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Predicting Equipment Outages Due to Voltage Sags

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***Abstract*— A methodology for predicting the number of equipment outages per year due to voltage sags is presented, allowing to evaluate their amplitude and duration. The methodology is based on Monte Carlo simulation of the network operation considering the stochastic nature of power system faults characteristics (location, type and resistance) and the probabilistic nature of successful fault clearance by the primary protection systems. Equipment susceptibility to voltage sags is included in the methodology by considering the standardized equipment ride-through capability curves. The methodology outcome are probability distribution functions of the number of equipment outages per year, thus allowing to characterize outages by using average or percentile values obtained from the distribution functions. An application example is presented, considering two different equipment types connected to different sites of the IEEE RTS, the corresponding number of outages being assessed. Results highlight the need to combine both equipment and network performance to assess compatibility.**

***Index Terms*— Equipment susceptibility, Monte Carlo methods, power quality, power system faults, protection systems, voltage sags**

I. INTRODUCTION

Voltage sags are disturbances in the voltage supply, at a point in the electrical system characterized by a sudden reduction of the voltage magnitude followed by voltage recovery after a short period of time [1]. The voltage sags neither can be completely eliminated nor the equipment made completely immune to all of them, at least at acceptable costs.

Voltage sags are a consequence of power system faults, and their characteristics at a given network site depend on the fault location and other fault characteristics, as well as on the network and protection systems characteristics. As power system faults occur randomly in time and location, voltage sags have a stochastic nature.

Information on the expected number of equipment outages per year is important to the owners of sensitive and critical equipment, as extra costs derive from these events, associated to the industrial processes interruption and restart. The number of outages depends on the network site the equipment ride-through capability.

Voltage sags prediction methods can be traced back to the pioneer work by Conrad et al. [2] which gave a first extensive overview of the voltage sag phenomenon, identifying the need to combine different computational tools to predict the residual voltage, duration, frequency and economic impact of voltage sags. The fault position method was introduced to address the prediction problem in meshed networks.

Qadar et al. [3] used the fault position method and developed the concept of exposed areas: network regions limited by fault positions that cause sags of equal residual voltage at the considered site. The fault position method has become the most common approach to voltage sags prediction.

Park et al. [4] have used the fault position method to determine the region in the power system where faults cause sags that affect the operation of sensitive equipment connected to a network site, the so called area of vulnerability. This concept was used to introduce the Expected Sag Frequency Index, which corresponds to the probability of such faults occurring in the area of vulnerability.

Methods based on Monte Carlo simulation were proposed by Bollen and Massee [5] and by Fonseca and Alves [6]. These methods simulate network operation during a defined time span (several years), and transmission line faults are considered according to the given transmission line fault rate. The calculated fault voltages in all network busses are computed, and typical values are assumed for the associated fault clearance times. Results are presented as average values, considering all sags occurring at each network site.

The fault position and the Monte Carlo simulation methods were compared by Olguin et al. [7] and by Moschakis and Hatziargyriou [8], concluding that both methods can produce comparable results although the last gives more complete network site characterization as it includes the yearly variability, whereas the first gives only long-term mean values.

Oliveira et.al [9] have reapplied the Monte Carlo simulation method considered by Olguin to compare monitoring and simulation results, aiming at analyzing the accuracy of the sag characteristics obtained from short monitoring periods.

Predicting voltage sag duration requires evaluating the protection systems performance, and few authors have addressed this important issue. Probably one of the first works is by Bollen and Massee [5], in which the reliability of

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electricity supply to industrial loads was investigated. The developed method combined Monte Carlo simulation to generate events and included the reliability of protections system by means of using Fault-Tree analysis [10]. Aung and Milanovic [11] have followed the same ideas to characterize fault clearance times, resulting from primary or backup protection operation. These authors have also modelled the probability of failure of the primary protection system using Fault-Tree analysis, and results where combined with the fault position method to characterize the sag duration and residual voltage. Wamundsson and Bollen [12] also proposed a method for predicting the sag duration, by treating the fault clearance time as a random variable associated to the transmission line distance protection operation Zones 1, 2 and 3 within in a Monte Carlo simulation. This random variable is considered to follow a probability density function resulting from network monitoring data.

From the conducted overview, one can conclude that the fault position method is being predominantly applied for voltage sags prediction. A disadvantage of this method is that it considers a constant fault resistance value, usually zero, giving pessimistic results for the sag magnitude, for faults involving the ground. Normal probability distribution functions have been used in Monte Carlo simulations to characterize fault resistance [13] and [14], although without justification of the chosen distribution and its parameters, and also of the inherent negative values, which are unrealistic and have no physical meaning.

As regards sag duration, published work give no evidences of correctly describing the working principle of the several protection schemes in operation or the reliability values of their components. Fault clearance times are usually described either by means of fixed values [4] or using Gaussian distributions [15], without justification.

The authors have develop a stochastic model of power system faults [16] which allows to reproduce time series of fault rate and type, as happening in real network operation, and also to include the probabilistic nature of fault resistance characterized by a Weibull distribution. The authors also addressed transmission line and busbar protection systems reliability [17][18][19], allowing to describe in detail the fault clearance process uncertainty associate to the random nature of fault conditions and to the protection system schemes and equipment reliability.

