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Computer-Based Voltage Dip Assessment in Transmission and Distribution Networks

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***Summary*: Digital simulation is a powerful mean to predict the voltage dip performance of a power network. Voltage dip characteristics can be accurately reproduced using present simulation tools and a stochastic prediction procedure that could incorporate the random nature of the voltage dip causes and the behaviour of sensitive equipment during this type of events.**

This work is aimed at providing a review of techniques that can be applied to voltage dip prediction, assuming that voltage dips are caused by faults. The paper includes a discussion on modelling guidelines to be used for representation of power system components in voltage dip calculations, a summary of the capabilities required in simulation tools applied to voltage dip studies (characterisation, assessment, index calculations) and a representative list of procedures presented to date for voltage dip assessment in both transmission and distribution levels. The last section is aimed at providing some information about the difficulties related to voltage dip assessment when distributed generation is connected to the grid.

Key words:
voltage dips,
modelling,
simulation,
stochastic prediction,
distributed generation

1. INTRODUCTION

A voltage dip is a sudden reduction of the voltage below a specified threshold followed by its recovery after a brief interval. The problems caused on sensitive equipment are the main concern on voltage dips, since devices like computers, process-controllers and adjustable-speed drives will trip when the voltage drops below a certain threshold. The causes of voltage dips are motor starting, transformer energizing and faults.

Monitoring and computer simulation can be used to assess the voltage dip performance of a site or an entire power system. However, the monitoring period required to obtain an accurate assessment is too long. This paper provides a summary of the work performed to date on voltage dip assessment using computer simulation. The document introduces the type of solution techniques and procedures used in voltage dip studies.

The paper assumes that faults are the main cause of voltage dips in power systems and their characteristics (location, duration, resistance, type) are random. A stochastic approach is then the most suitable way to predict the number and the characteristics of voltage dips. Voltage dip simulations are as accurate as models and data used in calculations. Data involved in voltage dip assessment are power system and component reliability parameters, which can only be obtained through observing the behaviour of the system component over a long period of time.

2. VOLTAGE DIP CHARACTERISATION

Figure 1 shows an example of a three-phase non-symmetrical voltage dip. The figure depicts how the rms voltages drop to different values for each phase during more than 3 cycles after which they recover to values equal to those prior to the event. Note that although the transition from pre-event to during-event rms voltages takes about 1 cycle, it takes place almost instantaneously in the left plot. This difference is due to the 1-cycle window used in the calculation of the rms voltage. Using a half-cycle window will give a faster transition but it could also give oscillations in the rms values.

Standards related to voltage dip characterisation are almost exclusively concerned with two parameters: root mean square (rms) value of voltage magnitude and duration

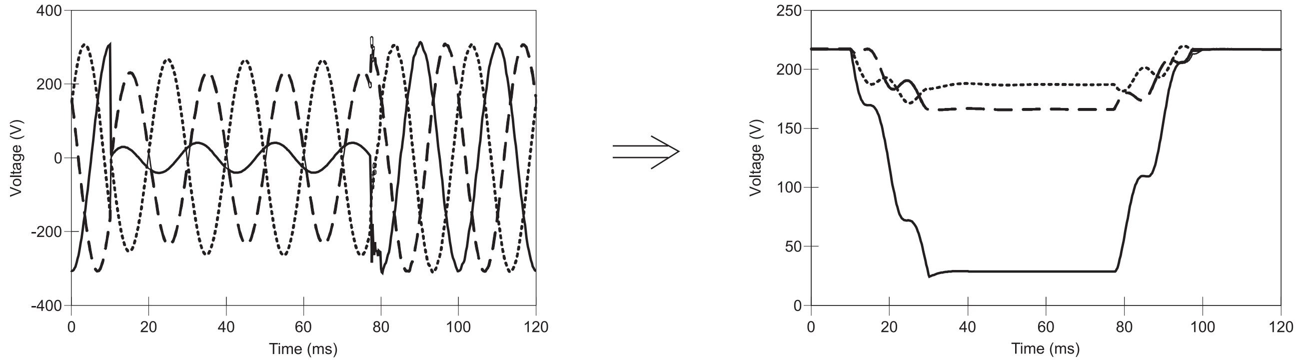

Fig. 1. Example of a three-phase voltage dip

[1, 2]. Magnitude denotes the retained voltage during the fault, usually given as a percentage of the rated voltage, while duration is the time difference between the moment at which the voltage falls below the corresponding dip threshold, and the moment at which the dipped rms voltage rises above it. However, both the initiation and the ending of a disturbance are related to the instantaneous voltage waveform, not to the rms voltage. Therefore, the use of the rms voltage values can result in non-negligible errors (see Fig. 1).

