Stochastic Analysis of Transient Overvoltages at Substations by Applying the Monte Carlo Method Integrated with ATP

L. Kräulich, A. C. Marchesan, L. Mariotto, F. Loose, M. C. Camargo, G. Marchesan, G. Cardoso Jr.

***Abstract*—The present paper proposes a methodology for stochastic analysis of electromagnetic transients caused by lightning and switching in substations. Such methodology consists on computer-aided simulations using the Alternative Transients Program (ATP) and employing the Monte Carlo Method (MCM) to reproduce the probabilistic phenomena of the aforementioned events. For atmospheric discharges, the method was used to estimate parameters such as amplitude, front time and tail time, considering their statistical features, while for switching it was used to generate commutations in different time instants. Since the original ATP does not provide the resources to perform such simulations, the authors present a procedure to incorporate them through the use of foreign models, available in the software mentioned above. Some examples are shown in order to demonstrate the use of the methodology.**

***Keywords*: ATP, Monte Carlo Method, Transient Overvoltages, Lightning, Switching.**

I. Introduction

THE determination of all possible dielectric stresses which may occur in devices of a substation is of extreme importance for its design and operation. Some types of transients in substations can produce voltages above those produced in laboratory tests. These overvoltages are disturbances that might occur, due mainly to electromagnetic transients – phenomena of short duration, caused by sudden changes in the power system operation.

Lightning phenomena are one of the main causes of external overvoltages in a power system. They are responsible for a significant part of interruptions in the energy supply, harm to equipment, as well as damage to the image of the companies with the consumers.

Moreover, in Extra-High-Voltage (EHV) and Ultra-High-Voltage systems, transients caused by switching are one of the most important factors considered in insulation coordination studies. In fact, with the increase of the voltage level, the system characteristic insulation degree is capable to support external overvoltages such as lightning strokes. In these cases, internal system overvoltages are the ones that determine the insulation level of the system.

Because of the relevance of the aforementioned events for insulation coordination studies, references [1], [2] and [3] address the physical principles of origin considering their probabilistic aspects to analyze the observed overvoltages caused by such events. However, these works are very succinct regarding the methodology used for implementation and simulation in a computer environment.

Therefore, this paper aims to demonstrate the required procedures for simulation of lightning and switching, using the (ATP) as a basis platform. The randomness of these events is contemplated by employing the (MCM).

Furthermore, the presented methodology uses the resource named "Foreign Interface of Models", available in the ATP, in order to incorporate the new functionalities in a single software for analysis. Such procedure increases simulation speed and programming flexibility by allowing the use of alternative programming languages, such as C++, used in this work. This paper is organized as follows: Section II presents the main parameters used in the simulation of lightning and switching, showing its influence on the emergence of overvoltages in electric power systems. Section III presents the MCM, contemplating the probability distributions used in the stochastic modeling of the events in study. Section IV comments on the procedure for the incorporation of the new functionalities in the ATP. Sections V and VI present an example of application using the developed tool, together with the obtained results. Finally, the conclusion is presented in Section VII.

II. Transient Overvoltages

The occurrence of transient overvoltages in power systems are usually caused by the following events: faults, fault clearings, switching operations, load rejection, transformer or transmission lines inrushes, resonance or ferroresonance, lightning and induced overvoltages [4].

The insulation coordenation studies is usually performed from computacional simulations of electromagnetic transients. This paper addresses the transients produced by lightning and switching operations.

A. Lightning transient overvoltages

A lightning strike can be defined as a phenomenon that occurs in the atmosphere, originated in storm clouds and

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L. Kräulich is with Universidade Federal de Santa Maria (UFSM), Santa Maria, RS, Brazil (e-mail of corresponding author: llkraulich@gmail.com).
A. C. Marchesan, L. Mariotto, F. Loose, M. C. Camargo, G. Marchesan and G. Cardoso Jr. are with Universidade Federal de Santa Maria (UFSM), Santa Maria, RS, Brazil (e-mails: adriano.marchesan@gmail.com; mariotto@ufsm.br; felipe.loose@gmail.com; matheuskmargo@gmail.com; gutomarchesan@gmail.com; ghendy@ufsm.br).

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expressing itself by an impulsive current flow of high density and short duration. The path that the lightning takes from cloud to ground is usually called the discharge channel [5]. Even though there are many variations of lightning, this work considered only the ones named as negative descendant discharges, comprehending most of the lightning events from cloud to ground.

Lightning induced transient overvoltages are classified as fast-front surges of short duration with decay times of less than 300 μs [5]. In substations and other power system components, such discharges can produce surges essentially in two different ways: through direct incidence over the conductors or equipment and through induction by the electromagnetic coupling between the conductors fields.