In the present paper, the previously developed methodologies are combined for voltage sags prediction. Voltage sags are treated as a stochastic phenomenon, thus results being obtained as probability distributions of occurrence, from which average or percentile values can be extracted. .Furthermore, a statistical analysis of voltage sags adequate for predicting equipment outages is proposed. The statistical analysis outputs have a directed correspondence to the adopted $SARFI\text{-}curve$ index [20].

By encompassing comprehensive modeling of the fault clearance time and the fault resistance probabilistic distribution, it is possible to properly account for the equipment voltage tolerance curve, and results will be more consistent with reality.

I. Equipment ride-through capability

The equipment voltage sag ride-trough capability is considered to depend on the sag type, duration and residual voltage, although other parameters may also be relevant, such as the magnitude of the pre-disturbance supply voltage, the voltage recovery time, the equipment control and the protection setting.

The SEMI standard F47-0706 [21], as well as the IEC 61000-4-11 and IEC 61000-4-34 standards [22][23] were published aiming at establishing a common reference for evaluating the equipment susceptibility to voltage sags.

The SEMI Standard F47-0706 defines the voltage sag immunity required for semiconductor processing, metrology, and automated test equipment. This includes, amid others, power supplies, computers and communication systems, robots and factory interfaces, AC Contactor coils and AC relay coils, chillers, pumps and adjustable speed drives. The standard requires the equipment immunity to the phase-to-neutral and phase-to-phase sags listed in Table I.

The IEC 61000-4-11 and IEC 61000-4-34 standards are not specific of a given industry, as the SEMI Standard. They refer to electrical and electronic equipment connected to low-voltage power supply networks, and define the immunity test methods and range of preferred test levels. These standards characterize equipment voltage sag tolerance as Class 1, 2, 3 and X, although only for Class 2 and 3 the immunity requirements are specified, according to Table II.

Immunity requirements for five different equipment classes, encompassed in IEC Class X equipment [22][23], have been proposed by CIGRE/CIRED/UIE [24] using a residual voltage/duration curve, the so-called voltage-tolerance curve. It is expected that a Class X equipment is capable to survive sags located above its declared voltage tolerance curve, while sags located below may cause misoperation or outage.

TABLE I: SEMI Standard F47-0706
Required voltage sag immunity

Sag depth	Duration at 50 Hz	Duration at 60 Hz
50 %	10 cycles	12 cycles
70 %	25 cycles	30 cycles
80 %	50 cycles	60 cycles

TABLE II: IEC61000-4-11 and IEC 61000-4-34 Standards
Preferred test level and duration for voltage sags

Class	Test level and durations for voltage sags (50Hz/60Hz)		
Class 2	70% during 25/30 cycles		
Class 3	40% during 10/12 cycles	70% during 25/30 cycles	80% during 250/300 cycles

The equipment immunity description allows equipment

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owners to evaluate the adequacy of the equipment, as regards the chosen network connection site, given the acceptable number of expected outages per year. This can be assessed by using historical voltage quality data, such as the $SARFI\text{-}curve$ value [20], which corresponds to the number of voltage sags, recorded at a network site during one year, which are below a specific tolerance curve. Alternatively to historical data, voltage sags prediction methods can be used.

II. Voltage Sags Prediction

A. Underlying Methodology

Voltage sags prediction requires:

- Adequate stochastic modelling of power system faults, considering historical network data, intended to obtain a probabilistic description of the fault characteristics.
- Correct reliability analysis of transmission line and busbar protection systems, including the description of the working principle reliability, the characterization of the system components by failure and repair rates, and the computation of the system reliability and availability indices.

Modelling of Power System Faults

A methodology for stochastic modelling of power system faults has been developed by the authors [16]. Fault rate, type and location are modelled as random variables characterized by appropriate distributions, resulting from data collected by transmission system operators for different voltage levels.

As regards fault rate, the methodology considers that the transmission lines and busbars will fail at a given rate $z(t)$, which individually characterizes each element. The probability of fault occurrence P_F in a network element is defined as [25]:

$$P_F(t_0) = 1 - \exp\left[-\int_0^{t_0} z(\tau)d\tau\right] \quad (1)$$

where t_0 is the duration of each trial in the Monte Carlo simulation. In the present work it was chosen 1 hour duration.

For fault type, i.e. number of affected faulty phases, the methodology considers a probabilistic distribution, per voltage level, based on historical network data. Concerning fault location along transmission lines, a uniform distribution is considered. For the fault resistance, a Weibull distribution is considered [16], based on published field data from several sources and corresponding to networks of different operating voltage, in the range 60 kV to 220 kV [26] [27].

The developed method generates stochastic short-circuit events in the form of time series, as presented in Fig. 1 and 2. Figure 1 shows a generated time series of the transmission line fault rate using a pre-defined yearly average fault rate value of 2.83 faults/100km/year (highlighted). Figure 2 presents the yearly based fault type distribution, considering as input: 69.8% single line to ground faults, 4.9% line to line faults, 10.6% double line to ground faults and 14.6% three phase faults.