Power frequency voltage can be seen as a complex quantity. A change in the system can cause a change in voltage that includes a change in the phase-angle, which is referred to as the phase-angle jump associated with the voltage dip. A phase-angle jump is not of concern for most equipment, but some static converters that use phase-angle information for their firing instants can be affected. In addition, the reinstatement of the pre-fault voltage after a voltage dip ending can cause inrush currents whose characteristics and effects will depend on the point of wave with which the dip ends [3].

Since the majority of voltage dips are caused by single-phase-to-ground and two-phase faults, three-phase equipment can experience a different magnitude, and even a different duration, on each phase. A conservative method of characterization uses the lowest of the three rms voltages and the longest duration.

Several methods for classification of three-phase voltage dips have been proposed [1, 4–7]. For instance, the *ABC* classification, which was introduced to describe the propagation of dips through transformers [1], and the *symmetrical component* method, which was originally developed for stochastic prediction of voltage dips.

3. EQUIPMENT BEHAVIOUR

The performance of a power system can be fully assessed if voltage dip characteristics as well as the voltage tolerance of equipment are known. For each piece of equipment it is possible to determine how long it will continue to operate after the supply becomes interrupted or the voltage drops below a certain threshold.

The concept of voltage-tolerance curve was introduced with the CBEMA (Computer Business Equipment Manufacturers Association) curve [8]. This curve was originally designed to identify computer vulnerability to power supply disturbances, and it has been redesigned and renamed for its supporting organization, the Information Technology Industry Council (ITIC) [9]. The applicability of these curves is limited to single-phase equipment, although they have also been applied to three-phase loads during symmetrical voltage dips.

Both testing and computer simulation can be used to obtain voltage tolerance of sensitive equipment. Although testing is the most efficient way, standards related to testing are almost exclusively concerned with the reproduction of rectangular voltage dips, and they neglect the presence and possible influence of non-ideal voltage supply characteristics [10]. Factors that may have an influence on the equipment response to voltage disturbances can be divided into the following categories: voltage supply related electrical characteristics; equipment specific electrical characteristics (i.e. factors related to operating/loading conditions and malfunction criteria); non-electrical characteristics (i.e. characteristics of the ambient in which both equipment and power supply system should operate: temperature, humidity or air pressure) [11–13].

4. SIMULATION TOOLS FOR VOLTAGE DIP STUDIES

Several types of simulation tools can be applied to voltage dip studies. Simulation tools, as well as solution techniques, are selected taking into account the goals of the study, the accuracy required in calculations or the voltage dip characteristics to be predicted: if only the retained voltage is of concern, a frequency-domain tool and steady state models can be used; however, if other characteristics must be estimated (e.g. the voltage dip duration), a more detailed model of the system will be needed and calculations will be more accurate if a time-domain simulation tool is applied. Table 1 shows the capabilities required as a function of the study goals.

Two main solution techniques are presently used in voltage dip calculations:

1. Time-domain solution

A time-domain calculation can capture all voltage dip characteristics (magnitude, duration, phase angle jump, point of wave) with high accuracy. The most common approach implemented in present time-domain simulation tools is a combination of the trapezoidal rule and the Bergeron's method, which are used to convert the differential equations of the network components into algebraic equations involving voltages, currents and past values. These algebraic equations are assembled using a nodal approach [16].

2. Frequency-domain solution

Although frequency-domain techniques can be used to obtain time-domain solutions, they are mostly applied to obtain the ac steady state solution of linear networks. At least, two approaches can be used in voltage dip calculations: bus admittance matrix and bus impedance matrix. An important disadvantage of these solution methods is that they cannot be applied in the presence of nonlinear components or variable topology circuits, which can produce steady state harmonics.

Hybrid techniques (a combination of time- and frequency-domain techniques) have already been used, mainly in steady state solutions of systems with non-linearities and variable-topology converters.

5. MODELLING FOR VOLTAGE DIP CALCULATIONS

The representation of equipment involved in transient phenomena is usually chosen taking into account the range of frequencies that are associated to the simulated phenomenon [14]. In general, transients associated to voltage dip causes

Table 1. Simulation tool capabilities for voltage dip studies [15].