Furthermore, lightning overvoltages with incidence in the ground or in closed objects occur more frequently. However, such nature of lightning usually cause overvoltages with relatively low amplitudes, being more relevant in distribution systems. On the other hand, direct incidence over the phase conductors, shield wires or system components may cause more severe overvoltages, even with shorter duration times, triggering the action of the protection equipment in the system.

Among the main parameters of lightning, this work considers the ones potentially capable to influence the value of the generated overvoltages: the *discharge peak current*, the *front time* and the *half tail time*. Such parameters are presented in Fig. 1.

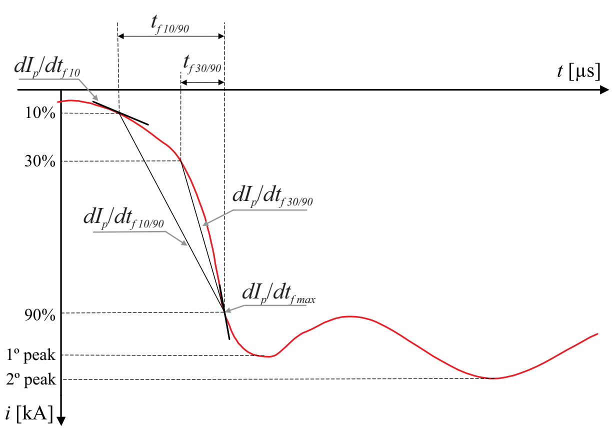

Fig. 1. Typical current rise of a negative cloud-to-ground lightning, adopted from [6].

- *Discharge peak current* (I_p): Corresponds to the maximum value (amplitude) of the discharge current waveform. In a general way, the currents waveforms related to the first incident discharges present two different current peaks, as shown in 1;
- *Front time* (t_f): Theoretically, it is the time interval between the beginning of the waveform until the reach of the first peak. In practical terms, however, it is hard to estimate its exact value. Thus, it is common to define virtual front times, known as $t_{f\ 10/90}$ e $t_{f\ 30/90}$, represented in Fig. 1. The last definition is the one adopted in the present work;
- *Half tail time* (t_h): The time taken between the beginning of the waveform and the instant of time, beyond the peak time, that it takes to reach 50% of the maximum value.

The typical waveform of lightning, illustrated in Fig. 1, is very difficult to reproduce experimentally and also it is not computationally efficient for simulations. Hence, different mathematical models of representation can be found in the literature to better represent the phenomenon [6][7]. These models aim to obtain a standard waveform of test to evaluate the behavior of power system components subjected to lightning induced overvoltages.

It is important to notice that the resulting overvoltage amplitude is dependent on the choice of the current waveform, as demonstrated in a comparative study showing in [8]. This work employed the mathematical representations of the waveforms known as Double Slope Ramp, Double Exponential and Heidler.

1) Double Slope Ramp Waveform: In order to simulate laboratory environments and digital simulation, the current waveform can be represented in a simplified way by an ideal source of a double slope ramp waveform, also known as triangular ramp. This curve is represented by a rising ramp (1) and a fall ramp with different angular coefficients (2).

$$i_{(t)} = \frac{I_p}{t_f} t \tag{1}$$

$$i_{(t)} = -\frac{I_p}{2(t_h - t_f)}(t - t_f) + I_p \tag{2}$$

Even though this waveform does not reflect certain characteristics that are present in the original curve, such as a concave wave-front, it rises the possibility of simulation of overvoltages that can be significantly represented [6]. Another advantage is the simplification that does not require a preliminary parameter adjust. The procedure is completely specified by the front time, half tail time and peak current, as described by (1) and (2).

2) Double Exponential Waveform: This waveform consists by the sum of two exponential curves with opposite signs and distinct time constants. The time constants are chosen in a way which the negative part attenuates faster than the positive part. The resulting sum shapes an impulsive aspect and is represented by (3).

$$i_{(t)} = \frac{I_p}{\eta}(e^{-\alpha t} - e^{-\beta t}) \tag{3}$$

where:
- I_p is the discharge peak current;
- α, β are the attenuation coefficients, can be approximated by $1/t_f$ and $1/t_h$, respectively;
- η is the correction factor of the peak current:

$$\eta = e^{-\alpha t_m} - e^{-\beta t_m} \tag{4a}$$

$$t_m = \frac{\log \beta - \log \alpha}{\beta - \alpha} \tag{4b}$$

- t_m corresponds to the time the current reaches its peak value.

The advantage of this waveform is the easy implementation in laboratory through a network of RC circuits. It is a widely used model to test the supportability of electric equipment and is also used in computer simulations. However, such curve cannot reproduce the concave wave front of real lightning phenomena, having the same problem for the double slope ramp waveform. Moreover, its maximum derivative, close to time zero, is different from waveforms that have its maximum derivative close to the first current peak [6].