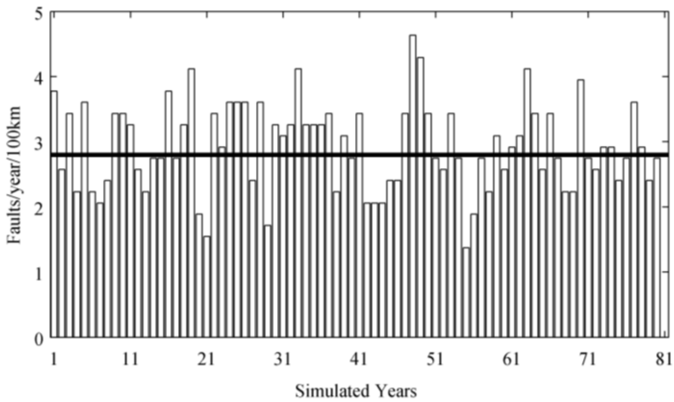

Fig. 1: Example of generated time series of the transmission line fault rate, from [16].

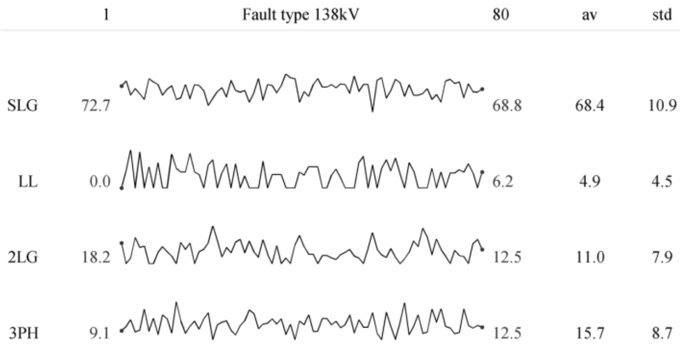

Fig. 2: Example of generated time series of the transmission line fault type distribution (percentage), from [16].

Protection System Modeling

Modelling of the transmission lines and busbar protection systems is used in predicting the voltage sag duration, as these are the most common faulty elements in transmission networks.

The approach focuses in determining the probability of successful fault clearance by the primary protection systems [28], corresponding to sags with duration lower than 25/30 cycles, for 50/60 Hz. Sags with longer duration are caused by faults cleared by backup protection, either by the remote backup protection, such as the transmission line distance protection Zone 2, or by the local backup protection, such as the breaker failure protection.

Protection systems reliability encompasses dependability and security, the first being the ability to trip when needed, and the second the ability to not trip when not needed. For the concern of voltage sag duration, only dependability is relevant and this is measured by the probability of primary protection system successful operation, i.e. fault clearance without additional time delay.

Transmission lines are commonly protected by distance protection functions with at least two independent operating zones. Zone 1 is set so as not to reach the remote bus and to trip instantaneously, while Zone 2 is set so as to reach the remote bus, but its trip is intentionally delayed to perform remote backup to the remote bus protection. In addition to the

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distance protection functions located at both ends, transmission line primary protection systems may also include communication channels used by a teleprotection scheme. This is intended to achieve fault clearance, without additional time delay, regardless its location along the line. A common teleprotection scheme is the Permissive Under-reach Transfer Trip (PUTT) [29], based on the acceleration of Zone 2 trip, once Zone 1 trips on the remote bus. Fault clearance without time delay is achieved by: (a) Zone 1 operation at both line ends; or (2) teleprotection operation.

The probability of successful operation of a transmission line primary protection system, encompassing redundant distance protection sharing single aided communication channel, is presented in Fig. 3. Results were obtained using the methodology developed by the authors presented in [17][18]. These results show that the probability of successful operation is not constant along the line, as it is affected by the fault location. The maximum value is observed at the line mid-point, where the overlapping of the distance protection operational Zone 1 from both line ends is guaranteed. The minimum values are found for faults at the line ends, as a consequence of successful operation by the teleprotection scheme being required for fault clearance by the primary protection.

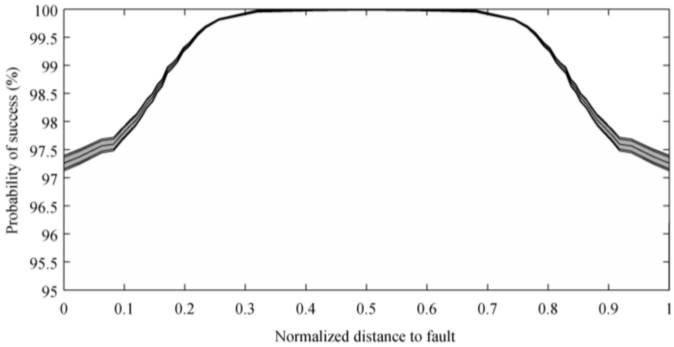

Fig. 3: Probability of transmission line primary protection system successful operation as function of normalized distance to fault. Average (central line) and 85% and 98% confidence intervals (shade areas). Redundant distance protection sharing single aided communication channel.

As regards busbar protection systems, the ultimate goal is to clear any substation fault, with a minimum time delay. The protection zone of the busbar protection system excludes all substation equipment, such as power transformers, shunt reactors and capacitor banks, which are protected by dedicated systems.

In general, busbar fault clearance requires current interruption by all substation circuit breakers, and consequently disconnecting all feeders causing shutdown of the corresponding voltage level. On complex substation arrangements, such as double busbar with bus coupler, more than one busbar per voltage level exist. These arrangements improve power system reliability, as busbar fault clearance only requires the operation of the circuit breakers from the feeders connected to the faulty busbar, leaving the other feeders in service.

Busbar primary protection systems are based on the undelayed operation of a current differential function, and the operational current is settled considering the minimum short-circuit power of the substation. A fail-to-trip can only occur if the fault current is lower than the set threshold, or if the protection is switched off, or in a blocking stage preventing the protection operation.

