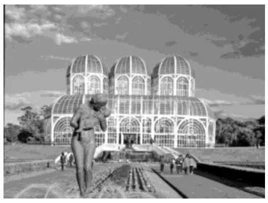
X International Symposium on
Lightning Protection
9th-13th November, 2009 – Curitiba, Brazil



LIGHTNING PERFORMANCE OF MEDIUM VOLTAGE OVERHEAD LINES

Marco A. M. Saran[1], Manuel L. B. Martinez[1]
[1] High Voltage Lab. of the Federal University of Itajubá, Brazil – marco@msaran.com, martinez@lat-efei.org.br

Abstract - The medium voltage systems performance front lightning discharges is very dependent on its modelling, as the model approaches the reality, more it becomes extremely complex and time expensive, as a result, it generally leads to the adoption of some sort of simplifications and approximations. The present work aims at the study of a large variety of effects of the lightning discharges, its impacts and preponderant factors for analysis in different real systems, as far as searching for a balance between the models approximation and the resultant errors. With this in mind, it uses models that are more precise, stochastic process simulations, electromagnetic transients simulations, real information from the networks and statistical analyses. Therefore, it is possible to establish the main intervention points for the improvement of the medium voltage overhead distribution systems performance front lightning discharges.

1 INTRODUCTION

The objective of this paper is to study the large variety of effects of the lightning discharges, its impacts and preponderant factors for analysis into different real distribution systems. Thus, establish the main intervention points for the performance improvement by the impact response of the equipment installed in the network, as an example: transformers, insulators, and surge arresters.

For this purpose, an entire analysis methodology and simulation have to be developed, generating a valid procedure to infer the behaviour of the system and of the installed equipment in the occurrence of a lightning surge.

The development of this methodology involves since the elaboration of a computational program for the treatment, exhibition and use of the geographic information databases of the system, as well as simulation, stochastic analysis, probability and statistics of the occurrence of surges caused by lightning.

In addition, an interface module was developed to do electromagnetic transient simulations, where all the dynamics of the distribution and dissipation of the surge will be detailed and analyzed, as well as the impact into the equipment and elements of the system.

2 MODELLING AND APPROXIMATIONS

The medium voltage distribution systems are, in great majority, composed of three-phase system, consequently demanding a surge analysis for each phase independently. However, by the relatively small distance between the conductors and considering the electromagnetic coupling of the phases, the effect of the lightning discharge surges are indeed shared by the three phases with small differences, which can be neglected. Then, to reach a better analyses speed and minor modeling complexity, a single-phase modeling of the circuits is used, which is a valid approach, that result in a faster analysis and less time expensive process.

As well as to reach a balance between the model complexity and the result error, it was adopted the use of a real topology for the distribution network, using geographic referenced database. In addition, to minimize the total error of the simulations, many cases were simulated with the Monte Carlo Method.

However, some simplifications had to be taken in order to reduce the complexity and the amount of information required of the real topology. For this reason, a plain area was adopted for the entire area of the distribution network, that is, without any information about topography or elevations. Also real elevated structures, like towers, buildings and trees had not been considered automatically; even so, they are simulated through the manual inclusion of high points.

The adoption of these simplifications was mainly taken by the difficulty and complexity of obtaining and dealing with digital data about topography and elevated structures, since it is necessary to implement the automated routines without considering such simplifications.

Taking these simplifications led to a larger number of direct interceptions from the lightning discharges for the distribution networks, in other words, an overestimated result for the worse case. However, through the manual inclusion of elevated structures some different cases can be simulated, since a low natural shield for the network up to one high degree of shielding, as a result with a larger number of induced surges.

3 PERFORMANCE SIMULATIONS

Each performance simulation is executed on a great area, covering the entire distribution network, however not much bigger than that, making possible to simulate a set of circuits. It can deal not only with a typical urban network, more uniform and with greater network density, but also with rural networks, more dispersed and non-uniforms, or even a mix of both.