Study	Goals	Capabilities
Single-event calculations	Obtain some or all charac-teristics of voltage dips at nodes of a power system.	— Three-phase calculations — Models adequate for steady state calculations when the retained voltage is the only variable of concern — Protection models, if the dip duration has to be estimated — Models to reproduce the transient behaviour and options to capture transients if other voltage dip characteristics are to be estimated.
Stochastic predictions	Obtain the probability density function of some or all characteristics of voltage dips at nodes of a power system. Obtain the rate of occurrence of different voltage dip characteristics.	Capabilities shown above plus a multiple run option (this should include all options required to perform a Monte Carlo solution) and post-processing capabilities (i.e. those capabilities needed to determine probability density functions and rates of occurrence).
Sensitivity analyses	Deduce the effect that some system and fault parameter can have on the voltage dip performance; e.g. the number of trips at a given load node.	Capabilities shown above plus a multiple run option and post--processing capabilities.
Voltage dip index calculations	Obtain index values for either sites or the entire system.	Similar to those required for stochastic predictions.

Table 2. Modelling guidelines for voltage dip studies [15].

Component	Modelling guidelines
Conventional and distributed generators	The representation of any generator will depend on the area of vulnerability of the voltage dip. If the generator is connected to an affected node then a detailed model, suitable for simulation of slow transients (incorporating control units and nonlinear effects) can be needed; otherwise a constant voltage source behind its transient reactance can suffice.
Network equivalents	The most accurate representation should be deduced from the frequency response of the transmission system that is feeding the distribution network; however, a three-phase Thevenin equivalent model deduced from the short-circuit capacity is good enough when simulating low frequency transients.
Lines and cables	Distributed-parameter models should be used to obtain very accurate simulation results; however, lumped-parameter models are usually acceptable and they should be used in probabilistic studies.
Transformers	Saturable models are needed when transformer energization is the voltage dip cause; however, when the event is caused by a fault, linear models will produce accurate enough results.
Protection systems	Circuit breakers, reclosers and any type of disconnectors can be represented as ideal switches in low-frequency transients. A non-linear resistance is needed to represent fuses. Protective relay models should only incorporate delays and reclosing times. A more accurate representation of the protection system should also incorporate instrument transformers. Generator and interconnect protection (including islanding detection and protection) is required for DG units running in parallel with the utility.
Power electronics equipment	A switching model with semiconductor devices represented as ideal switches will generally suffice, although averaged or steady state models can be also considered. Very rarely more advanced and detailed models will be needed.
Loads	A constant impedance (i.e. a parallel R-L) model can be good enough in many dip studies; a more accurate load model could also show voltage dependence, dynamic behaviour and voltage dip sensitivity. In probabilistic studies, the load model could incorporate a daily variation and a random nature.

can be classified as low frequency and slow front transients. If only voltage dips caused by faults are simulated, the frequency range of transients is in general below 5 kHz; therefore, models should be capable of reproducing very accurately transients within this frequency range.

Table II provides a summary of guidelines to be considered when modelling the most important power components for voltage dip simulations and a time-domain technique is used.

Models to be used with a frequency-domain calculation will be rather different. Most commercial and user-developed simulation tools based on this technique cannot handle nonlinearities and variable-topology converters; in addition, they are generally used for calculating voltage dip magnitudes only. Therefore, models that could accurately reproduce voltage and current unbalances, with parameters specified at power frequency (50/60 Hz), will usually suffice.

6. VOLTAGE DIP PREDICTION

Voltage dips can be studied from different perspectives, see Table I. The simulation tool, as wells as the model used to describe the disturbance and the system model, have to be selected accordingly. To obtain statistics on magnitude of fault-caused voltage dips only, modelling based on phasors and the use of the bus impedance matrix will suffice. If statistics about other voltage dip characteristics are needed, then a time-domain simulation could be required.

The most common methods proposed for stochastic prediction of voltage dips are described below:

1. The *method of critical distances* calculates the fault position for a given dip magnitude; that is, the part of the system in which a fault would lead to a dip of given characteristics at a desired location [1, 17, 18]. The number of dips below a given threshold will be equal to the number of faults that are closer to the load than the indicated position. This method, as presented in the above references, is limited to radial systems only.
2. The *method of fault positions* calculates the characteristics of voltage dips for a number of faults spread throughout the system [1, 19]. The first step is the selection of the fault positions. Faults may occur at any location in the power system and they are randomly distributed. The choice of the fault positions and their distribution may significantly influence the accuracy of the prediction. Obviously, the accuracy of the results is increased by increasing the number of fault positions.