The probability of successful operation of a busbar primary protection system has been calculate by the authors [19] for several protection architectures using the same developed methodology for transmission line protection. Figure 4 presents the probability of successful operation of a centralized busbar protection architecture, computed for several substation sizes.

Results show that the probability of successful operation is reasonably described by a linear decrease, when the substation size increases:

$$P(N) = P_0 - m_P N \quad \text{with} \quad N = 2, 3, 4, \ldots \qquad (2)$$

where P_0 is the maximum value of the successful operation probability, and m_P its decrease rate. This dependence is a consequence of adding system elements, such as circuit breakers and current transformers, at each substation bay

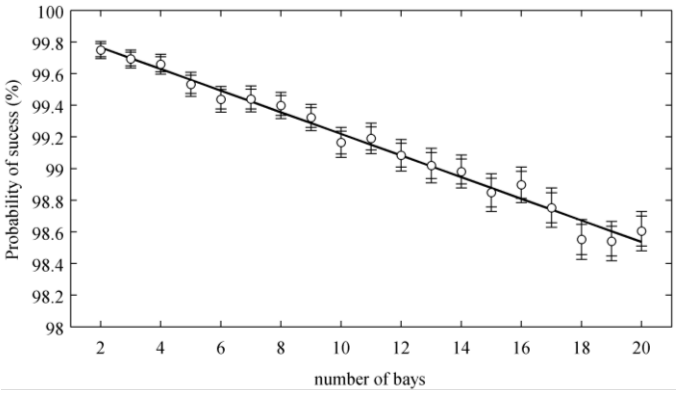

Fig. 4: Probability of busbar primary protection system successful operation. Average (circles) and 85% and 98% confidence intervals (vertical lines) as function of the number of substation's bays.

Prediction of Voltage Sags Characteristics

The developed methodology for voltage sags prediction is based on simulating the network operation, during a defined time span, by means of two consecutive Monte Carlo simulations. The network is characterized by its topology, and by the characteristics of generators, transmission lines and transformers. Transmission line and busbar failure rates are considered. Protection systems performance takes into account failure rates and time to repair of their components.

The first Monte Carlo simulation follows the methodology proposed by the authors in [16], allowing to generate the network faults, during a simulation time span of representative significance. The simulation time span is divided into an equal number of time intervals (named trials) of one hour duration. During a trial more than one network element can fail, as the probabilities of the network elements failure are independent.

The fault characteristics are determined using probabilistic

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models. The simulation outcome, which will be referred as Network Faults Scenario (NFS), is the sequence of faults observed in the network during the simulation time span, each fault being fully characterized by:

1. Time – the trial at which the fault occurs;
2. Faulty network element – the transmission line or busbar where the fault occurs;
3. Fault type – 3PH, SLG, LL or 2LG;
4. Fault resistance – different from zero in case of a transmission line fault affecting the ground;
5. Fault location – in case of transmission line faults.

The computational flowchart used in creating a NFS is presented in Fig 5. At this stage, for each identified fault, a random value, between 0 and 1, is also generated, to be used in the second Monte Carlo simulation, for assessing the successful operation of the primary protection system. This parameter is identified as the protection system successful operation index (PSSOI).

The amount of information contained in a NFS obviously depends on the network size and simulation time span, but it also depends on the reliability of the network elements, resulting in different number of faults during a simulation time span N_{NFS}. Considering the flowchart in Fig. 5, the number of faults in a NFS is:

$$N_{NFS} = \sum_{i=1}^{N_T} F_i \quad (3)$$

where F_i is the number of faults occurring during the i^{th} trial and N_T the total number of trials in the simulation time span.

The second Monte Carlo simulation uses the NFS as input and, for each network fault, computes the corresponding voltages on the three phases, at all network sites of interest. The voltages are then used to determine the corresponding sag magnitude and type. The probabilistic models of the protection systems successful operation, developed by the authors [17][18][19] are included in the simulation in order to assess the sag duration. Sags are classified as X1 or X2, the first corresponding to faults cleared by the primary protection (duration within [0.01 s, 0.2 s]), and the second by the backup protection (duration within]0.2 s, 0.5 s]). For this purpose, the PSSOI value associated to a fault is compared to the probability of successful operation of the primary protection system. If the PSSOI value is lower than that probability value, the sag is classified as X1, otherwise as X2.

In case of a transmission line fault, the probability of successful operation is affected by the fault location, as well as by the protection scheme [18]. In the case of a busbar fault, the protection architecture and the number of bays in the substation affect the probability of successful operation [19].

Figure 6 presents the computational flowchart used in predicting voltage sags. The outcome of this Monte Carlo Simulation is the Network Sags Scenario NSS, which contains all sags recorded at all network sites of interest, each being characterized by four parameters: year of occurrence, magnitude, duration and type.