In this total area, and based on the number of discharges to the ground by square kilometer per year (discharges/km²year), adopted by the regional characteristic or an average, the Monte Carlo Method is used to simulate many years of lightning discharges. These simulations generate an enormous mass of data that can be analyzed statistically, as a result giving data that are more reliable for the studies.

The probable position of the discharge impact is defined randomly within the total area, in the same way that the current intensity, which follows a lognormal distribution with average of 31 kA, is random as also as the correlated speed of the return stroke.

After these definitions, of the descending impact point and current intensity, the verification of the attractiveness area are initiated, following the Electro-Geometrical Model [1,10], defining if that discharge will reach some structure, the network or the ground.

When the discharge intercepts the network directly, the peak overvoltage is calculated based on the parameters of the travelling waves and surge impedance of the line. On the other hand, when the lightning do not intercept the network but generates an induced surge, it is necessary to calculate the distance from the impact point to the closer network point and the electromagnetic fields, in order to verify the total induction, as a result the surge peak overvoltage.

The method adopted for the calculation of induced surges was the LIOV-EFEI [13, 14], this is based on the LIOV Code [3] (Lightning Induced Over-Voltage) developed in the University of Bologna and adapted, with some simplifications, by the High Voltage Laboratory (LAT-EFEI) of the Federal University of Itajubá, Brazil.

The LIOV-EFEI model only considers steep surges and the ground is adopted as lossless. Commentaries could be made regarding the procedure precision; however, as the method maximizes the amplitude of the induced surges, it is considered that the introduced errors compensate the adopted simplifications, resulting in an efficient approach, extremely useful for engineering analyses.

To define this model, in the form of an equation that relates the discharge current intensity and the distance to the line, getting the amplitude of the induced tension, simulations had been carried through using the Monte Carlo Method and the LIOV code. Based on this procedure, functions that relate the values of the discharge chain intensity and distance of the point of impact to the line had been defined for the calculation of the induce surge amplitude.

For the performance simulation, three major cases were simulated: one rural network, one flat urban network and an urban network considering elevated structures.

3.1 Rural Simulation Results

The rural network by possessing a much greater area than the urban, needed a large amount of lightning discharges simulations. A total of 707,214 discharges were simulated, equivalent to 364 years for the case of an average of 6 discharges/km²year and 323.85 km² of total area. From this total, only 4.34% had directly intercepted the network, this is caused by the sparse distribution of the circuit into a big area, leading to a small probability of interception by the network of a lightning discharge.

For the 30,693 discharges of direct interception, the histogram of the current intensities is shown in the Fig. 1. From the fitted lognormal distribution it was obtained the current intensity value with 50% of probability: 40.24 kA; with 90% probability: 16.66 kA and with 10% probability: 97.22 kA.

In the case of the discharges that had not intercepted the network directly, that is, the remaining 676,521 occurrences, they had generated the overvoltage histogram of the induced surge, as it can be seen in the Fig. 2. In which it is possible to see the low values found, that were caused by the general great distances from the impact point to the network. From the fitted lognormal distribution it was obtained the value of surge with probability of 50% of occurrence: 6.46 kV; with probability of 90%: 1.28 kV and with 10%: 32.61 kV.

3.2 Urban Simulation Results

In the case of the urban network without the presence of elevated structures, it was simulated 286,237 lightning discharges, what is equivalent to 2,141 years of lightning discharges in the network. Number achieved by the total area of 22.28 km² and the regional average of 6 discharges/km²year.

From this total, 95,392 discharges intercepted the network directly, where, by the fitted lognormal distribution, it was obtained the current intensity with 50% of occurrence probability: 38.14 kA; 90% of probability: 16.81 kA, and 10%: 86.53 kA, as it can be seen in the Fig. 3.

The remaining 190,845 discharges that did not intercept the network represent more than twice of the number of direct interception. The Fig. 4 represents the overvoltage's histogram.

The distribution that got optimum performance was the tri-parametric Weibull, in which it is possible to obtain the overvoltage value with 50% probability of occurrence that was 29.49 kV; the 90% probability: 6.46 kV and the 10% probability: 77.62 kV.