3) Heidler Waveform: In order to compensate the limitations presented by the double slope ramp waveform and the double exponential waveform, Heidler [9] proposed an analytic function able to represent very accurately the discharge current waveforms produced by lightning. This curve is obtained by the so called *Heidler Function* (5) and it is been widely adopted in computer simulations [6].

$$i_{(t)} = \frac{I}{\eta}\frac{(\alpha t)^n}{1+(\alpha t)^n}e^{(-\beta t)} \tag{5}$$

where n is the growth factor of the current, α and β are coefficients, can be approximated by $1/t_f$ and $1/t_h$, respectively.

The current discharge growth factor can be determined by (5) for the instant t_m, when the derivative is zero. Nevertheless, it is not possible to obtain the value of t_m in an analytic way, therefore required to resort upon the iterative process represented by (6) [9].

$$t_{m(k+1)} = \frac{1}{\alpha}\left(n\frac{\alpha}{\beta} - \alpha t_{m(k)}\right)^{\frac{1}{n+1}} \tag{6}$$

B. Switching overvoltages

Switching overvoltages may occur due to rapid changes in the circuit breaker contacts and other substation equipment. This is very common in the energization of power transformers and transmission lines, load rejections and clearing short-circuits.

Compared to lightning overvoltage, switching overvoltages have impulsive waveforms and are in general over damped and of short duration. Also, they are characterized by a slower front time [5].

As mentioned before, in EHV and UHV systems, switching transients are one of the main determinant facts for the design and operation of substations. This fact is given by the reason that such overvoltages can be potentially intensified by the inherent capacitance values of these systems.

The magnitude of this type of overvoltage is influenced by the system parameters and its configuration, together with the intrinsic characteristics of the substation equipment. Additionally, the voltage electric angle and the dispersion time between the switch breakers poles give to the event a random aspect, justifying the employment of probabilistic techniques [10].

III. The Monte Carlo Method

The MCM is one best known tools for analysis of stochastic processes. It is a class of statistical methods that seeks to provide a solution estimative of a problem through mathematical simulations of its process [11]. Thus, the method finds itself in contrast with other deterministic methods that aim for the solution of the set of equations that rule the problem.

In the application of the MCM, a very important detail for the quality of the generated results is the definition of the probabilistic model that describes the process to be analyzed. In most cases, this model consist in one probability distribution, i. e., a measure of the probability content of a random variable.

Once known the probability distribution, the procedure takes successive random samples from it using a Random Number Generator (RNG). This procedure mathematically emulates the realization of an experiment to the case study to obtain the results. The RNG is responsible for reproducing the randomness of the event. However, the method does not indicate the exact solution of the problem, providing only one estimative of it. With the increase of a sufficiently number of simulations, the precision of the estimative is also increased, with the most likely result is through a statistical treatment [12]. A simplified structure of the MCM is represented in Fig. 2. Because of its characteristics, the MCM is employed in this work to reproduce the stochastic behavior of the overvoltages caused by lightning and switchings.

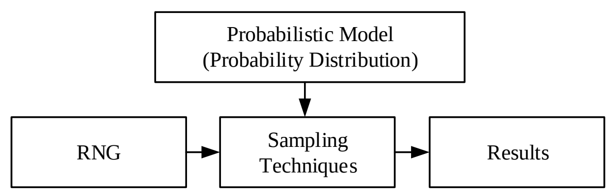

Fig. 2. Simplified structure of the MCM.

A. Probability Distribution

A probability distribution associates the probability of each numeric result of an experiment, i.e., indicates the probability of each value of a random variable. If the random process variable is continuous, then its probability distribution is called "continuous probability distribuition". The equation used to describe a continuous probability distribution is called probability density function (*pdf*) [13].

In the case of events that consider lightning transients, the specialized literature shows that the parameters front time, half tail time and peak current are affected by great regional variations. Table I presents the parameters values which are adopted by the CIGRE [14].

TABLE I
Parameters of the first stroke for negative cloud-to-ground lightnings [14].

Parameter	Mean	Standard Deviation
Peak current	31.1 kA	0.484 kA
Front time ($t_{f\ 30/90}$)	3.83 μs	0.553 μs
Tail time	77.5 μs	0.577 μs

For the probabilistic representation of lightning current waveform parameters, it is possible to use the Log-Normal Distribution [6], described in (7).

$$f(x) = \begin{cases} \dfrac{1}{x\sigma\sqrt{2\pi}}e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}} & , \quad x > 0 \\ 0 & , \quad x \leq 0 \end{cases} \tag{7}$$

On a logarithmic scale, μ and σ can be called the *location parameter* and the *scale parameter*, respectively [13]. In contrast, the mean and standard deviation of the non-logarithmized sample values are respectively denoted here as m and sd.

$$\mu = \ln\left[\frac{m^2}{\sqrt{m^2+sd^2}}\right] \tag{8a}$$

$$\sigma = \sqrt{ln\left[\left(\frac{sd}{m}\right)^2+1\right]} \tag{8b}$$

In the case of a switching event, the parameter to be considered is the electric angle of the voltage waveform at the instant os switching.