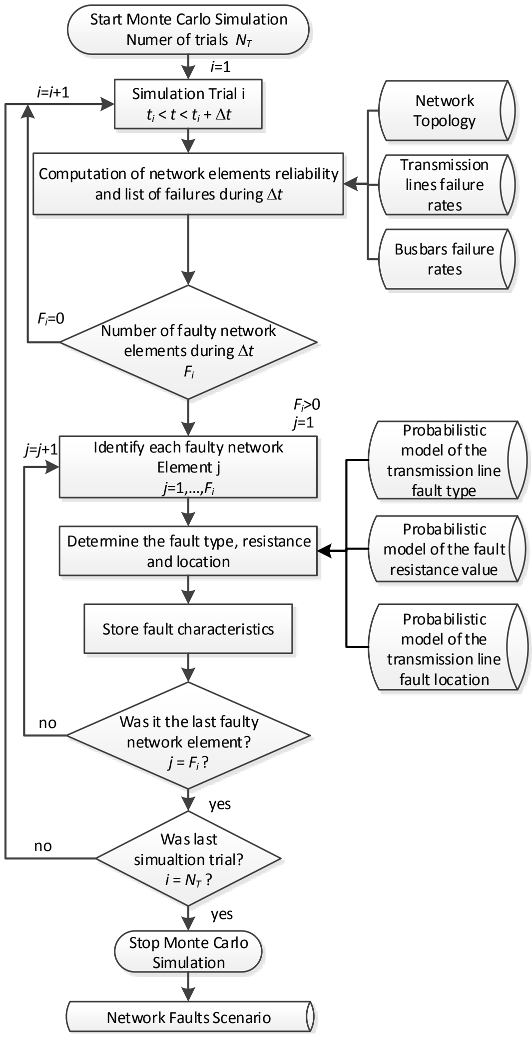

Fig. 5. Computational flowchart used in creating Network Faults Scenarios.

B. Statistical analysis of voltage sags

The sags contained in the NSS are classified according to the equipment voltage-tolerance curve of interest.

Annual equipment outages are described by computing the probability density $f(n)$ and cumulative $F(n)$ distribution functions of the number of sags n below the equipment voltage-tolerance curve observed in each year of the simulated time span, for each network site:

$$f_{SARFI-Curve}(n) \qquad F_{SARFI-Curve}(n)$$

The number of outages may be characterized by the average value or by adequate percentile values, these being obtained from the distribution functions:

$$SARFI\text{-}Curve_{av} \qquad SARFI\text{-}Curve_{xx}$$

were av means average and xx the chosen percentile.

The choice of average or percentile values depends on the nature of the study. If the study is to be used in network planning, only long run trends are typically considered and the av value is adequate. Notwithstanding, this can lead to some

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optimistic characterization, as the dispersion of results is not quantified.

On the other hand, percentiles should be used if the nature of the study requires predicting the number of outages lower than a predefined criteria. These studies are normally addressed by network users to whom the number of outages is of great concern.

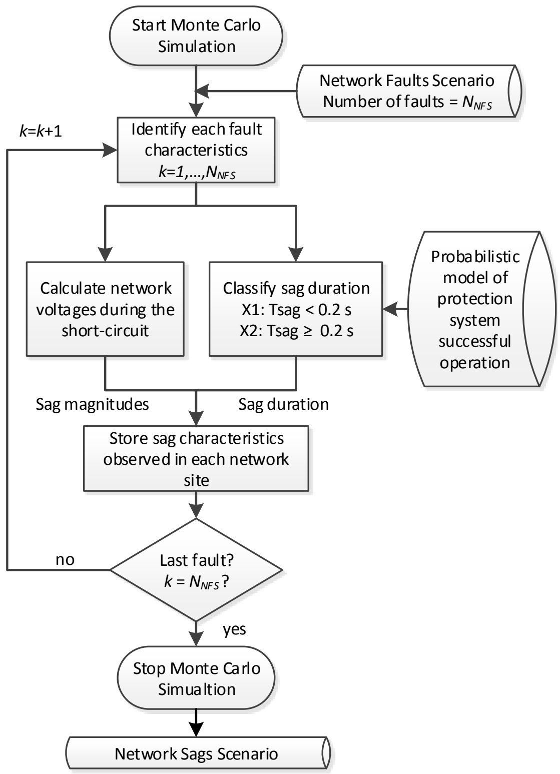

Fig. 6. Computational flowchart used in Network Sags Scenarios prediction.

III. Equipment outages prediction

The proposed methodology is used for network site comparison, as regards connecting sensitive equipment, and to select the most adequate equipment voltage-tolerance curve, aiming to minimize the expected number of equipment outages per year. This being a general case-study to show the potential of the developed methodology, the intermediate transformers were not considered, as they are specific of each user. Transformer models may be included in the simulation, if the winding connections are so that change the type and residual voltage of the sags at the connected equipment terminals.

The methodology was applied to the IEEE RTS network (see appendix) and the NSS was build up. Recorded sags were used to compute, on a yearly basis, the relevant SARFI-curve indices. This value is assumed here as a reference value for the number of equipment outages, although in reality equipment compliment to a voltage tolerance-curve may be different from equipment performance.

The time series of the computed SARFI-SEMI index along the first 80 years of simulation, for one of the network sites, is presented in Fig.7. Results show that index values change considerably, ranging from 0 to 6 sags per year in the 80 years period. Therefore, the convergence of the method must be assessed, so that the chosen simulation time span is long enough to extract confident results.