3.3 Urban with Elevated Structures Simulation

To make the simulated urban circuit better represent a real case of an urban area, it is necessary to take in consideration the presence of elevated structures, as trees, buildings, high constructions, towers, among others. Thus, through the inclusion of simulated elevated structures in the circuit, which attracts the lightning discharges, diverting them from the networks, it will supply a shielding effect.

Tests had been made with configurations for the simulations of elevated structures, resulting in direct interception index from 2.24% to 15.43% [5, 7].

These two previous simulations had shown a behavior of a dense and a sparse urban region respectively, simulating an urban zone of a central region of a great city and a small town. An intermediate case was adopted, that could contemplate a large number of cases, representing an average condition.

In this condition, 259,250 lightning discharges had been simulated, or the equivalent to 1,939 years of lightning discharges reaching this region. From these, only 2,938 had been intercepted directly by the network. On the other hand, an elevated structure or the ground intercepted 256,312 discharges, which is equivalent to 98.87% of the cases.

The shielding of the network was relatively high, however the study continued for the good statistical representation of this case and by being a better study condition for the induced overvoltage's.

In the case of the direct interceptions, the fitted distribution found the value of discharge current intensity with probability of 50% of occurrence was obtained by the fitted lognormal distribution and was 11.60 kA; for the case of probability occurrence of 90%: 5.29 kA, and for 10% probability: 25.44 kA.

It is easy to see the fall in the direct interception current intensities observed, form 38.14 kA to 11.60 kA in the occurrence probability of 50%. Due to the fact of the bigger intensity discharges, by possessing a greater attraction distance, that reaches firstly an elevated structure than the network conductors.

In the histogram of the induced overvoltage's the distribution fit was the tri-parametric Weibull distribution. Where can be obtained the values of surge overvoltage's with probability of 50% of occurrence: 31.45 kV; of 90% probability: 13.70 kV and of 10% probability: 72.20 kV.

The increase in the found surge levels is notable, where the maximum limit increased from 160 kV, in the case without the presence of elevated structures, to 375 kV in this in case. It was due to the high intensity discharges that reaches elevated structures closer to the network. However, as in the previous case, the biggest concentration was in the band of the 10 to 30 kV, what resulted in the values of probability very similar between the two cases.

Where for the 50% probability it was increased from 29.49 to 31.45 kV, and 90% probability from 6.46 to 13.70 kV, however, the 10% probability had indeed a small decrease from 77.62 to 72.20 kV.

4 TRANSIENT SIMULATIONS

Electromagnetic transitory simulations through the ATP program had been executed to detail and analyze the dynamics and distribution of the surge into the system and the response from the installed equipment.

For this reason, 45 cases of induced overvoltage's due to lightning discharge had been simulated, plus 45 more simulations for overvoltage's generated by direct impact lightning discharge, totalizing 90 simulations. All of them executed in an urban feeder, in which 36 of them, that is, 40% had been executed with the presence of elevated structures.

The simulations take in care the line surge impedance, surge arresters, medium voltage transformers and its basic insulation level, insulators and the line critical flashover overvoltage for the entire distribution network under analyses.

The surge arresters was modeled by the voltage by current standard curve for gapped silicon carbide (SiC) surge arresters, this was made necessary for the, up till now, great amount of units installed in the field of surge arresters with the older technology gapped silicon carbide, being then possible to compare the results.

The Fig. 11 shows the histogram of the simulation results for the current dissipated by the surge arresters under the network direct interception lightning discharge. In this histogram, it is possible to see that the majority of the surge arresters dissipation stayed between 1.5 to 10 kA.

On the other hand, Fig. 12 shows the histogram of the simulation results for the terminal overvoltage in the transformers generated by network direct interception lightning discharge. From this histogram, it is possible to notice that the medium voltage transformer class 15 kV, are receiving surges bigger than its basic insulation level, between a 100 to 500 kV.

In the opposite case, when the surge arresters and transformers are under induced surges, it is notable the lower intensities. As it is possible to see in Fig. 13, all of the current dissipated by the surge arresters are under one kA.