Other methods have been developed. They are generally based on an alternative formulation that solves analytically the calculation of voltage dip magnitude. Table 3 presents a summary of the main features and the applicability range of some procedures for stochastic prediction of voltage dips [20–35]. The list is not complete but representative of the work performed during the last years.

The procedures referred in Table III were implemented in a broad range of simulation tools, since authors used from custom-made simulation tools to commercially available packages.

Monte Carlo based approaches could be considered a variant of the method of Fault Positions based on an iterative procedure in which random variables are calculated according to their statistical distributions every time the system is simulated.

An alternative methodology, called Expected Sag Frequency (ESF) by the authors [34], has been also proposed to obtain the area of vulnerability due to both balanced and unbalanced faults in meshed network combined with the voltage-tolerance characteristic of sensitive equipment.

A majority of procedures are based on frequency-domain calculations, because this solution technique is faster when only the steady state retained voltage is of concern. Very few procedures have been developed for assessment of both magnitude and duration of voltage dips, although in this case both frequency- and time-domain techniques have been applied. In general, when a frequency-domain technique is used, the solution is based on the bus impedance matrix, while calculations based on a time-domain technique use the nodal admittance matrix.

The number of equipment trips has been obtained using a frequency-domain calculation method [29], or a time-domain calculation method [32]. In all cases, equipment was represented by a voltage tolerance curve. As mentioned in Table II, a complete load model may include voltage and frequency dependency, dynamic behaviour and voltage tolerance. Voltage dip characteristics can be strongly influenced by the selected model. Not much experience is available on the application of probabilistic load models, which can be extremely complex [36].

Other works related to this subject were presented in references [37–41].

IMPACT OF DISTRIBUTED GENERATION

The term Distributed Generation (DG) refers to a variety of compact generating technologies that are often combined with energy storage devices and used to improve the operation of transmission and distribution systems [42–47]. The assessment of voltage dips in power systems with distributed generation (DG) can be performed by following the methods already revised. There are, however, some significant differences that are worth taking into account when embedded generation units are running in parallel with the system under study.

1. Standards do not allow the operation of part of a system in island conditions where DG is supplying part or the total load of the island. DG is usually equipped with an islanding detection method responsible for disconnecting the generation units once an islanded condition occurs [48]–51]. The IEEE Std 1547 standard dictates that the island condition be detected and the DG cease to energize within 2 seconds of the island occurring [52]. Abnormal frequencies and voltage ranges are also specified, which could be used as a basis for an anti-islanding technique. This can have an impact on voltage dips since islanded generators cannot always maintain voltage within an acceptable level, but there are many situations in which a quick disconnection can aggravate the scenario.
2. DG can have a significant impact on the coordination of protective devices in distribution networks [53, 54]. Embedded generators do not change the radial topology of these networks but the power will no longer flow in a single direction. Protection devices are coordinated such that the primary protection operates before the backup can take action. However, interconnecting the DG increases the short circuit level and depending on the original protection coordination settings along with the size, location and type of the DG, uncoordinated situations, loss of sensitivity or unwanted bi-directionality may be caused. The loss of coordination can take place between any pair of protective devices, i.e., fuse-recloser, fuse-fuse, overcurrent relay-recloser, overcurrent relay-fuse. Fuse nuisance blowing can increase the frequency of voltage dips and interruptions.
3. The interaction between distributed resources and the system in which they are embedded involves several phenomena that are worth investigating. Thorough studies of the impact of different DG technologies and their implementation could be required. These studies should cover both the steady state as well as the dynamic behaviour of the system. The design of distribution networks has not included stability issues as the network remains stable provided the transmission network is itself stable, but this is changing as DG penetration increases. The areas that need to be considered include transient stability (first swing) as well as long term dynamic stability. Dynamic simulation is essential for planning and operation studies of systems with distributed generation, but it can be also important for voltage dip assessment.
4. The dynamic behaviour of the various DG technologies can be very different from each other (e.g., photovoltaic

Table 3. Procedures for stochastic prediction of voltage dips.