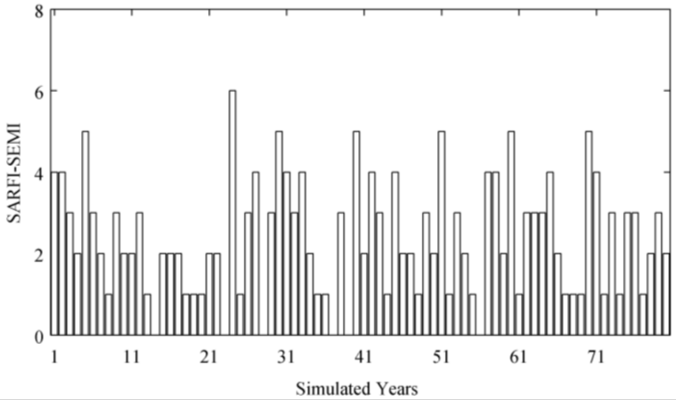

Fig. 7. The computed $SARFI\text{-}SEMI$ for Agricola 104 network site, during the first 80 years of simulation.

A convergence analysis is made by observing the $SARFI\text{-}SEMI_{av}$ value in all network sites, during the progression of the Monte Carlo simulation. Results show that the $SARFI\text{-}SEMI_{av}$ values rapidly stabilize as the simulation proceeds. For the tested network, results in Fig. 8 show that the index value starts to converge for a simulation time span longer than 500 years and, it completely stabilizes after 700 years.

The chosen Monte Carlo simulation time span is 800 years, so to guarantee convergence of the $SARFI\text{-}SEMI_{av}$ value in all network sites.

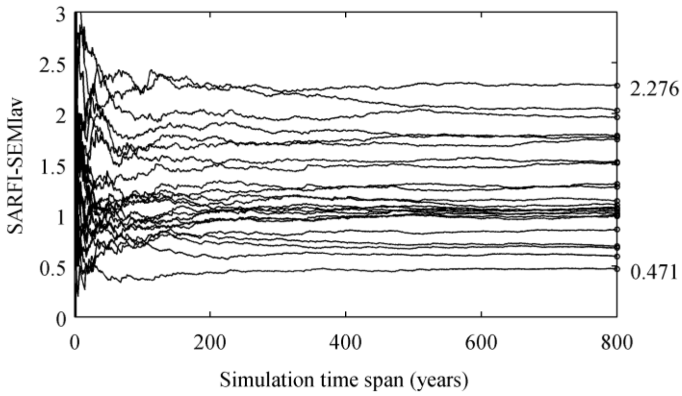

Fig. 8. $SARFI\text{-}SEMI_{av}$ convergence analysis of Monte Carlo simulation outcomes. Computed values at all the IEEE RTS sites.

The SARFI-SEMI$_{av}$ values for all network sites, corresponding to the 800 years simulation time span, are also shown in Fig 8. Values range from 0.471 to 2.276 outages per year, highlighting the large differences that can be expected between network sites, for a given equipment type.

In this example, two network sites are chosen for assessing the number of equipment outages, corresponding to a low and a highly exposed site. The chosen sites are Abel 101 and Agricola 104, characterized by SARFI-SEMI$_{av}$ equal to 0.695 and 2.276 respectively. In order to assess the adequacy between equipment characteristics and connecting network

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site, the equipment immunity level IEC 61000-4-11 Class 2. Is also considered.

Accordingly, in the considered example, the prediction problem is defined as:

- Assessing how many equipment outages are expected to occur in one year, when a given equipment is connected to Abel 101 or Agricola 104 sites.
- Assessing how many equipment outages are expected to occur in one year, when the equipment immunity level is SEMI F47-0706 or IEC 61000-4-11 Class 2.

The computed density $f(n)$ and cumulative $F(n)$ distribution functions of $SARFI\text{-}SEMI$ and $SARFI\text{-}IEC\ Class2$ values for the network sites Abel 101 and Agricola 104 are shown in the histograms presented in Fig. 9.

Given the characteristics of the probabilistic distributions that may be expected [30], the theoretical Poisson distribution values, calculated from the computed average values, are overlaid in the histogram. A perfect match is observed. This explains the different shapes of the obtained distributions (skewed or closely symmetrical), and their relation to the average value.

In the case of connecting equipment type SEMI F47-0706 to Abel 101 site, the average number of outages is lower than 1 and the histogram is skewed to the right, showing the equipment robustness to the expected voltage sags. In the case of connecting equipment type IEC 61000-4-11 Class 2, the average number of equipment outages is between 3 and 4 and the histogram is more symmetrical in the vicinity of the 50 % percentile.

For equipment connecting to Agricola 104 site, either SEMI F47-0706 or IEC 61000-4-11 Class 2 type, the histograms show symmetry in the vicinity of the 50 % percentiles. The average number of equipment outages is close to 3 and 6 for SEMI F47-0706 and IEC 61000-4-11 Class 2 equipment type, respectively.

It can be concluded that the shape, skewed or symmetrical, indicates the degree of sensitivity of the equipment to the observed sags. Robust equipment for the expected sags have skew histograms, while sensitive equipment have symmetric histograms.

For the simulated time span, as the histograms in Fig. 9 show, the number of equipment outages per year range from 0 to a maximum of 14 in the case of IEC 61000-4-11 Class 2 equipment type connected to Agricola 104 site. The computed 95 % percentile values are summarized in Table III.