Also for the transformers overvoltage's, we can see in Fig. 14 that all of them are under the minimum transformer basic insulation level of 95 kV for the 15 kV class.

In other words, when the distribution systems are inside a dense urban region, with many elevated structures that can deviate and dissipate the lightning discharge, there is no problem or fault occasioned by the induced surges in the transformers or even in the surge arresters.

In fact, not even the insulators are requested, because none of the cases provoked surges bigger than the lines critical flashover overvoltage. In these cases, the worse problem will be the transferred surge to the low voltage circuit, which cannot deal with that amount of energy.

However, if the distribution system was intercepted directly, a common situation in rural or less dense urban regions, the surges achieve high values that are capable of causing a transformer, an insulator, or even a surge arrester to fail. The Table 1 shows the probability of a direct interception lightning discharge to cause a failure in a transformer, according to its basic insulation level for the 15 kV class, or to cause an insulator flashover, according to the lines critical flashover overvoltage.

Table 1: result summary for the simulations of direct lightning discharge interception.

Condition	Probability
> BIL 95 kV	80.0%
> BIL 110 kV	75.6%
> CFO 150 kV	46.7%
> CFO 175 kV	35.6%
> CFO 200 kV	26.7%
> CFO 225 kV	22.2%

The occurrence probability of transformers overvoltage and surge arresters current, obtained by the fitted distribution from all the simulations, as it consider half of the cases as direct interception and the other half as induced surges, must be properly pondered with the bigger probability of the induced surges, which could indeed decrease the values shown.

Since there are 45 cases of direct interception, it should have 300 cases of induction, or 7 times more, considering a direct interception probability of 15%. Table 2 shows the adjusted case.

Table 2: probability summary: adjusted values.

Probability %	Transformer Overvoltage [kV]	Surge Arrester Current [A]
5	116.21	4,612.70
10	90.79	2,514.12
50	38.00	39.94
90	15.91	0.001
95	12.43	0
9	95.0	------
5	110.0	------

5 FIELD VALIDATIONS

Through a research and development project in partnership with AES Sul Brazilian utility, approximately 300 gapped silicon carbide surge arrester unities had been removed from the same distribution urban network of the simulations. These unities were submitted through an analysis technique for the measurement of the bigger current intensity that the surge arrester had discharged; this is done based on the electrodes etchings measurement and comparison with laboratory made marks.

From this great data volume, the graph of Fig. 15 was traced, in which it is possible to verify the great proximity and similarity between the simulated and real measurement cases.

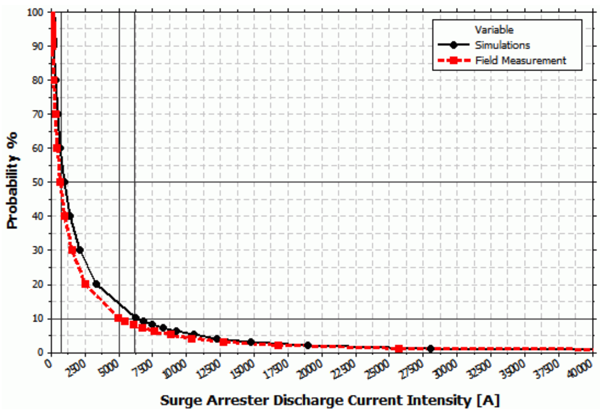


Fig. 1 – Field fitted distribution vs. simulation fitted distribution comparison.

It is clearly in Fig. 15 that, mainly for the current intensities with 50% probability or greater, both curves presents a great similarity, in fact, only below the 40% probability that the curves diverge a little. From the graph, we can notice that the occurrence of current intensities of 700 A or lesser possesses probability equal or superior than 50%. For a 10% probability, we have that the current intensity situates in the band of 5 to 6 kA, for a current intensity of 10 kA the probability will be approximately 5%, and for a current intensity of 20 kA the probability will be approximately 2%.