In Power Electronics, it is straightforward the use of the techniques known as Zero Voltage Transition (ZVT) and Zero Voltage Switching (ZVS) to minimize the occurrence of overvoltages caused by the commutation of semiconductors devices (switches). In Power Systems, however, it is not usual the supervision of the voltage electric angle in switchings. Thus, it can be inferred that the instant of the waveform when such event occurs is of random feature, which can be modeled by an uniform probability distribution [10]. The *pdf* that describes this distribution is presented in (9).

$$f(x) = \begin{cases} \dfrac{1}{b-a} & , \quad a \leq x \leq b \\ 0 & , \quad \text{otherwise} \end{cases} \tag{9}$$

where a and b are the minimum and maximum values of the function, respectively.

B. Random Number Generator

The Monte Carlo simulation has been performed by sampling the *pdf*, which is realized through generated random numbers. For example, a sequence of numbers r_1, r_2, r_3, $\ldots$, r_n, in the range 0 and 1 is random if it presents the proprieties of uniformity and independence [15]. To produce a sequence it these features, one can use algorithms called Random Number Generators (RNG).

Theoretically speaking, the sequence of numbers generated by a RNG algorithm is actually called pseudorandom because it is obtained by a deterministic process.

Its initial value is known as the seed and its size it is usually called the period. Thus, once reached the end of the period, another identical sequence is generated, creating a cyclic repetition of values [16].

Therefore, the quality of the RNG in simulations is a determinant point to the fidelity of the results. In this work, it was employed the RNG named “Ran” [15], which is capable of fulfill the majority demand of random numbers, including the ones needed for the simulation of the Monte Carlo Method.

C. Sampling Techniques

With the aid of a RNG, it is also needed to make use of a sampling technique in order to reproduce some specific *pdf*. In the case of an Uniform Distribution, one can employ the technique of Inverse Transformation. Such technique consists of the obtainment of an analytic expression (10) for the random variable through a process of integration of the *pdf*.

$$x = a + (b-a)r \tag{10}$$

where r is a random number generated by the RNG.

To obtain the Log-Normal Distribution, the aforementioned technique is non-trivial due to the difficulty of integrating its *pdf*. However, is it possible to use, as an input, the random variable N with zero mean and unity standard deviation. To generate the variable N, a technique called “Box-Müller Technique” [17] was employed.

$$x = e^{(\mu+\sigma N)} \tag{11}$$

IV. The Alternative Transients Program

The ATP is a program for simulation of polyphase electric networks in both transient and steady states, being one of the most widely known programs for such purpose. This software permits the incorporation of new components defined by the user, offering resources as TACS (Transient Analysis of Control System) and MODELS, ATP own programming language.

Through MODELS, it is possible to implement a pré-defined mechanism known as “Foreign Interface of MODELS” for the integration of external models which are developed in other programming languages. In other words, any other language capable to be compiled as object files, such as Fortran, C and C++, can be used to create foreign models to the ATP [18].

Hence, because of its flexibility with the C++ programming language, such methodology was adopted to incorporate the ATP to other mechanisms in order to generate lightning and switching transients through the use of the Monte Carlo Method.

A. Creation of a foreign model

First, to generate a *foreign model*, the ATP must be adapted and added to a personalized program composed by the original codes and the new information about the designed features. Although such procedure is permitted, it is important to emphasize that only authorized users are allowed to obtain the files needed to re-design the ATP kernel. Such files are kept in private domains through the internet and can be accessed only by licensed users.

With the files needed to redesign the ATP, one must implement the new function, to be added as a *foreign model*. In the case of overvoltages originated by lightning, a function was designed to receive the statistical parameters for the discharge as inputs. Thus, the input parameters are the mean, the peak current standard deviation, front time and half tail time. From these parameters, the MCM was implemented with a Log-Normal Distribution to generate the values to be used in the simulation. To generate the current waveform, the function offers the choice of the waveforms Double Slope Ramp, Double Exponential and Heidler. Moreover, to set the time instant occurring discharges was used MCM with uniform distribution causing such events are generated at random intervals.

For the analysis of switching overvoltages, the function receives as input the total number of switchings to be realized (both closing and clearing operations), and the switching start time and end time in the simulation. Through these parameters, the MCM was employed using an Uniform Distribution to define the instants of the switchings.

After the implementation of the new functions, to be added as foreign models, it is also needed to incorporate them to the original ATP. For this, one must change the file name as *fgnmod.f*, a fragment of the ATP code, written in Fotran. These changes are characterized by the addition of the function calls (initialization and execution) of the *foreign model*.