TABLE III: NUMBER OF EQUIPMENT OUTAGES PER YEAR ($SARFI\text{-}SEMI_{95\%}$ AND $SARFI\text{-}IEC\ Class2_{95\%}$)

	SEMI F47-0706	IEC 61000-4-11 Class 2
Abel 101	2	6
Agricola 104	5	10

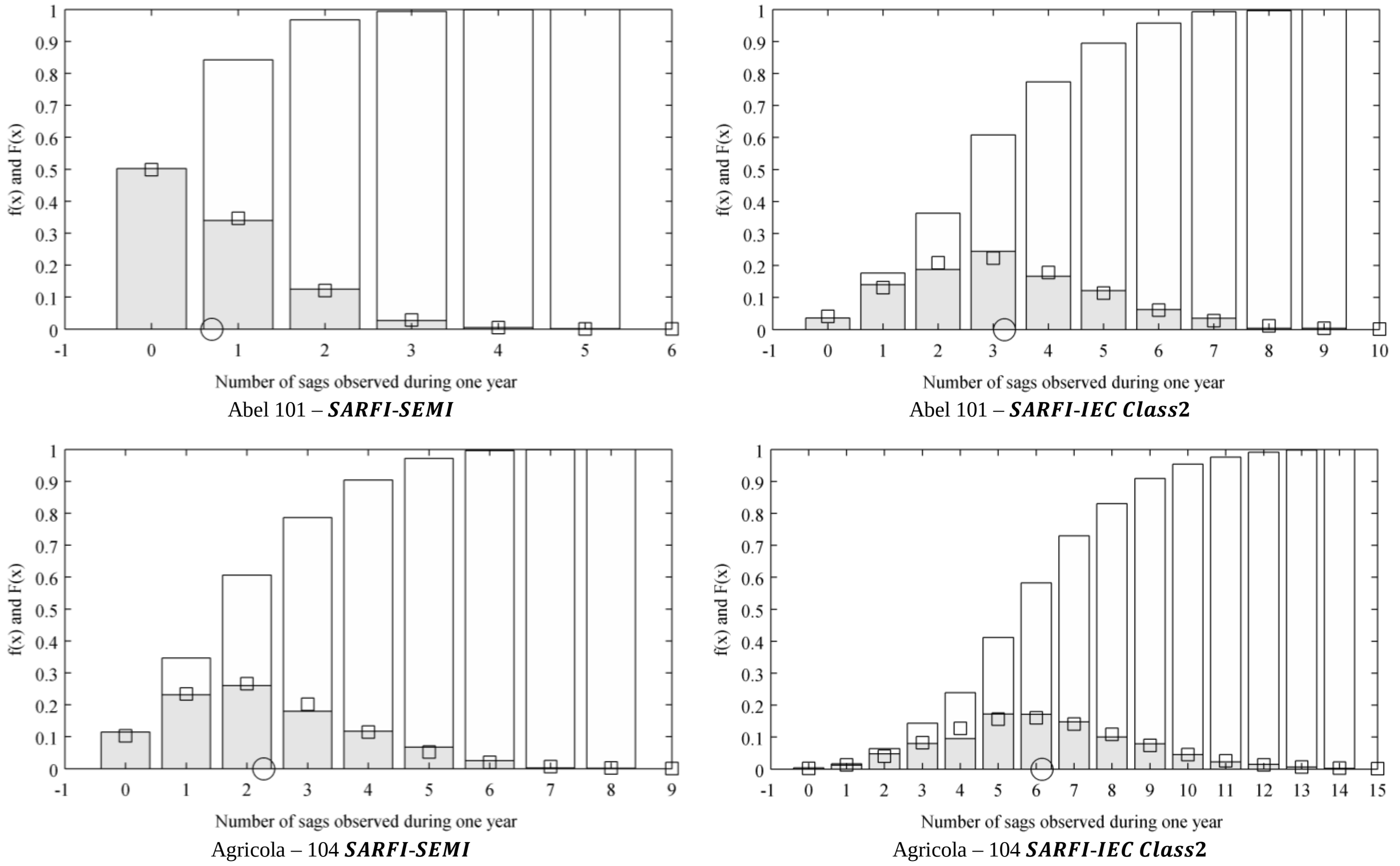

Fig. 9 Density $\boldsymbol{f(n)}$ and cumulative $\boldsymbol{F(n)}$ distribution functions. $\boldsymbol{SARFI\text{-}SEMI_{av}}$ (circle). Theoretical Poisson distribution values (square).

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Considering SEMI F47-0706 equipment type, in 95 % of the simulated years the number of outages is lower or equal to 2 if connected to Abel 101 site. This number is 5 if connected to Agricola 104 site. In case IEC 61000-4-11 Class 2 equipment type, the number of outages is 6 and 10 when connected to Abel 101 or Agricola 104 respectively.

When comparing equipment IEC 61000-4-11 Class 2 type and the SEMI F47-0706 type, both have equivalent performances, i.e. have practically the same number of outages per year, if connected to Agricola 104 site and Abel 101 site respectively.

The presented example shows the importance of combining the equipment performance, characterized by a voltage-tolerance curve, with the network site characterization, for assessing the number of expected equipment outages per year. In fact, the example illustrates that practically the same number of the outages can be expected for the two equipment types, if connected to adequate network sites. Accordingly, the network site and the equipment performance should be chosen together to fulfill certain performance criteria defined by the user.

As regards validation of results by means of site monitoring, this can only be done, with a high degree of certainty, if the number of monitoring periods is large enough. This is somehow impossible to achieve, as the network topology is continuously changing due to the implementation of network development plans.