6 CONCLUSIONS

Through these system performance simulations for lightning surges, it is possible to figure the improvement possibility of the system protection. Where, for predominantly rural systems, the surges by lightning direct impact stayed below 4% probability, with an average current intensity of the order of 40 kA and overvoltage of the order of 6 kV.

On the other hand, for the less dense urban network, that is, small towns, where the amount of elevated structures is small, it has a direct impact index with 15% of probability. However, for an urban network of metropolitan region, with higher density of constructions, an index of only 2% of direct impact was achieved.

The result for an average case had presented around 10% probability of direct interception by the distribution system, with average current intensity of the order of 12 kA and average overvoltage intensity of order of 31 kV.

It is obvious the importance of better studies of the surges provoked by electromagnetic coupling over the ones caused by direct interception, where the average probability stayed around 90% of the cases being by induction.

Analyzing the results of the electromagnetic transient simulations it is possible to observe that, for induced surges: none surge arrester dissipated current superior than 1 kA; none transformer was submitted to an overvoltage superior to its basic insulation level (BIL) and the occurrence possibility of a flashover in the insulators only could be verified in 2 cases, that is, 4%.

As this represented around 90% of the cases, it is evident that the medium voltage overhead distribution systems would not be subjected to failures or interruptions caused by induced surges. However, to this be an absolute truth, the operational condition of the surge arresters, insulators and the transformers withstanding must be in satisfactory conditions.

It is also important to remind the necessity of the presence of surge arresters in the each medium voltage terminal of every transformer installed in the system and even through the network. Condition that, not rare, is verified inadequate or for the lack of units or by miss specification. As a result, we have that the no observance of all the above requirements, mainly for the transformers and surge arresters, let the system into situations of failures, faults or interruption even for the cases of lightning induced surge.

Although for the simulated cases of direct interception, the situation becomes critical. Since it has the average current dissipated by the surges arresters goes up for an average of 9 kA; and the transformers overvoltage's surpassed the withstanding in 80% of the cases and the flashover probability in the insulators was next to 50%.

The Table 3 contains a summary of the electromagnetic transient performance simulations of the system, in the cases of surges by induction and direct impact.

Table 3: summary of the results of the transitory simulations of electromagnetic.

	Surge Arresters Discharge Current [A]			Transformers Overvoltage [kV]		
Surge	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**
Induced	22	283	892	10	27	53
Direct Impact	680	4,779	48,412	39	214	2,173

It is possible to notice by the values presented in the Tables 1, 2, and 3 that for the condition of surge caused by direct interception, the probability of failures and interruptions in the system could be very high. In the surge arresters, the dissipated current reached the mark of 48 kA, intensity superior than the capacity of almost all of the surge arresters for distribution networks class 15 kV.

For the transformers, the fault probability stayed between 70 and 80%, as the average overvoltage value of 214 kV is very superior the biggest standard BIL of 110 kV. As for the flashover probability in the insulators, for the standard condition of 150 kV of critical flashover overvoltage (CFO), it achieve 50%, however this value can be reduced to 20% with the increase of the lines CFO to 225 kV. Therefore, for the direct interception surges in the system the possibility of an interruption is almost certain.

To validate the simulations, a comparison of the results with the current intensities dissipated by the gapped silicon carbide surge arresters units removed form the field was made, Fig. 15. In which, the similarity of the simulations with the real cases can be verified, occurring a little distortion for the probabilities lower that 40%, where the simulations had presented bigger values than the real cases.

These differences could be attributed to the approach used and the simplifications adopted, which tend to present a small error regarding to the physical event that they model, consequently the sum of these errors cause the verified discrepancy, indeed leading to an overestimated result, the worse situation.

6 REFERENCES

[1] Marco A. M. Saran, "Lightning Overvoltage's in Medium Voltage Lines", Master Thesis, Federal University of Itajubá, Brazil, Feb. 2009.