In the function fragment *fgnmod.f* shown in Appendix C, it is shown the incorporation of the foreing models knowns as LIGHTNING and SWITCHING, which were developed in this work.

In addition, with the *fgnmod.f* prepared with the new functions, the file must be compiled together with all the ATP source-codes using a GNU Fortran compiler, version 2.95.2. The new function to be incorporated also must be compiled using an adequate compiler. In this case, a compiler for the C++ language. Finally, the connection of the resulting object-files must be performed for the creation of the personalized ATP. This procedure is explained in detail in [18] and [19].

In order to facilitate the use of a *foreign model*, it is possible to use a graphical pre-processor software to the ATP, named ATPDRaw. The access of the new function accomplished through the block named MODEL.

For example, to access the *foreign model* LIGHTNING, one can choose the option "Default model" and edit the existing code in MODELS language as shown in Appendix B. Through the definition window of the MODEL block, the user can choose the statistical parameters of the atmospheric discharge, the start time, end time and the interval between consecutive discharges. Furthermore, the option "Waveform" offers the possibility to choose the wished current waveform by using the following code: 0 – Double Slope Ramp, 1 – Double Exponential, 2 – Heidler. The *foreign model* LIGHTNING monitors and exports the observed voltage maximum value at each stroke.

In a similar way, to access the *foreign model* SWITCHING shown in Appendix A, the user must use the following code in MODELS language. Therefore, with the aim of providing data to analyze the influence of the system voltage electric angle value at each operation over the generated overvoltages caused by this action, the SWITCHING *foreign model* automatically exports a file in text format containing the angle at the time of the switching together with the maximum voltage verified after the respective event.

V. Example of Application

To demonstrate the functionality of the developed tool, this section presents two simulations based on the schematic displayed in Fig. 3, which corresponds to a substation named "Santa Maria 3 – SM3", belonged to a local utility, named CEEE-GT, at Santa Maria, Brazil. This substation is composed by three 230/69/13.8 kV – 83 MVA transformers, two 13.8 kV/220-127 V – 225 kVA auxiliary transformers, three 230 kV and four 69 kV transmission lines, respectively.

In order to simulate the occurrence of direct lightning strokes generated by the LIGHTNING *foreign model*, a simulation was performed using the software ATPDraw to design a schematic of the 69 kV side from the secondary of transformers PT-1, PT-2 and PT-5 at the beginning of the transmission line. To represent the high-frequency model of each equipment, typical values found in [20] and are presented in table II.

TABLE II
Parameters for high frequency equipment models [20].

Equipment	Value
Capacitive Voltage Transformer (CVT)	5.0 nF
Current Transformer (CT)	0.5 nF
Power Transformer (PT)	4.0 nF
Circuit Breaker (CB)	0.1 nF
Circuit Switcher (CS)	0.1 nF

The surge arresters were modeled based on the MOV element (type 32) available in the ATP. The values used for the $V \times I$ model characteristics are presented in table III. For the 69 kV surge arresters, the Nominal Arrester Rating is 54 kV, together with a Maximum Continuous Operating Voltage of 42 kV. For 230 kV, the Nominal Arrester Rating is of 180 kV, together with a Maximum Continuous Operating Voltage of 144 kV.

TABLE III
Surge arresters $V \times I$ characteristics.

Current [A]	69 kV SA Voltage [V]	230 kV SA Voltage [V]
50	90000	344000
100	100000	352000
400	110000	371000
1000	115000	387000
2000	120000	402000
3000	123000	413000
5000	128000	441000
10000	139000	476000
20000	153000	526000
40000	175000	597000

The lightning statistical parameters used in the simulation follow the determination of the International Council on Large Electric Systems [14], which gathers data from several authors, groups and measurement towers of atmospheric discharges. These values are presented in table I.

For simulation purposes, 100 discharges were performed in phase "a" of the transmission line "Santa Maria 4". The following work did not consider the influence of the shield wires, neither the region's lightning strike density, facts that influence in the current amplitude and the number of strokes that directly affect the phase conductors. However, the *foreign model* interface allows the insertion of these parameters by the user, in cases where such information is desired in the simulation.