Ref.	Method	Voltage level	Main characteristics
[20]	Monte Carlo	Transmission	— Time-domain solution — Prediction of dip magnitude and duration — Fault duration has a Rayleigh distribution — Protective devices are not modelled
[21]	Analytical solution based on the bus impedance matrix	Transmission, Subtransmission and Distribution	— Frequency-domain solution — Prediction of dip magnitude only — Calculation of dips experienced at LV nodes but caused at any voltage level
[22] [23]	Fault Positions	Transmission, Subtransmission and Distribution	— Frequency-domain solution — Prediction of dip magnitude only — Sensitivity analysis with respect to the statistical distribution of the fault positions
[24]	Monte Carlo	Distribution	— Time-domain solution — Prediction of dip magnitude and duration — Fault duration has a normal distribution — Protective devices are not modelled
[25]	Critical Distances	Distribution	— Frequency-domain solution — Prediction of dip magnitude and duration — Tripping time is deduced from the inverse time-current characteristics of circuit breakers
[26]	Fault Positions	Transmission	— Frequency-domain solution — Application of the bus impedance matrix — Prediction of dip magnitude only
[27]	Monte Carlo	Transmission and Subtransmission	— Frequency-domain solution — Prediction of dip magnitude only — Includes the study of voltage dip mitigation using STATCOM
[28]	Fault Positions	Transmission, Subtransmission and Distribution	— Frequency-domain solution — Prediction of dip magnitude and duration — Dip duration is deduced from typical fault clearing times at different voltage levels — Includes probability of protection system failure
[29]	Fault Positions	Transmission, Subtransmission and Distribution	— Frequency-domain solution — Prediction of dip magnitude and duration — Calculation of the expected number of trips — Dip duration is deduced as in [28]
[30]	Analytical solution based on the bus impedance matrix	Transmission and Subtransmission	— Frequency-domain solution — Prediction of dip magnitude only — Different types of fault distributions
[31] [32]	Monte Carlo	Distribution	— Time-domain solution — Prediction of dip magnitude and duration — Modelling of protective devices — Assessment of the number of sensitive equipment trips
[33]	Critical Distances	Transmission and Distribution	— Frequency-domain solution — Prediction of dip magnitude only — Analytical solution of voltage dip magnitudes — Comparison to results derived from the Fault Position and the Monte Carlo methods
[34]	Expected Sag Frequency	Transmission	— Frequency-domain solution — Prediction of dip magnitude only — Analytical solution of the vulnerability area together with the voltage-tolerance characteristic of sensitive equipment
[35]	Fault Positions	Distribution	— Frequency-domain solution — Prediction of dip magnitude only — Fault distribution based on a 2-D (bivariate) normal distribution — Line and transformer failure rates are included

installations have no moving parts, while a wind energy conversion unit is a complex mechanical system whose dynamic behaviour is not easy to represent) [55]. In addition, some DG technologies are connected to the utility network via a static converter [56], while others can be directly connected. All these issues can complicate the analysis and simulation of transients.

5. Some renewable distributed sources are intermittent or stochastic by nature [57], which can be an important issue in voltage dip calculations.
6. Energy storage is another aspect to be considered when DG units are connected to the grid. It is recognized that many drawbacks related to some DG technologies can be solved by including energy storage devices [58]. For instance, fast response and high power supercapacitors can complement the slow power output of fuel cells to improve their load following characteristics [59].
7. There are some overvoltage issues associated with DG that have to be accounted for: (a) ground faults together with improper application of DG grounding or interface transformer connection can cause temporary overvoltages; (b) resonant over-voltages may arise during islanding conditions, while overvoltages may be caused by a high DG power injection. Ferroresonance may occur when the DG is connected to a section of the system that has been isolated from the utility distribution network, and these voltages can cause either damage to connected equipment or their tripping [60, 61].

It is very obvious from the above discussion that an accurate assessment of voltage dips can be more complex with DG than without DG, mainly in distribution networks when protection devices are usually set to run under faulted conditions during intervals much longer than in transmission networks, and the dynamic behaviour of small power generators may be important for voltage dip assessment.

Not much experience is already available to assess the voltage dip performance of utility networks with distributed generation. Some recent works are summarized below.

A. Reference [62] presented a simple method based on the diagram of Figure 2 for prediction of voltage dips at MV equipment terminals. The equivalent circuit shown in the figure is used to predict the number of events when the cause of the voltage dip is at the transmission level. The approach is very simple and aimed at estimating the dip magnitude and the number of dips (SARFI indices) as a function of the degree of DG penetration (fraction of distributed generation with respect the substation rated power), using a frequency-domain (phasor) calculation and considering only symmetrical dips.