[2] Manuel L. B. Martinez, Pedro H. M. dos Santos, "Study of the Induced Voltages in Distribution Networks, Guide for the Performance Improvement of the Overhead Distribution under Lightning Discharges", High Voltage Lab., Federal University of Itajubá, Brazil, March, 2004;

[3] Carlo A. Nucci, Mario Paolone, "Calculation of Induced Voltages in Medium Voltage Overhead Systems due to Lightning Strokes Using the LIOV Code", Report for the Second Phase of the R&D Project for the AES Sul Utility, October, 2003;

[4] Marco A. M. Saran, Rafael R. Bonon, Manuel L. B. Martinez, Hermes R. P. M. De Oliveira, Carlo A. Nucci, Mario Paolone, "Performance of Medium Voltage Overhead Distribution Lines Against Lightning-Induced Voltages: A Comparative Analysis", GROUND'06 e 2nd LPE - International Conference on Grounding and Earthing & 2nd International Conference on Lightning Physics and Effects, Maceió, Brazil, November, 2006;

[5] Marco A. M. Saran, Manuel L. B. Martinez, Hermes R. P. M. De Oliveira, "Performance of Medium Voltage Urban And Rural Distribution Lines Front Lightning Discharges And Induced Surges", GROUND'06 e 2nd LPE - International Conference on Grounding and Earthing & 2nd International Conference on Lightning Physics and Effects, Maceió, Brazil, November, 2006;

[6] Marco A. M. Saran, Rafael R. Bonon, Manuel L. B. Martinez, Hermes R. P. M. De Oliveira, Carlo A. Nucci, Mario Paolone, "Performance of Medium Voltage Overhead Distribution Lines Against Lightning Discharges", International CIGRÉ Symposium – TPLEPS – Transient Phenomena In Large Electric Power Systems, Zagreb, Croatia, April, 2007;

[7] Marco A. M. Saran, Manuel L. B. Martinez, Hermes R. P. M. de Oliveira, "Performance of Medium Voltage Urban and Rural Distribution Lines Front Lightning Discharges and Induced Surges", 15th International Symposium on High Voltage Engineering, Ljubljana, Slovenia, August, 2007;

[8] Marco A. M. Saran, Manuel L. B. Martinez, Carlo A. Nucci, Mario Paolone, Hermes R. P. M. de Oliveira, "Performance Analysis of Medium Voltage Overhead Distribution Line Against Lightning", 19th CIRED, International Conference on Electricity Distribution, Vienna, Austria, May, 2007;

[9] Marco A. M. Saran, Manuel L. B. Martinez, Carlo A. Nucci, Mario Paolone, Hermes R. P. M. de Oliveira, "Comparative Performance of Medium Voltage Overhead Distribution Lines Designs Submitted to Induced Voltages", Power Tech, Lausanne, Switzerland, July, 2007;

[10] IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines, IEEE Std 1410-2004, T&D Committee, IEEE Power Engineering Society;

[11] John G. Anderson, Thomas A. Short, "Algorithms for Calculation of Lightning Induced Voltages on Distribution Lines", IEEE Transactions on Power Delivery, Volume 8, Number 3, Pages 1217-1225, July, 1993;

[12] Parameters of Lightning Strokes: A Review, Lightning and Insulator Subcommittee of T&D Committee, IEEE Transactions on Power Delivery, Vol. 20, No. 1, January, 2005;

[13] Pedro H. M. dos Santos, "Performance Analysis of Medium Voltage Circuits Front Induced Lightning Impulses", Master Thesis, Federal University of Itajubá, Brazil, March, 2007;

[14] Ricardo G. de Oliveira Jr., "Induced Voltages in Medium Voltage Lines", Master Thesis, Federal University of Itajubá, Brazil, August, 2008;

[15] Andrew R. Hileman, "Insulation Coordination for Power Systems", Marcel Dekker Inc., 1999;

[16] G. Vernon Cooray, "The Lightning Flash", IEE Power Series, Volume 34, 2003;

[17] Lou van der Sluis, "Transients in Power Systems", John Wiley & Sons, 2001;

[18] Mustafa Kizilcay, "Power System Transients and Their Computation", Osnabrück University of Applied Sciences, Germany, 2000;

[19] Protection of MV and LV Networks against Lightning, Joint CIGRE-CIRED Working Group C4.4.02, 2005.