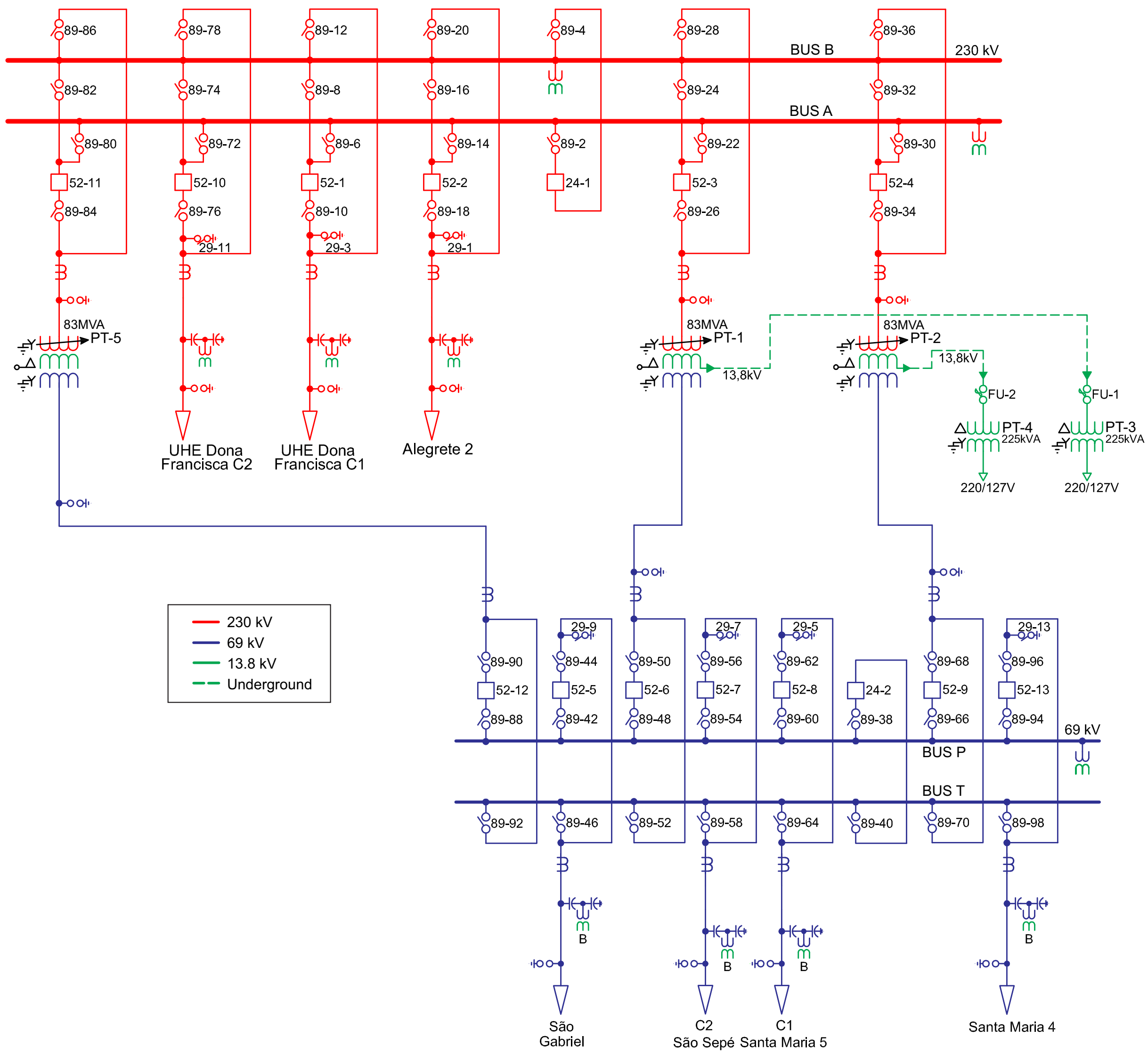

Fig. 3. Representative schematic of substation “Santa Maria 3”.

Furthermore, for the SWITCHING *foreing model*, transformers PT-1, PT-2 and PT-5 were modeled with the aid of the “Saturable 3-phase” model available in the ATP, and the values of the impedances in per unit on a 100 MVA base presented in table IV. The circuit breakers and circuit switchers were considered as ideal switches. Current transformers and capacitive coupling transformers were not represented.

TABLE IV
POWER TRANSFORMERS DATA

Power Transformer	Parameter	R [p.u]	X [p.u]
PT-1	Z_{ps}	0.00713	0.1703
	Z_{pt}	0.01362	0.2964
	Z_{st}	0.01304	0.1051
PT-2	Z_{ps}	0.00705	0.1692
	Z_{pt}	0.01342	0.296
	Z_{st}	0.01286	0.1033
PT-5	Z_{ps}	0.0043	0.1637
	Z_{pt}	0.01362	0.2964
	Z_{st}	0.01304	0.1051

Finally, a simulation was performed, corresponding to 100 switching for the 52-13 circuit breaker connecting the transmission line “Santa Maria 4”. To represent this breaker specifically, a TACS switch (type 13) element was used in order to receive the commands from the SWITCHING *foreing model*.

VI. Simulation Results

This section shows the results obtained by the simulations performed. Fig. 4 presents the following waveforms, implemented in the LIGHTNING *foreign model*: Double Slope Ramp, Double Exponential and Heidler. The choice of the waveform is determined by the user. In this work, the simulations were performed considering only the Double Slope Ramp waveform.