IV. Conclusions

The developed methodology proves to be adequate in assessing the number of equipment outages due to voltage sags. It takes into account the equipment immunity to voltage sags, described by a voltage-tolerance curve, and the network performance, affected by transmission line and busbar failure rates, as well as protection systems performance. Furthermore, by being able to predict the protection system trip duration it is possible to account more realistically for the equipment voltage tolerance curve. Additionally it is expected that obtained voltage sags magnitude will be more consistent with the reality, due to the probabilistic description of the fault resistance.

The proposed methodology results in probability density and cumulative distribution functions of the number of equipment outages, based on assessing the number of voltage sags below the equipment voltage-tolerance curve.

Results highlight the need to combine both equipment and network performance, as the equipment immunity is not able, by itself, to be used in predicting of the expected number of outages per year.

By describing probabilistically the relevant indices, derived from the distribution functions, the methodology allows determining percentile values, further to the average values. This is an important feature, as the average values lead to optimistic characterization, not giving information on the dispersion of results. Percentile values are more adequate to be used in voltage sags prediction studies for equipment performance characterization, as they account for the yearly variability. The chosen percentile reflects the confidence level required by the user.

V. Appendix

The IEEE RTS [31] one line diagram is presented in Fig A.1. The considered test network comprehends: 32 generators, corresponding to 3.4 GW installed power; 33 circuits, with two voltage levels, 230 kV and 138 kV, consisting of 1630 km transmission lines and 24 stations, including 5 substations, with one transformer each. In the present paper, it is assumed that each station contains 2 busbars, per voltage level. The transmission lines are protected by redundant distance protection sharing single aided communication channel. The busbars are protected by one centralized busbar protection. The 138 kV and 230 kV transmission line failure rate equals to 2.8 and 1.9 faults/(year x 100 km) respectively. The 138 kV transmission line fault type distribution is: 14.6 % (3PH), 4.9 % (LL), 10.6 % (2LG), and 69.8 % (SLG). The 230 kV transmission line fault type distribution is: 7.5 % (3PH), 19.3 % (LL), 13.7 % (2LG), and 59.5 % (SLG). The 138 kV and 230 kV busbar failure rates are: 0.29 and 0.46 faults/(100 busses) respectively. The 138 kV and 230 kV busbar fault type distribution is: 20 % (3PH) and 80 % (SLG). Transmission line SLG and 2LG fault resistance of follows a Weibull distribution with parameters: δ=33.1156 and β=1.4594 (138 kV network), and δ=38.2712 and β=1.8406 (230 kV network).

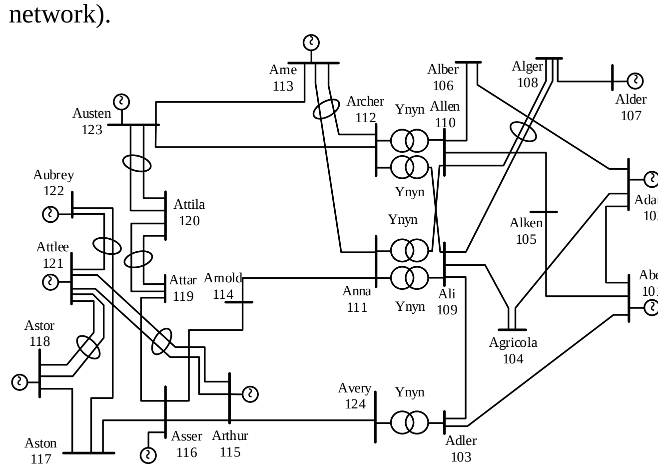

Fig A1 – IEEE one area Reliability Test System 96.

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BIOGRAPHIES

André dos Santos works for the Portuguese Transmission System operator since 2002, currently is head of Protection and Automation Conception and Design division. For more than 10 years was responsible for protection studies in the transmission network, and in the design of protection schemes used in Phase Shift Autotransformers, EHV capacitor banks and shunt reactors, and schemes based on nonconventional instrument transformers. Secretary of CIGRE SC B5 / WG 16: Modern Techniques for Protecting Busbars In HV Networks and member of CIGRE WG B5.23. Currently he is doing his PhD thesis in Instituto Superior Técnico (IST), the Engineering School of the University of Lisbon in the subject of Stochastic Prediction of Voltages Sags Depth and Duration in Electric Power Transmission Systems.

Maria Teresa Correia de Barros received the Doctor degree in 1985 and the Habilitation in 1995, both from the Technical University of Lisbon. Professor Correia de Barros has a long academic career at Instituto Superior Técnico (IST), the Engineering School of the University of Lisbon. Together with teaching and research, she fulfilled different management positions, namely as Vice President of the Scientific Council of IST and Pro-Rector of the university. From 2001 to 2009 she was working in Industry, at EDP -Energias de Portugal, namely as Member of the Executive Board of Labelec, the company in charge of Studies, Development and Testing. Her main research interests are the fields of High Voltage Engineering, Electromagnetic Transients and Electrical Power Quality. Currently she is Vice-President of the Power Systems Computation Conference and Chair of International Conference on Power Systems Transients. For more than twenty five years she actively contributed to CIGRÉ activities. Professor Correia de Barros become an IEEE Fellow (2000) in recognition of her contribution to modeling and analysis of power systems transients. Since 2002, she is also a Fellow of the Portuguese National Engineers Association (Membro Conselheiro da Ordem dos Engenheiros). She was granted the CIGRÉ Technical Committee Award 2008 and the ICLP Scientific Committee Award 2014.