowing for a more standardized and user-friendly approach for probabilistic distribution system analysis, specifically focusing on probabilistic load flow, than what is currently available.

INTRODUCTION

Distribution system planners are being asked to design a safe, reliable, and resilient system while addressing a system that is increasingly dynamic, complex, and uncertain. Deterministic analysis can provide the expected value, minimum or maximum value, or the value of any other needed point. However, a deterministic analysis cannot provide the probability or likelihood of their occurrence. Current planning tools and methods are deterministic in nature and cannot sufficiently account for the growing uncertainty in distribution systems. Thus, they are unable to meet the requirements of probabilistic analysis. Much of the commercially-available probabilistic analysis tools that are current available are either designed for other industries or for general analysis [1]. Thus, they can be difficult to apply directly to distribution system planning and analysis. The goal of the toolset proposed here is to provide methods that permit the accurate computation of system load flow analysis considering variations and uncertainties of the distribution system, while addressing the complex correlation factors between system components. Building upon the OpenDSS platform [2], the toolset will facilitate the comparison and validation of assessment techniques, derivation of industry guidance, as well as drive innovation in industry assessment tools.

This paper explores the current state of probabilistic distribution system analysis and the requirements for the probabilistic simulation toolset, while providing the foundation for evaluating and defining future probabilistic assessment practices. In determining the requirements, the paper will explore:

- the tradeoffs of various solution methods, both analytical and simulation based;
- quantifying the uncertainty of various system aspects, e.g. forecasted temporal load and distributed energy resources, system configuration, and contingency events; and
- the correlation between system aspects, how the correlations may differ due to changes in the system, and how this correlation will impact the analysis.

The toolset itself is not presented, but rather a thorough analysis of all the considerations and requirements that should be addressed while creating the probabilistic simulation toolset.

BACKGROUND INFORMATION

The deterministic "fit-and-forget" approach served the industry well when the flow of power was unidirectional – flowing from the source to each customer – and the system is typically planned against a single worst-case scenario. If the system can meet the worst-case, then all other scenarios will be fine. In some cases, the analysis may involve several deterministic simulations depending on the scenarios being considered. Depending upon the defined scenario, deterministic analysis can provide the expected value, minimum or maximum value, or the value of any other needed point. However, deterministic analysis cannot provide the probability of their occurrence. With the possibility of two-way power flow and increasing uncertainties in location, direction and output, a worst-case scenario may not be enough, or even easily defined. Furthermore, building the system to handle a future worst-case scenario that is unlikely to occur may result in unnecessary capital expenditures and possible low utilization of assets. A probabilistic analysis provides a statistical approach to account for the uncertainties in the system, providing the probability of an event occurring on top of its impact, allowing planners to make more informed decisions [3].

Probabilistic Distribution System Planning

Figure 1 shows a general framework for planning of active distribution systems, which has been proposed by the CIGRE C6.19 working group [4], and Figure 2 shows EPRI's proposed framework for the simulation and assessment of advanced control within distribution planning [5]. CIGRE's framework is that of a more general probabilistic planning process, while EPRI's proposed framework examines more specifically the needs and structure of future distribution assessment tool. Both frameworks highlight the importance of probabilistic

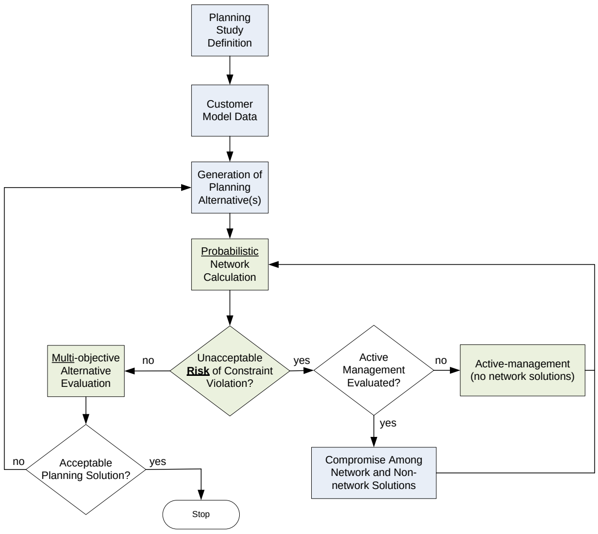

Figure 1: General procedures for active distribution system planning proposed by CIGRE Working Group C6.19 [4]