Fig. 5 shows the incidence of lightning in the system. The non-regularity of the time intervals between each stroke is noteworthy, characterizing the random nature granted by the use of the MCM. This aspect is also noted in the lightning parameters such as the current amplitude, front time and tail time at each occurrence.

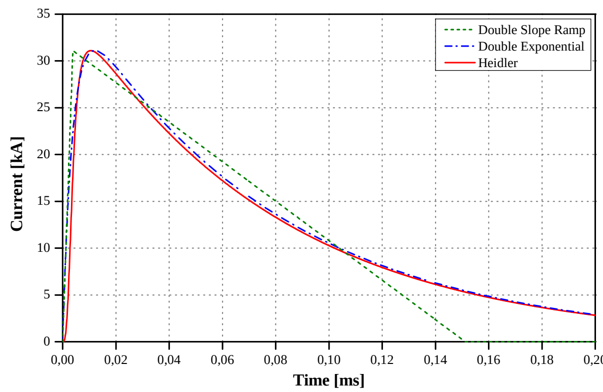

Fig. 4. Implemented Double Slope Ramp, Double Exponential and Heidler waveforms.

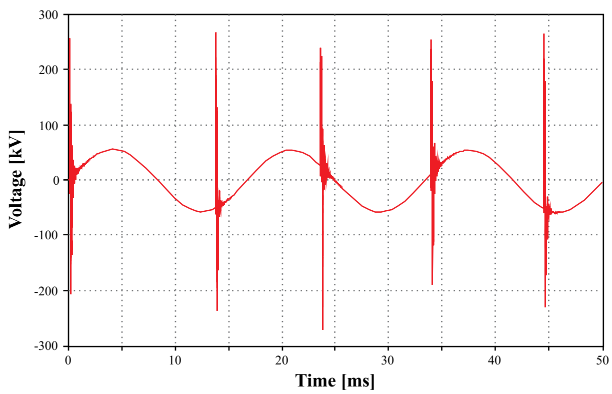

Fig. 5. Measured voltages in phase A of 69 kV substation bus with overvoltages produced by atmospheric discharges.

Fig. 6 presents a histogram containing the statistical analysis of the overvoltages in the system, caused by the lightning strokes. Thus, the graph relates the number of events occurred versus the overvoltage range. It is verified that in 18% of the events the were between 265 kV and 270 kV.

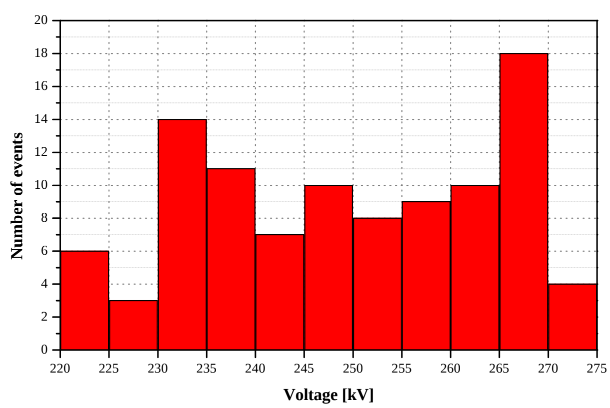

Fig. 6. Histogram of the number of events in relation to the lightning voltage range.

Fig. 7 shows the overvoltages produced due to switchings in the system. They also occur at non-regular time intervals due to the use of the MCM. It is also worthy to notice in detail the overvoltages generated by switching the circuit breakers. It was observed that in 38% of events the voltages were between 104 kV and 108 kV.

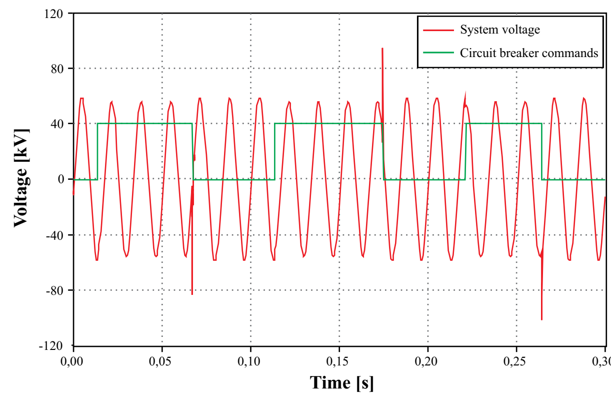

Fig. 7. Voltage generated during breaker switching operation according to the time interval.

Once the switchings are responsible for overvoltages of internal origin, it is interesting to perform an analysis on the influence of the voltage electric angle in which such events occur by associating it with the generated overvoltage. Fig. 8 displays a histogram of the maximum voltages observed versus the switching electric angle. The results show the occurrence of the greatest values in ranges from $120°$ to $140°$ and from $300°$ to $320°$.