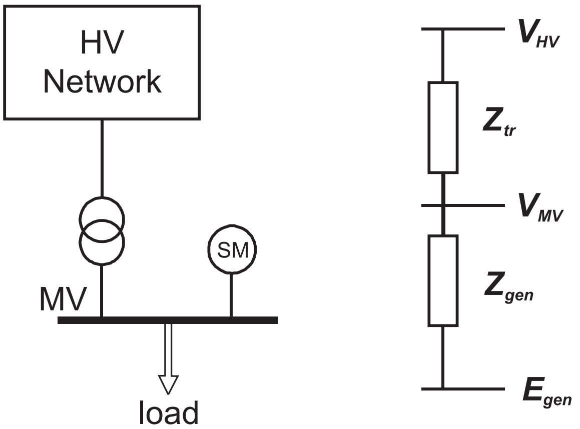

Fig. 2. Equivalent circuit of a distribution network with synchronous generator at MV level for voltage dip analysis during a transmission-level dip.

B. A more detailed study is presented in [63]. In fact, the authors analysed two different networks [64, 65], considering symmetrical and asymmetrical faults at various voltage levels and locations. Voltage dip characteristics and propagation were studied considering the amount of distributed generation and the type of generation (synchronous or induction). The goals of the first study with a radial network included the estimation of voltage dip magnitudes and phase-angle jumps at the PCC by moving the fault position, considering three scenarios: no DG and static loads, no DG plus dynamic loads (induction motors), DG plus dynamic loads. The main goal of the second study with a larger network (transmission, subtransmission and distribution levels) was the voltage dip propagation (areas experiencing voltage dips of different magnitudes) considering three scenarios similar to those mentioned above.

C. Not much experience is already available using time-domain simulations. To date there are no works aimed at estimating the number of dips experienced by sensitive equipment in systems with embedded generators. Although the approach to be used can be similar to those applied without DG, the model must be more complex, as discussed above. Accurate and sophisticated time-domain models could be needed to check the coordination of protective devices, the dynamic performance of the system after a disturbance, anti-islanding detection methods or the influence of the various controls implemented in the different generation sources. There are, however, a few studies using time-domain tools whose goals and main conclusions can be useful for a deeper prediction of voltage dips in systems with DG.

— A recent work has analysed the influence on the voltage dip of the excitation control (constant power factor output) implemented in a real generator during a fault [66]. According to the conclusions of this work, the limited reactive power support of the synchronous DG (with a size similar to the connected load) can prevent from a satisfactory dip recovery since the machine may not be able to provide the required voltage support due to its limited reactive power capability, the excitation control strategy and its slow response.

— The works presented in [67] and [68] showed that DG can have a positive effect on the performance of distribution networks with faults caused at any voltage level if embedded generators remain connected and the fault duration is shorter than 2 s. A proper selection and setting of protective devices, as well as the implementation of fuse blowing, can reduce the number of sensitive equipment trips.

— The dynamic simulation of a representative distribution network with DG was analysed in [69], considering noncompliance with IEEE Std 1547, faulty resynchronization of embedded generators, and only synchronous machines. From the simulation results some interesting conclusions were derived: inability to disconnect the DGs from the grid during disturbances did not have drastic consequences, and transients due to faulty resynchronisation of the DGs would not introduce undamped oscillations or cascading events.

— The reduction of unnecessary disconnection of embedded generators was the main subject of the work presented in [70]. The authors analysed the response of protection systems (namely loss of mains) to non-islanding conditions.

Other works related to the impact of distributed generators on voltage dips were presented in [71] and [72].

Another important aspect to be accounted for the assessment of voltage dips in future networks is the intentional islanding of generation and loads that can be accomplished by means of microgrids [73, 74].

8. CONCLUSIONS

Computer simulation is an efficient mean to analyze the effect of disturbances and the behaviour of sensitive equipment. Present simulation tools can be used to perform any type of voltage dip study: by combining capabilities of two or more software tools, users can develop new component models, embed new signal processing algorithms for voltage dip characterisation or calculate voltage dip indices.

Simulation results are as accurate and reliable as models and data used in simulations. The procedures developed to date for stochastic prediction of voltage dip studies are very flexible and sophisticated. However, important drawbacks still exist; they are mainly related to the limited knowledge on sensitive equipment behaviour during unbalanced dips and the characterisation of three-phase unbalanced dips. In addition, the characterisation of some random factors (e.g. fault characteristics) is not well known and, therefore, poorly represented in computer models.

Voltage dip assessment in networks with a high penetration of distributed generation is another important challenge since the simulation of transient events caused by faults that lead to voltage dips can require more sophisticated models than those required without embedded generators, mainly when the study deals with distribution networks.

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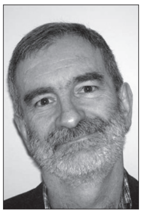

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