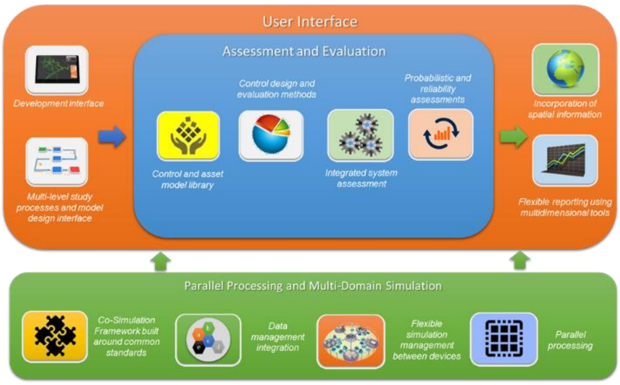

Figure 2: Modular framework of future distribution planning and assessment tools [5]

assessments and network calculations. A probabilistic assessment can be defined as an analysis performed through probabilistic load flow (discussed in the next section) where the output of the calculations are the stochastic or probabilistic representation of nodal voltages and branch currents, during both normal and emergency conditions, which can be evaluated in terms of acceptable risk of constraint violations. And it is this probabilistic assessment that is the main objective of the probabilistic toolset.

An overview of the currently available commercial tools is available in [1]. While there are plenty of probabilistic tools, there is a lack of any focus on power or distribution system analysis. This is especially apparent within the distribution system simulation tools themselves, that focus specifically on deterministic analysis. Multiple tools support scripting capabilities allowing for expandability. The proposed probabilistic toolset leverages this capability within OpenDSS.

Probabilistic Load Flow

Probabilistic load flow is an extension of the deterministic load flow calculation taking into account stochastic uncertainty. There exists a large variety of deterministic load flow techniques. Most are accurate and allow for detailed deterministic modeling of the power system. However, their downside is their reliance on the input variables, which are generally not well known. In cases with stochastic or statistical uncertainty, the problem can be addressed using a statistical approach, probabilistic load flow. A brief review of the most cited probabilistic load flow literature up to 2008 can be found in [6] and a newer comprehensive review up to 2017 is presented in [7]. For a more detailed explanation of probabilistic load, including an illustrative example, a brief history of the evolution of probabilistic load flow, and a comparison of probabilistic load flow methods see [3].

Simulation Versus Analytical Techniques

Probabilistic load flow can be solved analytically, with any preferred convolution technique, or through a Monte Carlo simulation. Due to the non-linearity of the load flow equations, most analytical techniques depend on the linearization of the load flow equations and may require a work around for other non-linear system components. Monte Carlo simulations can utilize the exact non-linear load flow equations, and while some assumptions may still need to be made, the statistical dependency between the inputs are easier to implement. However, Monte Carlo simulation methods can be very time and resource intensive. Current research trends are working on improving solution techniques (e.g. parallel processing), typically with advanced Monte Carlo techniques and faster computers. Monte Carlo simulation techniques are also commonly used to validate/compare the results of analytical methods, as the accuracy of the Monte Carlo simulations depends on the number of simulations, which can become time intensive as the number of solution points increases and the solution may not always converge. Because of its accuracy and ability to address both non-linear components and correlation of system components over analytical techniques, Monte Carlo simulation will be the primary method adopted in the probabilistic toolset.

Correlation Between Variables

One of the greatest concerns with probabilistic load flow is how to determine and properly handle correlation between the various probabilistic inputs. Very few works on probabilistic load flow assume any dependence between the loads and other inputs, let alone try to model real-world correlations. The correlation between inputs can have a major effect on the resultant power flows and voltages.

Customer behavior, non-linear components (voltage regulators, capacitor banks, reactors etc.), controls and more, all play a role in future distribution systems and the correlation between the various inputs of a feeder model. A small change in one of these may have a significant impact on the results. For example, different electric vehicle charging schemes can change the correlation between the electric vehicle charging loads and the standard household loads leading to different power flow and voltage density functions, as shown in Figure 3. The histograms represent the actual results and the various lines are the results from a probabilistic load flow analysis under different correlation assumptions. The left column plots the active power flow at the feeder head and the right column plots the voltage magnitude for a customer point of connection at the end of the feeder. In the analysis three different charging scenarios are considered, and the effects on the resulting distributions can be seen in the figure. When the electric vehicle charging controls are present (b, c, e, and f), they remove the correlation that is implicitly present, i.e. the fact that on average customers in the same demographic (neighborhood) arrive home at the same time to charge their vehicle and they start charging their vehicle as soon as they arrive home, which is then independently controlled by the charger. More information on the study can be found in [9] and [10]. By being able to account for the correlation between the probabilistic inputs, a more accurate representation can be found through the analysis leading towards a better decision process.

Use Cases

While there is extensive literature on probabilistic load flow for improving both the accuracy and required solution time; there is a lack of documented "real-world" use cases. Most work focuses on the algorithm alone or academic exercise with renewable energy and electric vehicle studies with little forethought on its practicality. The only "real-world" application of probabilistic load flow, the authors have found, is from the 1990's in Brazil where probabilistic load flow had been utilized for power system operational and expansion planning [11] – [13]. Different operational and expansion policies are analyzed with the probabilistic load flow providing a more detailed result allowing for the operators and planners to make a more informed decision and implement a different policy in their process than they normally would have with traditional deterministic methods.