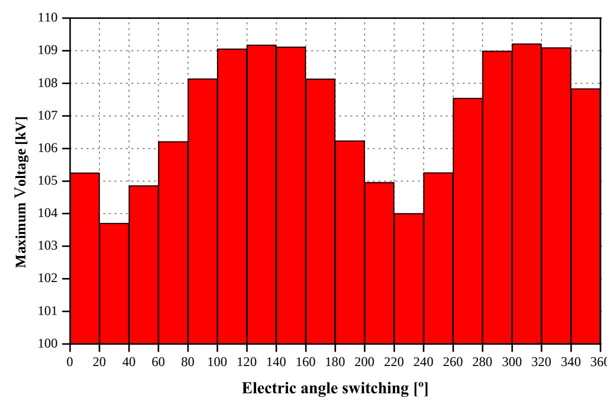

Fig. 8. Histogram of maximum voltage in relation to the electrical angle switching.

VII. Conclusion

This paper presented a methodology for stochastic analysis of transient overvoltages caused by lightning and switching in substations. It has been used the Monte Carlo Method for representing the randomness of these types of events.

To reproduce the simulations, the ATP was chosen, since it has the advantage of enabling the implementation of mathematical models proposed by MCM in C++ language. The decision to set up algorithms with high-level languages and later attach them in a new executable ATP turned the work more flexible and optimized. Furthermore, it is important to emphasize that this methodology gives to the user the possibility to set the parameters of interests for simulation of such events.

The methodology has been applied on a real power system, and it can be seen that in the overvoltage caused by lightning the MCM provides the random behavior to the waveform by the parameters that correspond to peak current, front time and half tail time, and also in the voltage electrical angle of incidence. Similarly, for switching overvoltages, the method attributes the probabilistic behavior to the voltage electric angle at the instant of closing and clearing the circuit breaker. In addition, data exported by the developed tool allow a statistical analysis of the voltages generated by the simulated events.

VIII. Appendix

A. Model code to access the foreign model swtich

```
MODEL SWITCH
DATA
  NumSW  {dflt: 0}
  Tstart {dflt: -1.0}
  Tstop  {dflt: 1000.0}
OUTPUT
  com
VAR
  com
INIT
  com:=0
ENDINIT

MODEL comSW FOREIGN SWITCHING {ixdata:3, ixin:4
     ixout:1, ixvar:1}

EXEC
  USE comSW AS comSW
    DATA xdata[1..3]:=[NumSW, Tstart, Tstop]
    INPUT xin[1..4]:=[t, starttime, stoptime,
         timestep]
    HISTORY histdef(xvar[1]):=0
    OUTPUT com:=xout[1]
  ENDUSE
ENDEXEC
ENDMODEL
```

. SWITCH.mod

B. Model code to access the foreign model lightning

```
MODEL STROKE
DATA
  Waveform {dflt: 0}
  Tstart   {dflt: -1.0}
  Tstop    {dflt: 1000.0}
  NumLG    {dflt: 10}
  Seed     {dflt: 17}
  IPm      {dflt: 31.1E3}
  IPsd     {dflt: 0.484E3}
  TFm      {dflt: 3.83E-6}
  TFsd     {dflt: 0.553E-6}
  THm      {dflt: 77.5E-6}
  THsd     {dflt: 0.577E-6}
OUTPUT
  wave
VAR
  wave
INIT
  wave:=0
ENDINIT

MODEL WaveSTR FOREIGN LIGHTNING {ixdata:11,
    ixin:2 ixout:1, ixvar:1}

EXEC
  USE WaveSTR AS WaveSTR
    DATA xdata[1..10]:=[Tstart, Tstop, NumLG,
         Seed, IPm, IPsd, TFm, TFsd, THm, THsd]
    INPUT xin[1..2]:=[t, timestep]
    HISTORY histdef(xvar[1]):=0
    OUTPUT wave:=xout[1]
  ENDUSE
ENDEXEC
ENDMODEL
```

. STROKE.mod

C. Change in the subroutine fgnmod.f

```
 (...)
DATA refnam(2) / 'LIGHTNING' /
DATA refnam(3) / 'SWITCHING' /
 (...)
ELSE IF ( iname.EQ.2 ) THEN
  IF (iniflg.EQ.1) THEN
   CALL lightning_ini(xdata, xin, xout, xvar)
  ELSE
   CALL lightning_exe(xdata, xin, xout, xvar)
  ENDIF
CONTINUE ! ------------------------------
ELSE IF ( iname.EQ.3 ) THEN
  IF (iniflg.EQ.1) THEN
   CALL switching_ini(xdata, xin, xout, xvar)
  ELSE
   CALL switching_exe(xdata, xin, xout, xvar)
  ENDIF
CONTINUE ! ------------------------------
 (...)
```

. fgnmod.f

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