The uncertainty around any aspect of the load flow problem can be modeled probabilistically, not just the typical input variables load and generation. For example, in [8] the location of a fault is varied randomly (based on historical data) and the voltage response is recorded providing a distribution of the voltages, Figure 4, for the system if a fault occurs. The distributions show that when a fault occurs in the system there is approximately a 10% chance that a 208-volt bus will have zero voltage, and the average voltage is approximately 0.7 pu, which is low enough for any motor loads to drop out.

PROBABILISTIC TOOLSET

While the development and application of probabilistic planning methods continues to be an active area of

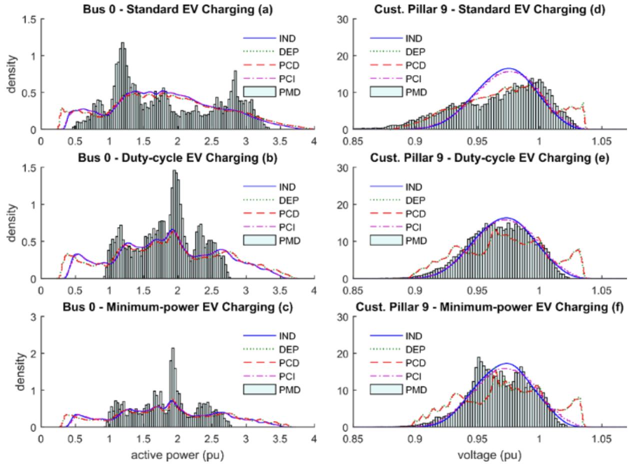

Figure 3: Probability density functions of select results from a probabilistic load flow analysis including multiple electric vehicle charging controls and assumed correlation scenarios [10]

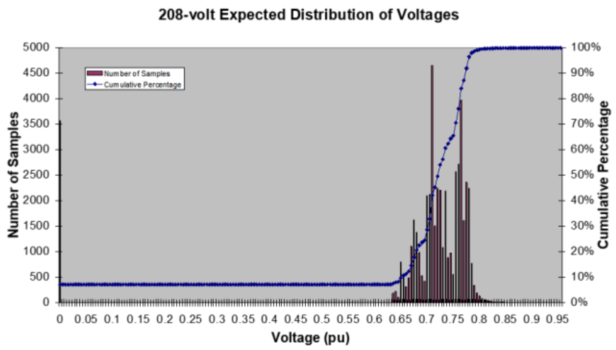

Figure 4: Distribution of the voltages magnitudes at a 208-volt bus from a Monte Carlo fault study [8]

research, these methods have not been widely integrated in distribution planning practices. An overview of the currently available commercial tools is available in [1]. While there are many tools for probabilistic analysis, very few address power or distribution system analysis directly. While most of traditional distribution system simulation tools do not support a probabilistic analysis directly, they include scripting capabilities for advanced users to realize probabilistic analyses. Table 1 lists the identified software and the available scripting interfaces. The main purpose of the probabilistic toolset is probabilistic load flow analysis and is a wrapper for OpenDSS and will utilize the COM interface as listed in Table 1.

There are five main parts to the analysis toolset. The input data, the analysis or simulation, data storage, the processing of the results, and the user interface. The probabilistic toolset hopes to address the concerns listed above and allow a thorough set of tools for probabilistic analysis. As stated previously, the focus of this toolset is on probabilistic network calculations, mainly probabilistic load flow.

Input Variables

The inputs for a probabilistic load flow are the same as any load flow or power flow, but with a few additional requirements. Since the toolset will rely on OpenDSS as the solver for the main analysis, all circuit parameters and base variables need to be in a compatible form. While parameters can be the same for a probabilistic load flow, the variables will be different. That is, instead of deterministic values, the variables will be random variables represented by a continuous or discrete distribution. If sample data is available, it can be used directly to create a discrete distribution; otherwise one of several continuous distributions, such as Gaussian or Weibull, can be selected with the appropriate parameters chosen by the user. Besides loads and generators, other circuit components can also be considered and represented by random variables – such as fault location [8], transformer models, equipment location, control schemes, etc.

Another aspect that needs to be addressed in any probabilistic analysis, is the correlation between the probabilistic input variables, for more information see [3]. Whether the input variables are correlated, independent or somewhere in between, it needs to be accounted for in the analysis. If the time-series data used to create the discrete distributions is available, the linear correlation coefficient can be calculated directly. If not, the user can once again define the values based on past analysis and/or experience. Remember, even small changes in various controls can have a big impact on the correlation between various variables and parameters in the analysis. Because applying probabilistic analysis to the distribution system is a new area of concern and research, there is not much insight on the correlations of various parts of the grid that can be provided without further analysis. One of the main reasons for this toolset is to help provide the necessary tools and insight to help provide guidance in future analysis.

Analysis

The actual analysis or simulation part of the probabilistic toolset leverages OpenDSS. The probabilistic load flow analysis will utilize a Monte Carlo simulation based technique for several reasons. The main two being accuracy, especially when including nonlinear components; and the ability to account for any correlation level. The probabilistic toolset will not be solving the individual load flows, but feeding the simulations into OpenDSS. OpenDSS also has parallel processing capabilities [14] that can be advantageous in speeding up the Monte Carlo simulations. The convergence values and maximum number of simulations should also be user defined to optimize the speed versus performance of the analysis depending on the use case.

Data Storage

To allow for repeatability and more transparent analysis of the results, care will be required in how to best store not only the probabilistic input data, but also the results from each simulation. If there are any anomalies in the results it will be easier to investigate them further with the results and input variables being saved for all the simulations. OpenDSS has several methods for calling and storing simulation data. The ideal solution will require more research to determine the most efficient manner to call and store the results. Multiple methods may be utilized depending on the results required and new methods may need to be developed.

Table 1: Scripting options of distribution system simulation tools

Software Name (Developer)	Scripting and Automation Options
CYMDIST (EATON)	COM interface and python scripting
DINIS (Fujitsu)	API for Java, Tcl/Tk or any Ole Automation (or ActiveX) aware development tool, such as Visual Basic or Delphi
DSATools (PowerTech)	Python scripting
GridLAB-D (PNNL)	API
Ipsa 2 (IpsaPower)	Python scripting
MATPOWER (PSERC)	MATLAB scripting
NEPLAN Electricity (NEPLAN)	API for C/C++
OpenDSS (EPRI)	COM interface
PandaPower (University of Kassel)	Python scripting
PowerFactory (DIgSilent)	Python scripting, DIgSILENT programming language, and API for C++
PSS SINCAL (Siemens)	COM interface
Synergi (DNV-GL)	COM interface and Python scripting

Processing of Results

Besides the actual simulation the most important step is in analyzing and conveying the results. The results of a probabilistic load flow analysis will be random variables. If the resultant random variables are of known distributions, which most likely will not be the case, they can be described quantitatively by their moments: expected (mean) value, standard deviation, skewness, etc. However, with multiple correlation factors, various distributions for the input variables, and nonlinear network components to name a few, it is highly unlikely the resultant random variables could be fully described by their first few moments. Plus, it is difficult to picture how the moment affects the distribution past the third moment (skewness), nor will the moments easily describe a discrete distribution function. Therefore, it may be more appropriate to examine the random variables' distributions directly as shown in Figure 3 and Figure 4.

The active and reactive power flows, voltage magnitudes and power losses will be some of the results of most interest. However, depending on the analysis, the state of switches, capacitors and other controls may also be of interest. New means may be required to plot and visualize the multidimensional results. Recently, work has begun on a probabilistic visualization tool [15], which can be integrated into OpenDSS and OpenDSS-G and could be expanded for the probabilistic toolset to increase the integration with OpenDSS. It may also be necessary to develop new metrics to support easily understood and comparable – apples-to-apples – reports and analytics from the calculated data.

User Interface

The probabilistic toolset is a wrapper for OpenDSS interacting with it through the COM interface and will require the system to be modeled in the standard OpenDSS format. The main user interface will be script based with functions to process the probabilistic input variables, run the Monte Carlo analysis, and save and process the results. The main structure for the probabilistic data files both input and output files for the toolset will be a comma-separated value (CSV) file or text file. Figures can be saved in a variety of commonly supported formats. The user will be required to specify the input files with the respective system components, as well as any other system parameter necessary for the intended analysis. While not as user friendly as a graphical user interface (GUI), the script based interface will allow for greater flexibility and development as probabilistic planning needs and practices mature, while keeping the door open for a possible GUI in the future.

CONCLUSION

There is a growing interest in probabilistic distribution system planning. However, while there are many viable load flow tools available, not many are probabilistic in nature, or they may require more intimate knowledge in programming, distribution systems, and/or probability and statistics to facilitate. The goal of the probabilistic toolset is to provide easy entry into the accurate computation of load flow analyses considering the variations and uncertainties of distribution systems, while also addressing the more complex concept of correlation between the system components. The toolset will leverage OpenDSS as its solver, allowing for a shorter learning curve for both users of OpenDSS and other common power flow tools because all of the system parameters, input files and out files will be formatted in a similar manner. The toolset will also facilitate the comparison and validation of assessment techniques, derivation of industry guidance, and drive innovation in industry assessment tools.

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